Why do ownership institutions change when energy systems change?

Tilman Hartley, University of Bristol, tilmanhartley@hotmail.com

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Abstract

In this working paper, I ask why different kinds of societies tend to have different ownership institutions, and what it is about the energy systems of those societies that helps explain the why these different kinds of institution survive. We know that foragers have simple norms of possession, that hunter-gatherers adopt communal ownership, that agriculturalists typically live under hierarchical 'command ownership' institutions, and that titled property becomes widespread in societies run on fossil fuels. But why do ownership institutions change when energy systems change? To address this question, I develop a simple formal model, set out in the appendix, which begins by defining the four types of energy ownership institutions in terms of rules governing individual behaviour regarding the transfer of energy flows and examines each ownership institution in turn to determine why different behaviours are more likely to survive in different energy systems. The interpretation of this model yields some short answers: possessiveness is more likely to survive when energy resources are not worth fighting over; communal ownership institutions are more likely to survive where resources are worth fighting over but are variable; command ownership institutions are more likely to survive where resources are more consistent but where their localisation makes them more easily monopolisable; and titled property institutions are more likely to survive when the energy return from those resources can be exponentially increased.

Introduction

Why do ownership institutions change when energy systems change? The question is asked across disciplines. Anthropologists reviewing food sharing in humans and other primates have noted that "[r]ights to property ownership vary by culture and by resource type... How these rules and norms came to exist, how they are maintained and enforced, and how they change over time is a fruitful

direction for future research" (Gurven and Jaeggi 2015). Economic historians have described the adoption of farming as "a cultural as well as technological revolution, requiring a new system of property rights" (Bowles and Choi 2013: 8830). Development economists have noted that during the Industrial Revolution a "unique potential was historically created by combining mineral resources with the institution of property. This unique combination can largely explain the current world domination of this particular metabolico-institutional system" (Gerber and Steppacher 2014: 458).

Scholars have frequently divided human history into different epochs characterised by their different energy systems (e.g. Polanyi 1944: 43-55, Polanyi 2005, Sieferle 2001, Smil 2008, Smil 2010, Debeir et al. 1991, Pryor 2005). Different scholars use different terms; here I classify four epochs in terms of the methods by which individuals in those societies obtain the majority of their energy: foraging, hunter-gathering, agricultural, and fossil fuelled. Foragers obtain the majority of their energy from collecting wild foods from the forests, without the use of tools or fire. Hunter-gatherers use hunting and cooking tools to hunt and to process energy obtained from plants and from larger animals. Agriculturalists obtain most of their energy from domesticated plants and animals that, unlike the resources of hunter-gatherers, must be tended and stored. Fossil fuelled societies obtain the majority of their energy from burning fossil fuels to drive inanimate machines.

Similarly, the ownership institutions that tend to be adopted in those societies have been described in a variety of ways using a range of terminology; here, I classify them as first possession, communal ownership, command ownership, and titled property. First possession is where an item is not taken if it is already possessed by another (e.g. Krier and Serkin 2015). Communal ownership is where initial possessors give at least some of what they possess to others; that is, it is community membership, not first possession, that entitles an individual to those items, even if those items are initially in the possession of another (adapted from Boehm 2004). Command ownership is where those who first possess a resource surrender at least a share of that resource to an individual of higher status, such as when a peasant or slave surrenders their produce to their lord or master. Titled property extends ownership of tangible physical possessions to the ownership of intangible rights to future resource flows, so that the first possessor of an item surrenders it to whomever has the legal right to that item (adapted from Heinsohn and Steiger 2013 with changes prompted by critiques from Lau and Smithin 2002 and Strunz, Bartkowski, and Schindler 2015).

The approach I take in this paper it to suggest ways in which ownership can be understood in terms of changes in individual behaviour, and then to try to identify why different energy systems might support different behaviours. As part of this process, I have developed a simple formal evolutionary model, set out in the appendix, which models the possible behaviours of individuals with regard to their own possessions and the possessions of others, and describes

how certain changes in the characteristics of an energy system can make some kinds of behaviour more successful than others. The formal model serves as a starting point for the argument and illustrative examples in the main body of the paper.

