# Warfare and the Multiple Adoption of Agriculture after the Last Ice Age

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**Abstract**

This paper examines the puzzle that human beings adopted agriculture independently at least seven and perhaps up to ten times independently in different parts of the world around ten thousand years ago, in spite of the fact that skeletal evidence suggests that the first farmers suffered worse health and nutrition than their hunter gatherer predecessors. It proposes an explanation based on investments in defence, which would have been more necessary for farmers (who being sedentary would have had more resources to defend), but which in turn made them an increased threat to their neighbours. This would have made adoption more attractive among communities whose neighbours had already adopted, leading to a snowball effect of adoption but not necessarily making the first farmers better off than they were before. The paper develops a formal model of this interaction and simulates equilbrium consumption levels, showing that these may decline in the productivity of agriculture over a significant range before eventually increasing.

Keywords: agriculture, defence, violence, contest functions.

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# 1 Introduction[1]

One of the great puzzles of prehistory is why agriculture caught on so fast. Agriculture seems to have been independently adopted at least seven times: in Anatolia, Mexico, the Andes of South America, northern China, southern China, the Eastern United States, and in sub-Saharan Africa at least once and possibly up to four times. It spread from the sites of its original adoption at a speed which seems slow to the modern traveller but is remarkable by the standards of earlier innovations in prehistory - around one kilometer per year westward across the European continent, for example. You might think that, once the idea appeared and the climate made it possible, the answer was obvious: why sweat going out to hunt and gather when you can sit and watch the grass grow? An overwhelming productivity advantage of the new technology would seem quite enough to explain its evident appeal to our ancestors. And yet this suggestion is inconsistent, at least on the face of it, with some puzzling evidence from the skeletons of the first farmers (Weisdorf, 2005, provides an overview). Studies of the bones and teeth of some of the earliest agricultural communities of the Near East show that farmers had worse health (due to poorer nutrition) than the hunter-gatherers who preceded them. Increases in agricultural productivity in later millennia more than made up for this eventually, but even so, the puzzle remains: what prompted agriculture to be adopted so quickly and often within a comparatively short space of time, if it did not achieve the one thing that a new agricultural technique surely ought to achieve - to leave people better fed than they were before?

This paper reviews some attempts to explain this paradox and proposes a new explanation, compatible with but supplementary to earlier accounts, which seem inadequate on their own. It is based on the fact that agricultural communities would have needed to devote substantially more resources to defence than their hunter gatherer predecessors. Sitting and watching the grass grow is not the idyll it seems, for those who are sedentary are also vulnerable. When enemies attack, farmers have much more to lose than hunter-gatherers, who can melt into the forest without losing houses, chattels and stores of food. This is not, of course, to deny that warfare may take place for many other reasons than to steal food (foragers have often engaged in very bloody battles over territory or women, for example - phenomena that lie outside the scope of this paper[2]). But the greater productivity of farmers is nevertheless a source of liability. Farmers not only face

[1] Some parts of this paper draw on material first published in Seabright (2004), though the formal model is original to this paper.

[2] See Baker (2003) for a model of conflict among foragers over access to land. One important difference between land conflict and conflict directly over food and other consumable assets is that the value of land to the victor is dependent on the victor's production technology, whereas the value of food and consumable assets (the focus of this paper) is not.

high risks, but they also need to spend time, energy and resources defending themselves – building walls, manning watchtowers, guarding herds, patrolling fields. This means less time and energy, fewer resources, devoted to making food. It could even happen that the greater productivity of the hours they spend growing and raising food is outweighed by the greater time they must spend defending themselves and the food they have grown – meaning that they produce less food in all. Almost certainly the end of the last ice age dramatically improved the productivity of agriculture compared with the hostile conditions beforehand. But what would that have mattered if all of the additional benefits of the new farming technology ended up being spent on defence?

On its own this story cannot resolve the paradox with which I began, since it explains the poor nutrition of the first farmers only at the price of making it mysterious why they should have adopted agriculture at all, let alone why this new technology should have spread with such rapidity. Stunted farmers would hardly have been a good advertisement to their hunter gatherer neighbours of the qualities of their new wonder diet. What is needed is an account that explains how agricultural adoption could have been individually rational even if perhaps collectively self-defeating, at least in the short run. Game theorists will recognize that we are in familiar territory here, territory this paper will attempt to explore.

We shall never know for sure exactly how important defence was to the first farming communities. The need for communities to defend themselves sometimes leaves clear traces, in the form of walls and weapons. But most of the time and energy absorbed by defence leave no archaeological record, so we cannot be certain that this is what explains the poorer nutrition of the first farmers. Still, what follows is a reasonable guess, and will be backed up by a range of direct and indirect evidence. Agriculture dramatically raised the advantages to mankind of banding together for self-defence. Once constrained by a sedentary lifestyle and unable any longer to play hide-and-seek with its enemies, a large group is much more secure than its members could be in multiple smaller groups. But the result of devoting time, effort and resources to defending yourself is not just to make you feel more secure. It usually also makes your neighbour feel less secure. And in that simple but grim externality lies not only an explanation for the paradox with which we began, but also one of the driving forces of modern society, of its stunning technological achievements as well as its capacity for brutality on an industrial scale.

Once the very first farming communities began to invest systematically in defence, the fact that they could do so began to make them a threat to their neighbours, including communities who were on the margins of adopting agriculture themselves. For there is no such thing as a purely defensive technology. Even walls around a town can make it easier for attacking parties to travel out to raid nearby communities in the knowledge they have a secure retreat. The club that prehistoric man used to ward off attackers was the same club he used to attack others. Once a community has invested in even a modest army, whether of mercenaries or of its own citizens, the temptation to encourage that army to earn its keep by preying on weaker neighbours can become overwhelming. So, even if the first farming communities were not necessarily any better off than they would have been if no-one had adopted agriculture, once the process had started many communities had an interest in joining in. These interactions could lead each to act ineluctably against the collective interests of all.

This paper is organized as follows. Section 2 summarizes briefly what we know about agricultural adoption, and reviews some explanations for the fact that it occurred in the way it did, concluding that these explanations are inadequate on their own, and outlining the elements of my proposed alternative explanation. Section 3 examines evidence for the existence of high levels of violence between human communities in prehistoric times, in the absence of which it would be unlikely that defence could have absorbed a sufficient proportion of resources to explain the paradox. Until perhaps thirty years ago it was widely believed that hunter gatherers and early farmers had lived relatively peaceful lives, but the more recent evidence that I shall summarize makes that now seem highly unlikely. Sections 4 and 5 set out a formal model of agricultural adoption by two communities, in two versions, one making adoption a continuous decision to allocate resources between hunting and farming, the other requiring a one-time adoption decision under which agriculture and hunting are incompatible. The purpose of the model is to show carefully that agricultural adoption can both improve the nutrition of any one community (relative to non-adoption and taking as given the behaviour of the other), while also worsening the nutrition of both communities relative to the status quo ante. I make no claim to have shown that the empirical evidence favors the theory set out here over possible rival theories: only that the theory is compatible with the facts as we know them, and that the mechanism outlined could explain a sufficiently large deterioration in nutrition after agricultural adoption to be worth taking seriously as a contribution to our understanding of this major episode in our human past. Section 6 concludes.

# 2 Agricultural Adoption and Its Context

Evidence about the existence of at least seven and possibly as many as ten independent adoptions of agriculture is summarized in Richerson, Boyd and Bettinger (2001). Independence for independent adoption has been found in Anatolia, Mexico, the Andes of South America, northern China, southern China, the Eastern United States, and in sub-Saharan Africa at least once and possibly up to four times. The subsequent rapid spread of agriculture around the world is documented in Bellwood (1996) and Cavalli-Sforza, Menozzi and Piazza (1994); many case studies are collected in Price and Gebauer (1995) and Bellwood& Renfrew (2002), and the complexity of the factors involved has been stressed by Bar-Yosef (2002) and by Bar-Yosef & Meadow (1995). Furthermore, the work of Cavalli-Sforza and his colleagues, as well as the subsequent literature inspired by it, has cast important light on the way the new technology spread - though their interpretation remains controversial. Cavalli-Sforza (2000) shows that there is a remarkable fit between the diffusion of agricultural technology (chiefly wheat) from the Middle East to various parts of Europe between 9,500 years ago and around 5,000 years ago, and the pattern of human genetic variation across Europe. One plausible interpretation of this evidence is that farmers gradually expanded across the continent (at an average of one kilometer per year for over 4,000 years). They interbred with local hunter-gatherer communities, who had different frequencies of certain particular genes that have left traces in their descendants alive today. For instance, we know that inhabitants of the Basque region of south-western France and northern Spain have significantly different gene frequencies from those of other Europeans, indicating that they resisted longer and more successfully against interbreeding with migrant agricultural groups from further East (though significant interbreeding certainly took place). They also speak a radically different language.