In the next four sections of this paper, I examine each of the four ownership institutions in turn, looking at the ultimate consequences of adopting the institution, the main proximate mechanisms that maintain the institution, and the characteristics of an energy system that make it more likely for those institutions to survive. The ultimate consequences of adopting the different institutions are the often unintended end result of groups of individuals adopting a particular kind of behaviour: first possession reduces conflict and allows groups to increase in size; communal ownership reduces the risks of variability in supply; command ownership results in increased surpluses and a division of labour; and titled property results in economic expansion and growth. The main proximate mechanisms that maintain those behaviours also differ between institutions: first possession is maintained through an aversion to loss and conflict; communal ownership is maintained through social pressure to be generous; command ownership is maintained through direct coercion and respect for hierarchies; and titled property through the impersonal enforcement of contracts. Each section then concludes by considering which characteristics of the different energy systems make the survival of some institutions more likely than others: first possession is more likely to survive when resources are small; communal ownership more likely to survive when resources are large and variable; common ownership more likely to survive when resources are less variable or storable and are limited to a given location; and titled property more likely to survive when the obtention of resources can be exponentially increased. A final section briefly summarises and concludes.

1 First possession

1.1 The ultimate consequences of a first possession ownership institution: conflict reduction and group augmentation

Individuals following a first possession institution restrain themselves from taking a resource that is already possessed by another. The ultimate function of such an ownership institution is that conflict between individuals within a community is reduced, so that those individuals and their communities are more likely to survive. John Maynard Smith (Smith 1979, Smith 1982) provides a widely influential account of the evolution of possessiveness over breeding sites, and a similar account can be provided for the evolution of possessive behaviour over energy resources (Gintis 2000, Gintis 2007). The simple model supposes two individuals who both want to consume a given resource. Consuming the

resource would, naturally, increase an individuals likelihood of survival; in evolutionary terminology, consuming the resource increases an individual's fitness. The model assumes that individuals can chose between two strategies, named 'Hawk' and 'Dove': individuals adopting a Hawk strategy fight over the resource until they have either won the resource or until they are seriously injured, with serious injuries reducing an individual's fitness; individuals adopting a Dove strategy do not fight, but avoid injury by surrendering the resource if they meet a Hawk or by sharing the resource if they meet a Dove.

Other strategies are possible. Most notably, individuals may adopt a hybrid Hawk-Dove strategy, which Maynard Smith names 'Bourgeois'. Individuals adopting a Bourgeois strategy behave like a Hawk and fight when already in possession of a resource, but behave like a Dove when arriving at a resource that is already possessed by another. As long as the value of resources is lower than the costs of fighting over them - an important qualification, as will be discussed below - then Bourgeois players avoid some of the fitness reducing conflicts that pure Hawks suffer, and win more encounters than the pure Doves. Once established, the Bourgeois strategy is evolutionarily stable against pure Hawk and pure Dove strategies: that is, once the majority of individuals adopt the strategy, individuals playing the pure strategies are unable to increase in number, and so cannot 'invade' the population of Bourgeois.

In effect, possession acts as a signifier that an individual intends to fight rather than surrender the resource in their possession. As a result of these individual behaviours, a convention arises in which the possessions of one individual are not taken by another (Sugden 1986: 95-107, aware that he is following Hume 1740, book 3, part 2, section 2). For the convention to work, it is important that there is some asymmetry between individuals that is generally recognised by others as a signifier of the intent to prevent an object being taken and so gives rise to the observation of a general insitutional rule in which the possessions of others are respected. Physically holding an object is perhaps the simplest way of signifying the intention to fight to maintain possession of a resource, but other signifiers can also be used. Such signifiers might include physical markers such as fences (Krier and Serkin 2015: 5) or verbal signalling such as food calls (Gros-Louis 2004), which extend simple first possession to include 'constructive possession', where an individual has both the ability and the intention to defend an object even though they are temporarily not actually physically in contact with it (Krier and Serkin 2015: 5).