How exactly does the fit between the genetic and the historical evidence show this? First of all, it rules out the possibility that the agricultural way of life spread entirely by cultural emulation, as hunter-gatherers simply copied the practices of their visibly prosperous neighbours (that it nevertheless spread partly by cultural emulation is nevertheless argued forcefully by Underhill, 2002, on the basis of Y-chromosome evidence). On the contrary, these practices were spread at least partly by migration: people and techniques moved together. This was not just a European phenomenon but was true of the other instances of agricultural diffusion that have so far been studied – such as the expansion from Mexico southwards to the Andes, or the Bantu expansion south- and eastwards through Africa beginning about 3,000 years ago. Less clear but still plausible evidence has been found for the hypothesis that corn agriculture was brought from Mesoamerica into the North American Southwest by farmers speaking and early form of Uto-Aztecan sometime before 2500 BCE[3]. Evidence from Eastern Asia is, however, less easy to interpret in this way (see Forster & Renfrew, 2002). Secondly, it rules out the possibility that migrant agriculturalists simply massacred all those hunter-gatherer communities they found along the way, or even just drove them permanently off the land. We don't know, of course, how many of the men they massacred even as they sought diligently to impregnate the women[4]. Evidence from later societies strongly suggests that, where agriculture was pro-

[3]See Leblanc (2005) which provides a nuanced account of this evidence, acknowledging that the low levels of representation of mitochondrial haplogroup A DNA found in indigenous Southwestern populations is hard to reconcile with a straightforward "wave of advance" model, and suggests a hybrid model in which agricultural techniques moved some way ahead of the frontier defined by the migrant farmer groups themselves.

[4]Richards (2003) reports point estimates for the proportion of mitochondrial DNA from Neolithic mi-

ductive enough to permit more than a purely subsistence existence, many of the captured males would have been put to work as slaves[5]. But that the migrant farmers interbred with the women is an inescapable conclusion[6].

If agriculture was such a wonderful invention, wonderful enough to make farmers either strong enough or persuasive enough to press their techniques upon the hunter gatherer communities with whom they came into contact, why had human beings not adopted it earlier? As Mithen (1996) points out, earlier humans had sophisticated biological knowledge of both animals and plants, so that it does not seem likely that the problem lay in lack of the kinds of skill that agriculture would have required. Also, as Ofek (2006) points out, earlier hominid evolution had seen a number of powerful scial and economic innovations including the hunter-gatherer lifestyle itself. Existing theories of agricultural adoption are dominated by two hypotheses: that of a late Pleistocene food crisis caused by population pressure (Cohen, 1977), and that of rapid climate change including global warming (Richerson, Boyd and Bettinger, 2001; Dow, Olewiler & Reed, 2006). The first is problematic because of evidence that hunter-gatherers were able to control population growth through various measures including infanticide. The second may only be a necessary and not a sufficient condition for adoption, given the evidence about the health of early farmers, due to Cohen & Armelagos (1984). Given that evidence, climate change might not have increased agricultural productivity enough to make its adoption inevitable. As Mithen points out, many previous episodes of comparable climate change had not led to agriculture (though Richerson et. al. cite other features of climate change in the Holocene, notably reduced climatic variance and higher carbon dioxide concentrations, which may have been different from earlier episodes). Mithen himself offers his account of an evolving human consciousness as a way of explaining why modern humans might have been more aware of the possibilities of agriculture than their biologically sophisticated but less symbolically creative forebears – they knew about wild animals and plants but were not used to thinking of them as potentially domesticable. His account is controversial but there is not need to take a stance on it here: once again, even if he is right this may explain adoption but cannot explain the poor health of early farmers.

Two additional theories help explain why adoption could have led to a "point of no return", though neither explains the initial adoption. Bar-Yosef and Belfer-Cohen (1989) suggest that sedentism removed constraints to population growth and made a return to hunting and gathering impossible. Bar-Yosef (2002) also emphasizes that population

grants from Turkey in northern Greek populations to be around 20% and the proportion of Y-chromosome DNA to be around 25% - a higher proportion of the latter being expected if indigenous females were incorporated into the migrants' gene pool at a higher rate that indigenous males

[5] This claim goes back to Nieboer (1900) but has been extensively considered and, broadly, supported by the work of later scholars (see Fogel & Engerman, 1974).

[6] This remains a controversial topic - see Sykes (2001) for a strongly contrary point of view, as welll as some of the contributions to Bellwood & Renfrew (2001) for overviews and discussions.

growth would have reduced the per capita benefits from increased agrciultural productivity (see also Guzman, 2007). Winterhalder & Lu (1995) provide a twist to this by suggesting that more intense hunting by the larger populations of already sedentary communities would have depleted big game, with the same consequence of rendering a return to hunting and gathering impossible. More generally, Malthusian dynamics might have led to the initial benefits of improved agricultural productivity being dissipated quite rapidly - too rapidly to leave much of a mark in the archaeological record.

Finally, Robson (2004) proposes that the poorer health of farmers was due not to dietary inadequacy but to disease, caused by greater crowding in villages. While very plausible in itself, it still needs to explain why the crowding occurred, and - importantly - why the combined lifestyle attracted so many converts.

What the present paper suggests, therefore, is that the important externalities imposed by defence needs are a way to reconcile the evidence about the health of early farmers with the possibility that climate change might nevertheless have made agriculture sufficiently productive to become strongly attractive to individual communities[7]. The greater defence needs of farmers arise from the fact that they are less mobile than hunter gatherers, and that they have more to steal, since they store food between harvests. The investments they devote to defence are then subject to a process of competitive escalation between communities, since the defence resources of any community makes it a greater danger to its neighbours. The model of sections 4 and 5 makes these suggestions more precise.

The model is related to two strands of economic literature. The first, which models in various ways the choice of economic agents to devote resources to protecting their property and (often simultaneously) encroaching on the property of others, is surveyed in Dixit (2004); an interesting contribution is Grossman (1998); see also Skaperdas (2002). The second consists of models embodying contest functions (Becker 1983, Dixit 1987, Hirshleifer 1989, Nitzan 1994, Aidt 2002), where the investments of one agent in some process that changes changes resource allocations in that agent's favour (lobbying, for instance) can be offset by the investments of a rival agent.

Finally, a long-standing literature in political theory, going back to Ibn Khaldun (1377) and Ferguson (1774), and excellently discussed by Ernest Gellner (1994), considers the need to raise a surplus for defence as constituting the foundation of the division of labour in modern society, and as giving rise to some of the most intractable problems of political organization.

[7]Some of the other mechanisms discussed above - population growth subsequent to adoption, for example - might also have imposed significant externalities from adopters on non-adopters. I am grateful to a referee for this point.

# 3 The Evidence for Violence in Prehistory

Even if it is granted that defence investments by a community impose negative externalities on its neighbours, is there any reason to think these would have been quantitatively important enough to account for the paradox with which I began? Was defence that important a preoccupation of the first farmers? Until around three decades ago, the majority view was that hunter gatherer and early agricultural communities lived a comparatively peaceful existence, though accounts differed as to how and why the modern rot set in[8]. However, that view now seems seriously misconceived[9].

Two kinds of evidence are relevant to assessing how important were violence, the fear of violence, and the need to protect oneself against violence for our early agricultural ancestors. One is modern behavioural evidence, from two sources: the behaviour of other animal species (especially those primates most closely related to human beings), and the behaviour of existing and historically recorded non-state societies, whether of hunter gatherers or of agriculturists. The second kind of evidence is archaeological, and comprises direct evidence of the marks of violence on human skeletons, as well as direct evidence from artefacts and fortifications allowing us to infer the presence of violence in the social environment in which these were constructed. I consider these types of evidence in turn.