One further consequence of a reduction in conflict is that serious or fatal injuries to other members of the group are less likely, and other members are less likely to avoid conflict by leaving the group to avoid conflict (for modelling see e.g. Aktipis 2011). As a result, the group may increase in size (West, El Mouden, and Gardner 2011, Kokko, Johnstone, and Clutton-Brock 2001, Schino and Aureli 2009: 46). Even without much direct interdependence between individuals, being part of a larger group can increase an individual's fitness as larger groups are better able to defend from rivals and predators, as well as providing a more

diverse gene pool.

1.2 Proximate mechanisms: loss aversion and conflict aversion

First possession institutions are maintained by the desire of the first possessor to defend an object they already possess, and correspondingly, the desire in a potential thief to avoid conflict with another who has signified their intention to fight. For the initial possessor of an object, there is strong evidence that individuals of many species value an object more highly if it is in their possession than if it is not. This has become known as 'loss aversion' or 'the endowment effect', and has been observed in chimpanzees (Brosnan et al. 2007, Brosnan 2011: 16) as well as humans (Kahneman, Knetsch, and Thaler 1990, Brosnan 2011: 16). The recognition that an individual highly values an object in their possession and is disproportionately prepared to fight over it acts as a deterrent to others from attempting to take that object from them (Eswaran and Neary 2011, Rohr, Burkart, and Van Schaik 2011). Indeed, it is rare among nonhuman primates for an object held by one individual to be taken by another (Gintis 2007: 8). For example, one study of long-tailed macaques found that when a tube stuffed with raisins was fixed to an object, a dominant new arrival would always initiate conflict and in every case took possession of the raisins from a subordinate incumbent in around a minute. But when the tube of raisins was left mobile and could be physically held by the subordinate, a dominant new arrival would take possession only ten per cent of the time, and even then after a median delay of 18 minutes (Kummer and Cords 1991; similar effect in rhesus in Russ et al. 2010; also discussed in Gintis 2007: 8).

A further example of inflicting costs on potential thieves is that third parties, who are members of the group but not directly affected by the attempted theft, may intervene in an attempt by one individual to take from another. There are observed cases in which third parties appear to intervene to prevent resources being taken: in the case of the long-tailed macaques mentioned above, when a dominant new arrival attempted to take the raisins from a subordinate while other group members were present, the subordinate would scream to draw the attention of third parties who would often intervene to prevent the new arrival from taking them (Kummer and Cords 1991; reviews in Stake 2004 and in Russ et al. 2010: 568, Tomasello and Vaish 2013). However, it is not at all clear that such behaviour is necessarily evidence of third party enforcement of a first possession institution; these instances of 'altruistic punishment' are subject to much discussion (Rohwer 2007, Jensen 2010) since such interventions might be accounted for by the fact that the interveners are simply annoyed by screaming (Rohr, Burkart, and Van Schaik 2011 cites Goodall 1986), or that higher ranking individuals use such interventions to assert their social dominance (e.g Castles and Whiten 1998, Rohwer 2007 805). Nevertheless, whilst it is difficult to be certain about the immediate motivations in nonhuman primates, the end

result is that a first possession institution is enforced by such interventions. Again, it seems likely that reducing conflict between group members will often have indirect benefits for the intervener, since preventing conflict maintains the number of group members, which in turn increases the genetic diversity of the group as well as increasing the size of the group who are able to take part in group defence. Where the intervener is a high ranked individual with a greater number of progeny, the ultimate fitness benefits of intervention are even greater since most of the offspring that are defended are likely to be genetically related to the intervener.

1.3 Why first possession institutions are likely to survive among foragers

So, the theory is that individuals living in communities that observe a first possession institution are more likely to avoid wasteful conflict and more likely to benefit from living in larger groups, and so are more likely to survive than those that do not. For fairly small and low value resources, a first possession institution affects individual behaviour through the direct mechanisms of instincts such as the endowment effect and the corresponding aversion towards taking the possessions of others, as well as less direct mechanisms that motivate third parties to intervene. But as noted in the discussion of the Hawk-Dove-Bourgeois model above, within that model first possession behaviours only enhance individual fitness as long as the value of resources is lower than the costs of fighting over them. Foraged foods fall into this category, but higher value resources such as large animals, grain stores, and crude oil do not. So whilst we would expect to find first possession institutions governing foraged foods, we might find that hunter-gatherers, agriculturalists, or fossil fuelled societies adopt different institutions.