## 3.1 Behavioural evidence

The evidence from the behaviour of other primates, particularly other apes, needs to be interpreted with caution, since there is great variety in primate behaviour, even between such closely related species as chimpanzees and bonobos, and this variety indicates that social and ecological factors can have a strong impact on the incidence of violent behaviour. This environmental flexibility in itself should come as no surprise: indeed, it is a central argument of Seabright (2004) that institutional arrangements have enormously increased the ability of human beings to live without violence among those they would otherwise be disposed to fight. But careful observation in the wild has nevertheless yielded sobering evidence[10]. When unconstrained by fear of reprisals, many other

[8]Even Steven Mithen's otherwise admirable recent book *After the Ice: A Global Human History 20,000-5000 BC* (Mithen, 2003) makes remarkably little reference to violence, and paints a large number of idyllic pictures of contented hunter gatherer communities going about their business with little concern for their own safety.

[9]See Bowles, 2006; in particular the online references.

[10]Evidence about infanticide in primates is set out in De Waal (2001), especially at pages 27, 30, 60-61 and 88-89. It is also discussed, in relation to primate and human violence more generally, in Ghiglieri (1999), especially pp. 129-133, though Ghiglieri overlooks the evidence that bonobos are strikingly less

primates systematically exploit opportunities to kill unrelated individuals. Infanticide by unrelated males, for instance, has been regularly observed among chimpanzees, gorillas and langurs (as well as in some other mammals such as lions). Among bonobos it is certainly less common and no documented cases are known; but this appears to be because females work cooperatively to ensure their infants are protected against marauding males, not because males themselves are intrinsically trustworthy. Among chimpanzees, related males regularly cooperate to launch violent unprovoked attacks against isolated and defenceless members of other troops, even when such attacks yield no food or other resources. Such incidents were not known until the work of Jane Goodall and her collaborators (and indeed the writings of Konrad Lorenz, 1963, had popularized the view that intra-species violence was largely ritualized, a view that is now known from field studies to be mistaken). The violence among chimpanzees is particularly revealing since it occurs to a large extent between groups of males of unequal size, and without particular provocation. This kind of behaviour reflects the random encounters of foraging parties and looks disturbingly similar to patterns of aggression between groups of human males. Violence, in short, is endemic among the species most closely related to man. Where it happens less often this is because of behaviour patterns that have evolved to deter it, and not because of instincts that would be purely peaceable without fear of reprisals. Whatever its fundamental causes, primate and especially great ape violence cannot be described as pathological.

Furthermore, it is hard to argue that the evidence from primate behaviour is irrelevant to prehistoric homo sapiens. If anything, it is likely that the evolutionary circumstances of early hominids would have increased the selective pressures in favour of violent behaviour compared to the behaviour of our primate relatives. There are good reasons to believe that intelligence and aggression co-evolve[11]. This is so both in the obvious sense that among violent conspecifics intelligence is a particularly adaptive trait, and in the less obvious sense that among intelligent conspecifics, aggression is particularly adaptive, due to the importance of sexual rivalry between males. In a species where contests are decided mainly by brute force, a male can eliminate a sexual rival simply by forcing him physically to submit. But the more intelligent the rival, the more likely it is that, having submitted now, he will find a cunning way to return to his sexual pursuit later on. So eliminating permanently the rival who has been temporarily defeated is a strategy that confers much

violent than chimpanzees. Diamond (1993), pp. 290-294 discusses the relevance for humans of intra-species violence in non-human species, and gives a graphic description of the violence witnessed by Jane Goodall and her team. This violence is also described in Ghiglieri, pp. 172-177, who points out that in chimpanzee groups he observed, recorded violence was lower than in the Goodall groups, apparently because they had reached a more stable accommodation between groups, in which each group had enough males to make defence possible without making attack attractive. The best overview of human and great ape violence is Wrangham & Peterson (1996).

[11] See Seabright (2004), pp. 48-51.

more selective benefit in an intelligent species.

The second type of behavioural evidence consists in ethnographic accounts of contemporary non-industrial societies, many of which (contrary to popular myth) are extremely violent . An outstanding and very comprehensive recent overview is given by Gat (2006). Considerable controversy still surrounds this evidence, and it is undeniable that levels of observed violence vary across non-industrial societies for reasons that are still very imperfectly understood. It may be true, for instance, that simple agricultural societies are somewhat more warlike than hunter-gatherers (a reasonable conjecture if only because they have more resources to fight over). Alternatively, this apparent tendency may reflect the fact that agricultural societies simply leave more evidence of the fighting they do (in the form of torched huts and pillaged storehouses), or that they are easier for anthropologists to visit in unsettled times. But whatever the explanation for these observed variations, the idea that pre-industrial societies were largely peaceful, which has had a seductive hold over human thinking since Jean-Jacques Rousseau wrote about noble savages in the 18th century, has now been convincingly discredited. Anthropologist Carol Ember wrote a pioneering article in 1978 called "Myths about hunter gatherers" which showed that nearly two thirds of hunter-gatherer groups for which records existed waged war at least every two years . Ethnographic accounts of high levels of violence, between individuals and between groups, exist for hunter-gatherers and shifting cultivators as different as the Akoa and the Bushmen through to the Tasmanians and the Yanomamo[12]. Among pre-industrial agriculturists, regular and deadly warfare has now been documented for societies once thought to be peace-loving, such as the Pueblo Indians of the American Southwest[13] . Many such ethnographies now exist: a striking example is described in the book *Blood is Their Argument*, in which anthropologist Mervyn Meggitt (1977) records the very bloody cycles of violence among the Mae Enga people of the central highlands of Papua New Guinea . Once again the message is sobering: where there are no institutional restraints on such behaviour, systematic killing of unrelated individuals is so common among human beings that, awful though it is, it cannot be described as exceptional, pathological or disturbed.

It is undeniable that this evidence is controversial, and questions about causality (such as whether there is an "instinct" for violence) are even more controversial than questions about the incidence of violence at particular times and places. For the argument I advance in this paper it is enough to show that human societies have usually been violent in the absence of institutions for deterring violent behaviour. Ember (1978) is, as already cited, an early survey of warfare (inter alia) among hunter-gatherers, and Gat (2000a,b) among pre-industrial societies more generally. Ferguson & Gat (2000) debate the reliability of

[12] Chagnon (1988).
[13] Leblanc (1999).

this evidence. Gat (1999) also contains evidence about the nature and purposes of such violence. A sobering overview of the human species' capacity for murderous violence is Diamond (1993), chapter 16. Robarchek & Robarchek (1997) compare two societies that, at the time of observation, had very different violence levels, though the more peaceful community (the Semai Senoi of Malaysia) had in previous years been successfully recruited into the anti-Communist armies used by the British colonial administration, where they became ruthless and efficient killers (Ghiglieri, 1999, p. 185).

## 3.2 Archaeological evidence

The first type of archaeological evidence consists of evidence from skeletons. Zollikofer et.al. (2002) report a reconstruction of a Neandertal skeleton from St. Cesaire, France, which shows marks of having been broken by a blow from a sharp knife or sword. More graphic evidence still comes from arrowheads embedded in skeletal remains, for instance from the Schild site in Illinois. I shall not survey such evidence in detail here, but Keeley (1996, appendix table 6.2) provides a summary of the evidence. Direct skeletal evidence almost certainly underestimates the proportion of deaths due to violence, since much violence does not leave identifiable marks on the skeleton. Keeley estimates that anything between 10% and 40% of deaths in hunter gatherer and early agricultural communities are likely to have been from violent causes, though this certainly varied considerably between communities. Even if this is an overstimate, it is strikingly about modern rates of violent death, which are a little over 1% of all deaths for the world as a whole.

The second kind of evidence is from artefacts and fortifications. I shall not consider the artefactual evidence here, since it is possible to argue that some weapons (swords and spears, for example) may have served purposes of ornament, status reinforcement, or sexual selection unrelated to combat. However, it is not possible to argue away the evidence from fortifications, since these conferred no individual advantage but were community-wide public goods. The first village settlement at Jericho, for instance, has been dated to before 9000 BC, and within a thousand years it had grown to a substantial settlement of several hectares of mud-brick houses with thick walls. The first evidence of the famous city walls comes from the early 8th century BC, and the presence of great water tanks, probably for irrigation, is attested from the 7th century. And a massive ditch, thirty feet deep and ten feet wide, was dug into the rock without metal tools. A single family could never have managed protection on this scale.