2 Communal ownership

2.1 The ultimate consequence of a communal ownership institution: conflict reduction and variance reduction

Individuals following a 'communal ownership' institution give at least some of what they initially possess to other members of the community. The puzzle is to explain why individuals no longer follow first possession, but adopt communal ownership instead. As noted above, one of the reasons that individuals benefit from adopting the first possession institution is because the costs of conflict are greater than the potential for gain from taking the possessions of others. In the case of large resources, this condition no longer applies: if an individual has managed to obtain a very high value resource from the environment, then a new arrival may well consider it worth the risk of fighting them for it. Since wasteful

conflict is harmful to the individual, one ultimate consequence of communal property is that conflict is avoided by first possessors surrendering at least some of what they possess to others in the group without the need for fighting.

A further consequence is that communal ownership reduces the variance in the food supply: unlike foraging for food, hunters may go a long time without a kill, since large game animals are less prevalent than smaller foraged foods, and an individual may be prevented from hunting through injury or illness or may simply be unlucky for an extended period of time (Kaplan et al. 1985, Gurven, Hill, and Jakugi 2004, Cosmides and Tooby 2013: 214). Communal ownership, then, benefits the individual by ensuring a less disrupted food supply. In addition to the benefits of group augmentation such as group defence and genetic diversity, communal ownership also ensures that individuals continue to benefit from having a larger number of other individuals to reciprocate should they suffer a reversal of hunting fortune in the future.

2.2 Proximate mechanisms: tolerated scrounging, kin selection, and 'attitudinal' reciprocity

Individuals adhering to a communal ownership institution do not aggressively defend their possessions but instead share what they possess to be consumed by others in their group. The end result is a dramatic reversal in behaviour compared with norms of first possession, but the mechanisms that maintain communal ownership institutions may have evolved much more gradually. Whilst the term 'food sharing' describes an active form of transferring resources, similar behaviours include 'tolerated scrounging', 'tolerated theft', and 'demand sharing' with the demander described as engaging in 'harassment' of the first possessor, all behaviours which diverge from first possession in that they are 'the unresisted transfer of food from one individual to another' (Jaeggi and Gurven 2013). Such behaviours form a continuum that begins with an initial possessor no longer defending their possession so aggressively, and over time develop towards the adoption of detailed sharing norms that govern how resources obtained by one individual are to be divided among all other member in the group.

The mechanisms proposed to account for its evolution classified into three broad categories: tolerated scrounging, kin selection, and reciprocity (Jaeggi and Gurven 2013). The first of these, tolerated scrounging, arises when the possessor of a resource does not aggressively defend their resources and instead allows those resources to be taken by another. This may be an important precursor to more active forms of sharing, and is consistent with the Hawk-Dove-Bourgeois model above, since the model includes the important qualification that a Bourgeois strategy of defending possessions is only evolutionarily successful as long as the value of a resource is less than the costs of fighting to defend it. If the value of the resource is greater then it becomes a better strategy to play Dove and surrender that resource than to engage in a conflict in which more is likely

to be lost than stands to be gained. But why, then, might a potential thief nevertheless risk such conflict? To explain this, it is necessary to account for a resource providing different levels of increased fitness to different individuals: most simply, the food might be worth more to a starving thief than to the well-fed initial possessor. This is particularly clear in the case of large items of food that can neither be stored nor entirely consumed by a single individual; once a hunter is full, maintaining possession of a freshly killed elephant does nothing to increase their fitness. This 'declining marginal utility' suggests that once the first possessor has eaten all they can, there is little fitness benefits to them continuing to defend possession of the resource, especially if there is risk of injury in a fight (Winterhalder 1996, Jaeggi and Gurven 2013). This is, in effect, the converse of Harold Demsetz's hypothesis that it becomes worthwhile to assert ownership when a resource becomes valuable (Demsetz 1967); in the case of soon to spoil elephant meat, as the value of a resource declines it becomes less and less worthwhile to risk violence to maintain possession of it.