Another striking instance is the circular ditch at Banpo neolithic village, near Xian in central China, is 300 meters long, 5-6 meters deep and 6-8 meters wide at the top.

Digging it required moving 10,000 cubic meters of earth – not a casual undertaking for people living on limited calorie supplies. It is inconceivable that such an investment would have been made unless the villagers had real defensive needs.

In short, there is abundant evidence that prehistoric violence, or the fear of prehistoric violence was high enough to be a problem consuming significant resources, and a problem consuming more resources of agriculturists than of hunter gatherers. That is all that is needed for the argument of this paper to be potentially quantiatively significant.

The remainder of this paper proposes a mechanism by which this might have occurred, and a simple simulation suggesting that the fall in output which resulted might have been of significant size.

# 4 A Simple Model

## 4.1 The basic framework: production and theft

We begin by describing a general framework and continue by setting out a more specific model which will allow us to characterize possible equilibria of the model in a more precise and informative way.

In the general framework there are two bands, $i = 1, 2$ of equal size, each endowed with one unit of labor[14].

Each band allocates labor $l_i^H$ to hunting, $l_i^F$ to farming and $l_i^W$ to warfare, with $l_i^H + l_i^F + l_i^W = 1$.

Both hunting and agriculture are forms of production, while warfare is an activity devoted to the theft of resources from others and defense against such theft.

We begin with production. Labor is used to produce income (interpreted as calories) in either hunting or agriculture, subject to weakly concave production technologies:
$H_i = H(l_i^H)$, with $H' > 0, H'' \leq 0$
$F_i = F(l_i^F)$, with $F' > 0, F'' \leq 0$

The first important assumption is that agriculture is more productive than hunting,

[14] Band size is therefore exogenous, unlike in Marceau & Myers (2006). Marceau & Myers explain post-adoption food crises by splintering of previously cooperative groups. Such mechanisms are of course compatible with the one discussed here - however, predicting when cooperation will occur and when it will break down is notoriously difficult, and the present model requires no such mechanism for food crises to occur.

in the sense that it produces more calories for any given labour input:

$$F(l_i^F) > H(l_i^H) \text{ when } l_i^F = l_i^H \tag{1}$$

Next we consider warfare. Warfare is valuable for each band only because it enables the band to appropriate the calories of its rival, and to resist similar attempts by the other band. In the model warfare results purely in theft, never in the destruction of resources; this simplification seems reasonable since if we were to take resource-destruction into account, it would be even easier to demonstrate the possibility of Pareto-inferior adoption equilbria.

We can write $\gamma_{ij}$ for the proportion of group $i$'s hunting income, and $\phi_{ij}$ for the proportion of its agricultural income, transferred from group $i$ to group $j$. In equilibrium there will typically be transfers in both directions: each group will steal to some extent from the other. These amounts transferred are an increasing function of the relative strengths of the labour devoted to warfare by the two bands:

$$\gamma_{ij} = Max[0, \gamma(l_j^W, l_i^W)], \frac{\partial \gamma_{ij}}{\partial l_j^W} > 0, \frac{\partial \gamma_{ij}}{\partial l_i^W} < 0, \gamma(l_j^W, l_i^W) \geq 0 \text{ when } l_j^W = l_i^W$$

$$\phi_{ij} = Max[0, \phi(l_j^W, l_i^W)], \frac{\partial \phi_{ij}}{\partial l_j^W} > 0, \frac{\partial \phi_{ij}}{\partial l_i^W} < 0, \phi(l_j^W, l_i^W) \geq 0 \text{ when } l_j^W = l_i^W$$

The nature of these functions will evidently make a difference to the incentives of the bands to invest in warfare as opposed to investing in production. Two particular points to note are:

1) There is no reason to expect the functions to be concave - indeed, it is plausible that their slopes will be steepest for intermediate values of $l_i^W$ and $l_j^W$, since it is when contests are evenly matched that additional resources can make the most difference. We capture this in the specific model by the use of a logistic function.

2) Functions that make the proportion of resources transferred a function of the absolute difference in labor of the two bands may behave differently from those that make

it a function of the ratio of the labor of the two bands. In the specific model we shall use the absolute difference as this simplifies the algebra, but nothing of qualitative importance turns on this.

Here all that is necessary to capture the greater incentive of farmers to invest in warfare is the assumption that the marginal product of labor in warfare against farmers exceeds that of labor in warfare when the two bands allocate the same amounts of labor to warfare:

$$\gamma'(l) < \phi'(l) \text{ for } l = 0 \tag{2}$$

We assume that each group acts to maximise its calorie income, which consists of the income from hunting that it succeeds in keeping safe from theft, and the income from farming that it keeps safe from theft, plus the hunting and farming income it succeeds in stealing from the rival band:

$$C = (1 - \gamma_{ij})H(l_i^H) + (1 - \phi_{ij})F(l_i^F) + \gamma_{ji}H(l_j^H) + \phi_{ji}F(l_j^F) \tag{3}$$

This can also be rewritten as an explicit function of the labour share devoted to warfare, as follows:

$$\begin{aligned} C &= (1 - \gamma_{ij})H(1 - l_i^W - l_i^F) + (1 - \phi_{ij})F(l_i^F) \\ &+\gamma_{ji}H(1 - l_j^W - l_j^F) + \phi_{ji}F(l_j^F) \end{aligned} \tag{4}$$

We shall refer in what follows to the assumptions in the model thus far as "the general framework". We now describe the specific model, which conforms to the assumptions of the general framework but imposes additional conditions, notably in the form of particular production and warfare functions.

### 4.2 The Specific Model

Production is given by an iso-elastic function of labor input as follows:

$$H\left(l_i^H\right) = \frac{\left(l_i^H\right)^{1-\eta}}{1-\eta} \quad \text{for } 0 \leq \eta < 1; \tag{5}$$

$$H\left(l_i^F\right) = f \ln\left(l_i^F\right) \quad \text{for } \eta = 1 \tag{6}$$

and farming is more productive than hunting by a linear coefficient $f \geq 1$:

$$F\left(l_i^F\right) = \frac{f\left(l_i^F\right)^{1-\eta}}{1-\eta}; \tag{7}$$

$$F\left(l_i^F\right) = f \ln\left(l_i^F\right) \quad \text{for } \eta = 1 \tag{8}$$

This specification captures a range of concavity assumptions ranging from linearity to logarithmic production. The marginal product of labor is given by

$$\frac{\partial H\left(l_i^H\right)}{\partial l_i^H} = \frac{1}{\left(l_i^H\right)^{\eta}} \text{ and } \frac{\partial F\left(l_i^F\right)}{\partial l_i^F} = \frac{f}{\left(l_i^F\right)^{\eta}}$$

The returns to warfare are given by a logistic function:

$$\gamma_{ij} = \frac{2\gamma}{1+e^{-\alpha l}} \text{ where } l = l_j^W - l_i^W \tag{9}$$

and

$$\phi_{ij} = \frac{2\phi}{1+e^{-\beta l}} \text{ where } \beta > \alpha \tag{10}$$

The derivatives of $\gamma_{ij}$ and $\phi_{ij}$ are given by

$$\frac{\partial \gamma_{ij}}{\partial l} = 2\alpha\gamma\gamma_{ij}\left(1-\gamma_{ij}\right) \text{ and } \frac{\partial \phi_{ij}}{\partial l} = 2\beta\phi\phi_{ij}\left(1-\phi_{ij}\right) \tag{11}$$

Note that the argument of the two functions is the absolute difference in warfare strength of the two bands, not the ratio of their strengths: it takes a minimum value of $-1$ and a maximum of $+1$, and when the two bands are evenly matched, $l = 1$ so that $\gamma_{ij} = \gamma$ and $\phi_{ij} = \phi$. Using the ratio of the strengths of the two bands complicates the algebra without adding insight.

## 4.3 Timing: one period versus two periods

We develop the model in two versions, one a single-period model and the other a two-period model. In the one-period model, bands choose simultaneously a labor allocation between all three activities, each taking as given the labor allocation of its rival. In the two-period model, they first decide to undertake production as either hunters or farmers, and then allocate labor between production and warfare subject to this constraint. In the one-period model we solve for a Nash equilibrium in labor allocations; we look for symmetric equilibria, although we cannot rule out that asymmetric equilibria may also exist. In the two-period model we look for a subgame-perfect equilibrium.

The single-period approach makes sense of the idea that agricultural adoption is not an all-or-nothing matter; many agricultural communities continue to do some hunting to this day, although in modern times this supplies in most cases a very small proportion of their nutritional needs. However, although agricultural adoption is not an all-or-nothing matter, there are a number of discontinuities and indivisibilities associated, not so much with agricultural adoption *per se* as with the accompanying lifestyle changes, notably with increasing sedentarism. Building a fortified village, for instance, is a substantial sunk investment that restricts the extent to which the group's members can realistically migrate in search of food (and conversely, one that is unlikely to be undertaken if significant migration is envisaged in the future). For that reason there may be some insights captured by a framework in which groups have to choose in a discontinuous way between hunting and farming.

We adopt both approaches here. It is worth noting also that the one-period model can also be interpreted in a statistical sense: each band faces a distribution of other bands, of which a certain proportion are hunters and the rest farmers. In this framework each band would have to decide whether to adopt agriculture as a function of the proportion of adopters it faced. Since bands are identical, a Nash equilibrium is the fixed point of an adoption function, indicating at what distribution of its neighbours between hunting and farming any one band would be just indifferent as to adoption.

Finally, it turns out that it is technically more difficult to show the existence of Pareto-inferior adoption equilibria in the two-period case than in the one-period case[15], so we

[15] This is because in the one-period case all that is necessary to establish the existence of Pareto-inferior adoption equilibria is to characterize a symmetric equilibrium and show that consumption is decreasing in agricultural productivity over a certain range. The model solves easily for a symmetric equiibrium and the comparative static finding is straightforward. In the two-period case, by contrast, it is necessary to show that each group would adopt agriculture even if the other did not, which requires solving for asymmetric equilibria in each subgame.

begin with the one-period case. This case also allows us to simulate equilibrium output and consumption levels as functions of the various parameters.

# 5 Solving the Model

## 5.1 The one-period case

Taking first order conditions for a maximum of expression 4 with respect to $l_i^W$, and applying the envelope theorem yields:

$$\gamma'_{ij}H(1-l_i^W-l_i^F)+\phi'_{ij}F(l_i^F)+\gamma'_{ji}H(1-l_j^W-l_j^F)+\phi'_{ji}F(l_j^F) = (1-\gamma_{ji})H'(1-l_i^W-l_i^F) \quad (12)$$

Doing the same with respect to $l_i^F$ yields:

$$\left(1-\gamma_{ij}\right)H'(1-l_i^W-l_i^F) = \left(1-\phi_{ij}\right)F'(l_i^F) \quad (13)$$

It is worth noting that equation (12) implies that agricultural adoption decisions are strategic complements. The share of labour in hunting declines as the share of other group in agriculture increases, which can be considered a ratchet effect of adoption.

Solving for a symmetrical equilibrium, we can write $H(1-l_i^W-l_i^F) = H(1-l_j^W-l_j^F) = H$ and analogously for $F$, which yields:

$$2\gamma'H + 2\phi'F = (1-\gamma)H' = (1-\phi)F' \quad (14)$$

This has three implications, which we set out in Proposition 1:

**Proposition 1**: In a symmetrical equilibrium of any one-period game that satisfies the conditions of the general framework, when the average productivity of agriculture increases a) the share of labor devoted to hunting strictly decreases, and will do so by more the less concave is the hunting production function; b) the share devoted to farming increases if the marginal productivity of agriculture at a given level of labor input increases in at least the same proportion as its average productivity; c) the share devoted to warfare increases if $\phi'$ is sufficiently large relative to $\gamma'$, if the increase in marginal productivity of agriculture is not too large relative to the increase in average productivity; it does so to a greater degree, the less concave is the hunting production function.

**Proof.** A rise in the productivity of agriculture raises $F$ in equation 14, which implies an increase in $H'$. In turn this implies a fall in the share of labor devoted to hunting, and a greater fall the less concave is the hunting production function, which establishes claim a. If the marginal productivity of agriculture increases in at least the same proportion as its average productivity, the right-hand side of 14 must increase by strictly more than the left-hand side unless labour input in agriculture increases, which establishes claim b). Claim c) follows from the fact that if $\phi'$ is large relative to $\gamma'$ and if the increase in marginal productivity of agriculture is small relative to the increase in average productivity, equation 14 can be satisfied with either a fall in labor in farming, or with an increase sufficiently small as not to outweigh the fall in labor in hunting. Since the share in warfare equals one minus the other two shares this means the share in warfare will rise if the fall in labor in hunting is either reinforced by a fall in labor in farming or is large enough not to be outweighed by a rise in labor in farming. ■

Proposition 2 shows, for the specific model, precisely what are the conditions under which labor allocations to farming and warfare are increasing or decreasing in $f$.

**Proposition 2**: In the specific model, labor allocated to hunting, farming and warfare are given by the following equations:

a) $l_i^H = \frac{1-\eta}{4\alpha\gamma^2+4\beta\phi^2\left[\frac{f(1-\phi)}{(1-\gamma)}\right]^{\frac{1}{\eta}}}$

b) $l_i^F = \frac{1-\eta}{4\beta\phi^2+4\alpha\gamma^2\left[\frac{(1-\gamma)}{f(1-\phi)}\right]^{\frac{1}{\eta}}}$

c) $l_i^W = 1 - \frac{1-\eta}{4\beta\phi^2+4\alpha\gamma^2\left[\frac{(1-\gamma)}{f(1-\phi)}\right]^{\frac{1}{\eta}}} - \frac{1-\eta}{4\alpha\gamma^2+4\beta\phi^2\left[\frac{f(1-\phi)}{(1-\gamma)}\right]^{\frac{1}{\eta}}}$

from which it follows that $l_i^H$ is strictly decreasing in $f$, $l_i^F$ strictly increasing in $f$, and $l_i^W$ increasing in $F$ provided that $\beta\phi^2$ is large relative to $\alpha\gamma^2$.

**Proof.** Substituting into equation 14 for the example yields: $4\alpha\gamma^2\left(1-\gamma\right)\frac{\left(1-l_i^W-l_i^F\right)^{1-\eta}}{1-\eta} + 4\beta\phi^2\left(1-\phi\right)\frac{f\left(l_i^F\right)^{1-\eta}}{1-\eta} = \frac{(1-\gamma)}{\left(1-l_i^W-l_i^F\right)^{\eta}} = \frac{f(1-\phi)}{\left(l_i^F\right)^{\eta}}$

Multiplying the first term on the LHS by $\left(1-l_i^W-l_i^F\right)^{\eta}$ and the second term by $\frac{(1-\gamma)\left(l_i^F\right)^{\eta}}{f(1-\phi)}$ (which is equal to $\left(1-l_i^W-l_i^F\right)^{\eta}$), and dividing through by $(1-\gamma)$ yields

$4\alpha\gamma^2\frac{\left(1-l_i^W-l_i^F\right)}{1-\eta} + 4\beta\phi^2\frac{\left(l_i^F\right)}{1-\eta} = 1$. Substituting $1-l_i^W-l_i^F$ for $l_i^F$ and re-arranging yields equation a), substituting $l_i^F$ for $1-l_i^W-l_i^F$ and re-arranging yields equation b), and equation c) follows from the fact that $l_i^H+l_i^F+l_i^W=1$. ■

If total labor allocated to production falls as agricultural productivity rises, this may lead to a fall in output if the fall in the share of labor is fast enough to outweigh the increasing productivity of the labor that remains in production. Is this realistic? Equation c) in Proposition 2 suggests this is more likely if $\eta$ is small (that is, if production is not too concave in labor input) as this will magnify the differences between $\beta\phi^2$ and $\alpha\gamma^2$. Figure 1 shows that this intuition is indeed sound.