The second of these mechanisms, kin selection, offers an account of the evolution of more active resource transfers. The logic is similar to the evolution of maternal instinct, where mothers sharing resources with their offspring has fairly clear evolutionary advantages. Such an instinct can evolve through genetic selection: individuals with mothers that care for their wellbeing are more likely to survive, and so this instinct is likely to become more frequent in successive generations, since the offspring of more caring mothers are more likely to survive and so inherit the instinct to share with their own offspring. A similar mechanism is generally accepted to apply to sharing between close relatives: individuals predisposed to share with their relatives are more likely to have relatives who are also predisposed to sharing, so the tendency to share amongst kin increases (e.g. Jaeggi and Gurven 2013).

The third mechanism, reciprocity, accounts for sharing between unrelated group members. Reciprocity is typically theorised as transfers that are conditional on the recipient having previously shared with the current giver (though a variety of sometimes contradictory definitions appear in the literature; see Carter and Wilkinson 2013: 5). Unlike tolerated scrounging, whereby an individual's fitness is directly enhanced through avoiding needless conflict, and kin selection, whereby a genetic propensity to share becomes inheritable by offspring, the mechanism of reciprocity relies on the adoption of behaviours that depend on the behaviours of others. In a seminal paper, Robert Trivers models the evolution of mutual reciprocity (what he called 'reciprocal altruism') in terms of a coordination problem in which an individual incurs a cost for helping another, but stands to gain a greater benefit in the long run if that help is later reciprocated, in which case both individuals benefit (Trivers 1971). Again, the result of such behaviour is that individuals in communities adopting communal ownership institutions are more likely to survive, as the fitness of both individuals increases.

It is relatively straightforward to identify proximate causes of the first two mech-

anisms. Tolerated scrounging will be maintained by an aversion to costly fighting over things that an individual does not highly value (and since hunting tools can also be used as weapons, the costs of fighting between hunters is that much greater than between unarmed foragers; see Gintis, Schaik, and Boehm 2015). Kin selection is maintained by indicators of relatedness, including simple proximity, and like maternal instinct is an inherited disposition to share with those who are related, or merely nearby. In both these mechanisms, the desire to share is hypothesised to be an inherited trait: conflict aversion and generous dispositions evolve as instincts.

The mechanisms by which a desire to reciprocate evolves have been more controversial. Unlike tolerated scrounging and kin selection, reciprocity relies on responding to the behaviour of others, and so early models appeared to assume some form of cost-benefit analysis, whereby an individual keeps score of their interactions with others in order to decide whether or not to share food with them. The long timescale of these interactions meant that reciprocity appeared to assume a high cognitive ability to keep track of previous food transfers in order for the mechanism to function (Jaeggi and Gurven 2013: 1). However, as Frank De Waal has pointed out, such 'calculated reciprocity' is neither hypothesised nor observed; instead, such behaviour is better thought of as a kind of 'attitudinal reciprocity' whereby individuals reciprocate with those with whom they have formed social bonds (Waal 2000. Though De Waal interprets the term 'attitudinal reciprocity' to apply over fairly short periods of time, the concept applies equally well, or better, to long term reciprocal relationships (Schino and Aureli 2009: 59; also Tomasello and Vaish 2013: 234). Neuromodulators such as oxytocin, which plays an important role in mother-infant bonding, also play a role in non-kin social bonds, suggesting that animals have evolved instinctive emotional responses that help to create strong social bonds between reciprocating individuals over time. These emotions then provide a proximate mechanism by which reciprocal behaviours develop, without the need for complex cognitive abilities (Schino and Aureli 2009).