[Figure 1 about here]

Figure 1 shows that it is quite possible for total output (which is equal to total consumption[16]) to fall, and by an important amount, as agricultural productivity increases over a certain range. It shows a Base Run with values of $\alpha = 1, \beta = 4, \gamma = 0.3, \phi = 0.4$ and $\eta = 0.2$. As can be seen, as $f$ rises above unity, overall output falls (because of the diversion of labor into warfare). It falls by over 20% at its lowest point, and does not reach the same levels again until $f$ is well above 2. So agriculture has to become more than *twice* as productive as hunting, given these other parameters, before it can compensate for the incentives it creates to divert effort into making war.

Three other simulations explore the effect of varying $\beta$ and $\eta$:

1) Setting $\beta = 2.5$ raises output for all values of $f$ but retains the feature that output falls when $f$ rises above unity, not returning to its original level until it is around 2 (the result that increasing agricultural productivity initially reduces output is robust to most values of $\beta$ provided it is at least somewhat above 1). In contrast, the result is much more sensitive to varying $\eta$, which is the degree of concavity of production.

2) For $\eta = 0.5$ (production highly concave in labor), output no longer falls as agricultural productivity rises. This is because, when production is highly concave, only a small fall in labor in hunting is needed to raise its marginal productivity enough to bring it into line again with the new higher marginal productivity of warfare.

3)For $\eta = 0.05$, however (production nearly linear in labor), the adverse effect of agricultural productivity on output is very strong indeed, and even at $f = 4$ output has still not yet risen by enough to compensate for the diversion of labor into making war. It is evident that the general result, that increasing agricultural productivity may reduce output for the reasons highlighted by the model, is not just a freak finding under very peculiar conditions, but captures a phenomenon that persists over a significant parameter range.

[16] This is the case since warfare is just a transfer between groups and since we are considering symmetric equilibria.

It is worth noting that these simulations can be interpreted either as purely comparative static exercises - as showing what the value of output could be given the discovery of a new agricultural technology - or as dynamic exercises showing how output changes over time as agricultural productivity gradually improves. Of course, in the latter interpretation it is important to bear in mind that other factors (population size, for instance) are held constant. In reality population would have been changing over time, and it is this fact which has often been held responsible for the poorer health and nutrition of the first farmers, as was noted above. The value of this simulation lies in showing that the first farmers could have been substantially less well nourished than their hunter gatherer predecessors even without the Malthusian effects of population growth.

We now turn to the two-period model.

## 5.2 Solving the two-period model

In the two-period model, we solve for a sub-game perfect equilibrium in the usual manner, backwards from the second period. This involves first choosing the proportion of labor time allocated to warfare to maximize expression 3, conditional on both the band's own choice of occupation (hunting or farming) in the first period and on the occupational choice of its rival. Next we find which choice or choices of occupation in the first period yield the highest maximized value of consumption, conditional on the occupational choice of the rival band.

In the second period, therefore, we have four distinct first order conditions, one for each combination of the two occupations of the band and its rival:

For hunters facing hunters:

$$\frac{\partial C_i}{\partial l_i^W} = -\gamma'_{ij}(l_j^W - l_i^W)H(l_i^W) + \gamma'_{ji}(l_i^W - l_j^W)H(l_j^W) + (1 - \gamma_{ij}(l_j^W - l_i^W))\frac{\partial H(l_i^W)}{\partial l_i^W} = 0 \quad (15)$$

For hunters facing farmers:

$$\frac{\partial C_i}{\partial l_i^W} = -\gamma'_{ij}(l_j^W - l_i^W)H(l_i^W) + \phi'_{ji}(l_i^W - l_j^W)F(l_j^W) + (1 - \gamma_{ij}(l_j^W - l_i^W))\frac{\partial H(l_i^W)}{\partial l_i^W} = 0 \quad (16)$$

For farmers facing hunters:

$$\frac{\partial C_i}{\partial l_i^W} = -\phi'_{ij}(l_j^W - l_i^W)F(l_i^W) + \gamma'_{ji}(l_i^W - l_j^W)H(l_j^W) + (1 - \phi_{ij}(l_j^W - l_i^W))\frac{\partial F(l_i^W)}{\partial l_i^W} = 0 \quad (17)$$

For farmers facing farmers:

$$\frac{\partial C_i}{\partial l_i^W} = -\phi'_{ij}(l_j^W - l_i^W)F(l_i^W) + \phi'_{ji}(l_i^W - l_j^W)F(l_j^W) + (1 - \phi_{ij}(l_j^W - l_i^W))\frac{\partial F(l_i^W)}{\partial l_i^W} = 0 \quad (18)$$

Note that in principle there may be multiple solutions to these first order conditions, since $\gamma_{ij}$ and $\phi_{ij}$ may not be concave. However, we can nevertheless characterize solutions even without knowing whether they are unique; in particular, we can state two useful Lemmas. First, to simplify notation, let us define values of allocations of labor to warfare that satisfy the four first order conditions. Let:

1) $l_{HH}^W = l_{HH}^W\left(l_j^W\right)$ denote a value of $l_i^W$ that solves equation 15 for given $l_j^W$;

2) $l_{HF}^W = l_{HF}^W\left(l_j^W\right)$ denote a value of $l_i^W$ that solves equation 16 for given $l_j^W$;

3) $l_{FH}^W = l_{FH}^W\left(l_j^W\right)$ denote a value of $l_i^W$ that solves equation 17 for given $l_j^W$;

4) $l_{FF}^W = l_{FF}^W\left(l_j^W\right)$ denote value of $l_i^W$ that solves equation 18 for given $l_j^W$.

Now write:

1) $H_H$ to denote output per band in a symmetric equilibrium of the subgame in which hunters face hunters. Thus $H_H \equiv H(1 - l_{HH}^W(l_i^W))$ for $l_i^W = l_{HH}^W$. $H'_H$ is the derivative of $H(.)$ evaluated at this equilibrium output level. Write $\gamma_{HH}$ to denote the value of $\gamma_{ij} = \gamma_{ji}$ in this equilibrium.

2) $F_F$ to denote output per band in a symmetric equilibrium of the subgame in which farmers face farmers. Thus $F_F \equiv F(1 - l_{FF}^W(l_i^W))$ for $l_i^W = l_{FF}^W$. $F'_F$ is the derivative of $F(.)$ evaluated at this equilibrium output level. Write $\phi_{FF}$ to denote the value of $\phi_{ij} = \phi_{ji}$ in this equilibrium.

3) $H_F$ to denote output per band of hunters in an equilibrium of the subgame in which hunters face farmers. Write $\gamma_{HF}$ to denote the value of $\gamma_{ij}$ in this equilibrium. $H_F^{'}$ is the derivative of $H(.)$ evaluated at this equilibrium output level.

4) $F_H$ to denote output per band of farmers in an equilibrium of the subgame in which farmers face hunters. Write $\phi_{FH}$ to denote the value of $\phi_{ij}$ in this equilibrium. $F_H^{'}$ is the derivative of $F(.)$ evaluated at this equilibrium output level.

The following two lemmas state one necessary condition, and three jointly sufficient conditions, for existence of an equilibrium in which farming dominates hunting as the choice of both groups even though the outcome is Pareto-domianted - that is, in symmetric equilibrium, farmers facing farmers produce (and consume) more output than hunters facing hunters would do. First a necessary condition:

**Lemma 1**: In any game that satisfies the general framework, if farming by both groups is a sub-game perfect equilibrium outcome of the whole game that is Pareto-dominated by hunting by both groups, then

$$(1 - 2\phi_{FH})F_H > (1 - 2\gamma_{HF})H_F \tag{19}$$

**Proof.** Each group will choose farming when facing hunters iff

$$(1 - \phi_{FH})F_H + \gamma_{HF}H_F \geq (1 - \gamma_{HH})H_H + \gamma_{HH}H_H = H_H \tag{20}$$

Likewise, each group will choose farming when facing farmers iff

$$F_F = (1 - \phi_{FF})F_F + \phi_{FF}F_F \geq (1 - \gamma_{HF})H_F + \phi_{FH}F_H \tag{21}$$

Iff farming is Pareto-dominated by hunting, then $H_H > F_F$. Substituting equations (20) and (21) and re-arranging yields the stated result. ■

Lemma 2 shows sufficient conditions for such an equilibrium to exist:

**Lemma 2**: In any game satisfying the general framework, if equations 20 and 21 hold and if, in addition, $H_H > F_F$; then there exists a subgame perfect equilibrium in which both groups choose farming, but that equilibrium is Pareto-dominated by the equilibrium of the symmetric hunting subgame. If $H_H, F_H, H_F$ and $F_F$ are unique solutions of their respective first order conditions, the equilibrium is unique.

**Proof.** Equations 20 and 21 together imply that farming is a dominant strategy and thus that there exists, for each set of values of $H_H, F_H, H_F$ and $F_F$, a unique subgame perfect equilibrium in which both groups choose farming. $H_H > F_F$ implies that the equilibrium is Pareto-dominated by the equilibrium of the hunting subgame. If $H_H, F_H, H_F$ and $F_F$ are unique solutions of their respective first order conditions, no other equilibrium exists. QED ■

The lemmas do not, of course, establish that such an equilibrium exists, though they will prove important in making that demonstration. We show that an equilibrium of this kind may exist in the specific model.

### 5.2.1 Existence of equilibrium: the specific model

In the specific model we can write the first-order conditions as

For hunters facing hunters:

$$\frac{\partial C_i}{\partial l_i^W} = 2\alpha\gamma\gamma_{ij}\left(1-\gamma_{ij}\right)\frac{\left(1-l_i^W\right)^{1-\eta}}{1-\eta} + 2\alpha\gamma\gamma_{ji}\left(1-\gamma_{ji}\right)\frac{\left(1-l_j^W\right)^{1-\eta}}{1-\eta} - \frac{\left(1-\gamma_{ij}\right)}{\left(1-l_i^W\right)^{\eta}} = 0 \tag{22}$$

For hunters facing farmers:

$$\frac{\partial C_i}{\partial l_i^W} = 2\alpha\gamma\gamma_{ij}\left(1-\gamma_{ij}\right)\frac{\left(1-l_i^W\right)^{1-\eta}}{1-\eta} + 2\beta\phi\phi_{ji}\left(1-\phi_{ji}\right)\frac{f\left(1-l_j^W\right)^{1-\eta}}{1-\eta} - \frac{\left(1-\gamma_{ij}\right)}{\left(1-l_i^W\right)^{\eta}} = 0 \tag{23}$$

For farmers facing hunters:

$$\frac{\partial C_i}{\partial l_i^W} = 2\beta\phi\phi_{ij}\left(1-\phi_{ij}\right)\frac{f\left(1-l_i^W\right)^{1-\eta}}{1-\eta} + 2\alpha\gamma\gamma_{ji}\left(1-\gamma_{ji}\right)\frac{\left(1-l_j^W\right)^{1-\eta}}{1-\eta} - \frac{f(1-\phi_{ij})}{\left(1-l_i^W\right)^{\eta}} = 0 \tag{24}$$

For farmers facing farmers:

$$\frac{\partial C_i}{\partial l_i^W} = 2\beta\phi\phi_{ij}\left(1-\phi_{ij}\right)\frac{f\left(1-l_i^W\right)^{1-\eta}}{1-\eta} + 2\beta\phi\phi_{ji}\left(1-\phi_{ji}\right)\frac{f\left(1-l_j^W\right)^{1-\eta}}{1-\eta} - \frac{f(1-\phi_{ij})}{(1-l_i^W)^{\eta}} = 0 \quad (25)$$

This allows us to state a lemma that relates the levels of output in symmetric equilibrium under farming and hunting:

**Lemma 3**: In equilibrium $F_F < H_H$ iff $f < \left(\frac{\beta\phi^2}{\alpha\gamma^2}\right)^{1-\eta}$

**Proof.** In symmetric equilibrium we can substitute $l_i^W = l_j^W, \gamma_{ij} = \gamma_{ji} = \gamma$ in 22 to yield

$$l_{HH}^W = 1 - \frac{1-\eta}{4\alpha\gamma^2}$$

Similar calculations yield

$$l_{FF}^W = 1 - \frac{1-\eta}{4\beta\phi^2}$$

from which we can see that

$$H_H = \frac{\left(\frac{1-\eta}{4\alpha\gamma^2}\right)^{1-\eta}}{1-\eta}$$

and

$$F_F = \frac{f\left(\frac{1-\eta}{4\beta\phi^2}\right)^{1-\eta}}{1-\eta}$$

from which it follows that $F_F < H_H$ iff $f^{\frac{1}{1-\eta}}\left(\frac{1-\eta}{4\beta\phi^2}\right) < \left(\frac{1-\eta}{4\alpha\gamma^2}\right)$. Rearranging this expression yields the stated result. ■

We have thus established that, if agriculture is adopted, for all values of $f$ between 1 and $\left(\frac{\beta\phi^2}{\alpha\gamma^2}\right)^{1-\eta}$ output will be lower than it would have been if both groups had commited themselves not to adopt agriculture. Call this range of values of $f$ the "inefficient range". Showing that agriculture will be adopted for some values of $f$ in the inefficient range is not so straightforward, since we cannot find analytic solutions to the output levels in asymmetric equilibrium (where one group adopts farming while the other remains hunting), and it is necessary to say something about these in order to show that adoption is a dominant strategy for both groups.

However, we can also state a lemma that characterizes the labor devoted to production in asymmetric equilibrium by farmers and hunters. Define $L \equiv \frac{\left(1-l_{HF}^W\right)}{\left(1-l_{FH}^W\right)}$ as the ratio of hunters' to farmers' productive labor in such an equilibrium. Similarly define $\lambda \equiv l_{HF}^{W} - l_{FH}^{W}$ as the difference between the hunters' and farmers' labor devoted to warfare in such an equilibrium. Then:

**Lemma 4**: In any asymmetric equilibrium of a subgame in which farmers face hunters, $\frac{(1-\gamma_{HF})}{(1-\phi_{FH})} = fL^{\eta}$.

**Proof.** From equation 23 with $i = H$ and 24 with $i = F$ we can write

$$2\alpha\gamma\gamma_{HF}\left(1-\gamma_{HF}\right)\frac{\left(1-l_{HF}^{W}\right)^{1-\eta}}{1-\eta}+2\beta\phi\phi_{FH}\left(1-\phi_{FH}\right)\frac{f\left(1-l_{FH}^{W}\right)^{1-\eta}}{1-\eta}=\frac{\left(1-\gamma_{HF}\right)}{\left(1-l_{HF}^{W}\right)^{\eta}} \quad (26)$$

and

$$2\beta\phi\phi_{FH}\left(1-\phi_{FH}\right)\frac{f\left(1-l_{FH}^{W}\right)^{1-\eta}}{1-\eta}+2\alpha\gamma\gamma_{HF}\left(1-\gamma_{HF}\right)\frac{\left(1-l_{HF}^{W}\right)^{1-\eta}}{1-\eta}=\frac{f(1-\phi_{FH})}{\left(1-l_{FH}^{W}\right)^{\eta}} \quad (27)$$

Since the left-hand side of the two equations are identical, this yields

$$\frac{(1-\gamma_{HF})}{\left(1-l_{HF}^{W}\right)^{\eta}}=\frac{f(1-\phi_{FH})}{\left(1-l_{FH}^{W}\right)^{\eta}} \quad (28)$$

which implies that

$$\frac{(1-\gamma_{HF})}{(1-\phi_{FH})}=fL^{\eta} \quad (29)$$

QED ■

We construct an inefficient equilibrium by first establishing that it is possible to choose $f$ such that the ratio $\frac{(1-\gamma_{HF})}{(1-\phi_{FH})}$ is equal to one, and then showing that under these conditions there are values of $f$ in the inefficient range for which adoption is a dominant strategy.

**Lemma 5**: For any real numbers $\alpha$ and $\beta$ such that $\beta > \alpha > 0$, for any $\gamma$ and $\phi$ such that $0 < \phi < \gamma < \frac{1}{2}$, and for any $\eta$ such that $0 \leq \eta \leq 1$, there exists a value of $f > 1$ such that $fL^{\eta} = 1$.

**Proof.** Suppose $\eta = 0$ and $f = 1$. Then $fL^{\eta} = 1$ and, by Lemma 4, $(1-\gamma_{HF}) = (1-\phi_{FH})$. Therefore $\gamma_{HF} = \phi_{FH}$, which implies that $\gamma e^{-\beta\lambda} - \phi e^{\alpha\lambda} = \phi - \gamma$. This implies that, for any $\phi < \gamma, \lambda > 0$ and therefore $L < 1$. Since $L < 1$, $fL^{\eta}$ is strictly decreasing in $\eta$ for $\eta \geq 0$, and for any value $\eta'$ of $\eta$ such that $0 < \eta' \leq 1$ there is a value $f' > 1$ of $f$ that leaves $fL^{\eta}$ unchanged, so that $L$ continues to satisfy $fL^{\eta} = \frac{(1-\gamma_{HF})}{(1-\phi_{FH})} = 1$ for $f = f'$ and $\eta = \eta'$. Therefore for any $\eta$ such that $0 \leq \eta \leq 1$, and for any $\phi$ such that $0 < \phi < \gamma < \frac{1}{2}$, there is a value of $f$ such that $fL^{\eta} = 1$. ■

This allows us to state:

**Proposition 3**: For any $\alpha$ and $\beta$ such that $\beta > \alpha > 0$, there exist values of $\gamma$ and $\phi$ such that $\sqrt{\frac{\alpha}{\beta}} < \frac{\phi}{\gamma} < 1$ and values of $f > 1$ and $\eta > 0$ such that farming by both groups is a unique sub-game perfect equilibrium that is Pareto-inefficient, being dominated by the outcome with hunting by both groups. In addition, for all $f$ such that $1 < f < \left(\frac{\beta\phi^2}{\alpha\gamma^2}\right)^{1-\eta}$, if farming by both groups is an equilibrium, it is inefficient.

**Proof.** The proof is in three steps. In the first, we show that for $\alpha$ and $\beta$ such that $\beta > \alpha > 0$, for $fL^\eta = 1$ with $\eta > 0$, the conditions of Lemma 1 are satisfied;

by Lemma 5 we can find $f > 1$ such that $fL^\eta = 1$ with $\eta > 0$, so Lemma 1 holds. Furthermore, the value of $f > 1$ such that $fL^\eta = 1$ with $\eta > 0$ can be found arbitrarily close to 1 for $\eta$ sufficiently close to 0. In the second step, we show that if Lemma 1 holds, and if $f - 1$ and $\frac{\phi}{\gamma} - \sqrt{\frac{\alpha}{\beta}}$ is small, the first two conditions of Lemma 2 are satisfied. In step 3 we show that if $f$ is greater than unity but below some upper bound that is also greater than unity, the third condition of Lemma 2 is satisfied, and thus by Lemma 2 the equilibrium exists.

Step 1: If $fL^n = 1$ then by Lemma 4 $\frac{(1-\gamma_{HF})}{(1-\phi_{FH})} = 1$.

Then $\frac{(1-2\gamma_{HF})}{(1-2\phi_{FH})} = \frac{(1-\gamma_{HF})}{(1-\phi_{FH})} = 1$

and therefore $\frac{f}{L^\eta} = \frac{F_H}{H_F} > f > \frac{(1-2\gamma_{HF})}{(1-2\phi_{FH})}$.

Since $\eta > 0, f > 1$; and therefore Lemma 1 holds if $fL^n = 1$.

By Lemma 5 there exists a value of $f$ such that $fL^n = 1$;

therefore Lemma 1 holds.

Step 2: If Lemma 1 holds with $fL^n = 1$,

$\frac{F_H}{H_F} > \frac{f}{L^\eta}$ which is strictly increasing in $f$ and is greater than unity.

Therefore there may exist values of $H_H$ and $F_F$ such that equations 20 and 21 can be simultaneously satisfied with $H_H > F_F$;

by setting $\frac{\phi}{\gamma} - \sqrt{\frac{\alpha}{\beta}}$ close to zero we can find $H_H > F_F$ close to zero

and therefore find $F_H > H_H > F_F > H_F$.

Therefore we can find values of $\gamma$ and $\phi$ sufficiently small so that equations 20 and 21 will be satisfied.

Thus the first two conditions of Lemma 2 are satisfied.

Step 3: $H_H > F_F$ if $\frac{\beta\phi^2}{\alpha\gamma^2} > f^{\frac{1}{1-\eta}}$.

Since $\frac{\phi}{\gamma} < 1$ and $f \geq 1$, this means that $1 \leq f < \left(\frac{\beta}{\alpha}\right)^{1-\eta}$.

The expression $\left(\frac{\beta}{\alpha}\right)^{1-\eta}$ lies strictly above unity since $\beta > \alpha$.

Thus for $\gamma$ and $\phi$ small, such that $\frac{\phi}{\gamma} - \sqrt{\frac{\alpha}{\beta}}$ and $\sqrt{\frac{\alpha}{\beta}} < \frac{\phi}{\gamma} < 1$,

the inefficient farming equilibrium exists.

In addition, for any $f$ such that $1 < f < \left(\frac{\beta\phi^2}{\alpha\gamma^2}\right)^{1-\eta}$,

if farming by both groups is an equilibrium, it is inefficient. ■

It might be thought obvious that an inefficient equilibrium will exist in the two-period model if it exists in the one-period model, but this is not so. In the one-period model, an increase in the productivity of agriculture induces a shift away from hunting by each group, which does not take into account the effects of its shift on the incentives of the other group to invest in warfare, since it is taking the strategy of the other group as given. In the two-period model, a group considering giving up hunting and adopting agriculture in the first period will take into account any induced incentives on the other group to invest in warfare in the second period: if these incentives are large enough, that may be enough to discourage agricultural adoption. Nevertheless we have shown that there are values of the parameters such that inefficient equilibria exist. It has not been possible to characterize these in as clear and intuitive a way as shown in Figure 1, and overall the one-period model remains overall a more convincing representation of the predicament of hunter-gatherer groups in the Neolithic era. But it is nevertheless reassuring to note that a model that captures some of the potential indivisibilities and discontinuities involved in agricultural adoption may still reproduce the main finding of the one-period model in which agricultural adoption was assumed to be continuous.

We now bring together these findings and draw some overall conclusions.

# 6 Conclusions

The arguments of this paper do not supplant but rather augment the explanations for the adoption of agriculture given in the existing literature. In summary, the fact and the speed of agricultural adoption are explained by the fact that, after the end of the ice age, agriculture became productive enough to be attractive to any given group, given the choices of other groups with whom they came into contact. This improvement in productivity compared to the alternative of hunting and gathering was due principally to climate change, as Richerson et al. (2001) have emphasized. However, the evolution of human cognitive capacities as described by Steven Mithen may also have played a part: the early neolithic phase of global warming may not have been the only comparable one in human prehistory, but it may have been the only one to occur after human beings were cognitively ready to take advantage of it.

The poor nutrition of first farmers, on the other hand, explained by the fact that, initially, agriculture was only a little more productive than hunting and gathering, and this was not enough to offset the increased investments in defence that were induced in equilibrium by the widespread adoption: each group had to invest more in defence both because of its own decision to adopt and because of the adoption decisions of its neighbours.

Paradoxically, too, the higher the proportion of adopters among a group's neighbours, the stronger the incentive for the group itself to adopt, even though this would also require it to spend more on defence. Together with the population growth effect described by Bar-Josef and Belfer-Cohen and the depletion of game described by Winterhalder and Lu, this would have created a ratchet effect of adoption that goes a long way towards explaining the speed with which the technology spread.

In conclusion, the greater productivity of agricultural labour over hunting and gathering can be reconciled with the evidence suggesting that agriculture did not, in the short-run, improve living standards for the adopters. Other explanations in the literature - notably crowding, disease and population pressure - undoubtedly played a part. But I have suggested that defence and its associated lifestyle changes may have been the more fundamental cause. Whether they were in fact is a question for further research.

At the heart of the story is a fundamental externality from defence – activities that make one community more secure make its neighbours less secure. Needless to say, the logic continues today.

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Figure 1: Total Output/Consumption as Agricultural Productivity Increases, various values of $\eta$ and $\beta$