The extent to which some form of non-kin reciprocity takes place among nonhuman primates, independently of tolerated scrounging and kin selection, has been the matter of substantial debate, though one recent meta-study concluded that some form of non-kin reciprocity does appear to take place (Jaeggi and Gurven 2013). Since the amount of hunted meat in the nonhuman primate diet is small and they largely rely on a fairly consistent supply of foraged food for survival, the selective pressures on nonhuman primates to reciprocate are fairly weak: for example, although chimpanzees that engage in the hunting of monkeys do avoid other members of the group who do not reciprocate, they "do not seem to resent or punish them actively for being a bad partner alone" (Tomasello and Vaish 2013: 236).

Among human hunter-gatherers, however, who derive the majority of their energy intake from hunted foods (Mann 2007:104), the selective pressure to remain part of a reciprocal community is much stronger. Among present-day groups

whose subsistence practices most closely resemble the hunter-gatherers of our early ancestors, the sharing of meat among group members is both negatively enforced by criticism of individuals who do not share enough (Mameli 2013: 920), and positively encouraged by the status afforded to generous individuals (Flannery and Marcus 2012). Further, archaeological evidence suggests that although human ancestors had already been hunting small animals for at least 1.5 million years (Ferraro et al. 2013: 62174), it is only after the earliest evidence for the hunting of large animals (Stiner, Barkai, and Gopher 2009) around 500,000 years ago that evidence also appears for communal butchery (Gintis, Schaik, and Boehm 2015 and references therein) and for meat sharing (Stiner, Barkai, and Gopher 2009, Riedl et al. 2012: 675). By around 200,000 years ago, cut marks on bones are those of a single butcher, indicating that procedures for butchering and sharing meat had become the responsibility of a single individual, as is the case in many present-day hunter-gatherers (Mameli 2013: 920).

Although frequently overlooked, the evolution of mechanisms that allow the transition from simple possessive behaviours to the adoption of communal ownership is an important and substantial change in behaviour. Whilst possessiveness is an evolved response to maintain what an individual already has in their possession, communal ownership entails that a group member has an entitlement to consume a resource that is in the possession of another. But since communal ownership is so important for long term survival, the institution must be sufficiently strong to enable individuals to overcome their evolved instinct to violently defend what they were the first to possess (Ketelaar 2015: 61 citing Frank 1988). Instead of violently defending what they possess, they peaceably share it with others in the group. This shift from merely possessing a thing to having a right to possess it is correctly identified and celebrated as a vital development in human affairs; it is rarely recognised that it is the shift away from individual possession to communal ownership that marks this change; in fact I have yet to see the claim explicitly stated. An oft quoted remark by Tony Honor seems entirely apt: "To have worked out the notion of 'having a right to' as distinct from merely 'having' . . . was a major intellectual achievement" (Honoré 1961:115); that achievement belongs to our hunter-gatherer ancestors during the adoption of communal ownership.

2.3 Why communal ownership institutions are likely to survive among hunter-gatherers

Individuals living in communities that rely on a variable supply of large resources are more likely to survive if they adopt a communal ownership institution, since this reduces both the costs of conflict and the risks of variance. A simple aversion to unnecessarily fighting over resources may account for the tolerating the 'theft' of resources declining in usefulness to the initial possessor; kin selection mechanisms provide an account of the evolution of a generous disposition

motivating individuals to share with their relatives; and reciprocity between unrelated community members may be motivated by the social bonds between group members, as well as social pressure through the negative and positive reinforcement of a sharing ethic. These institutions enforce an effective egalitarianism, with those who try to obtain or retain more than their share, even though they may actually be the first possessors of those resources, are resented and punished. As Boehm, Flannery, and Marcus repeatedly emphasise, among hunter-gatherers there is continual social pressure to share and not to hoard, to reciprocate gifts that build social bonds, and to exhibit the virtue of generosity (Boehm and Boehm 2009, Boehm 2012, Flannery and Marcus 2012). When individuals must rely on high value foods with high variability, the institution of communal ownership helps individuals to repress their possessive instincts in the short term in order to increase their chances of survival in the longer term, as well as providing the other benefits of group membership such as group defence (Boehm 2012, Mameli 2013). So we might expect communal ownership institutions to govern resources that are large and highly variable or difficult to store, whilst societies whose main energy resources are less variable, or more easily stored, may no longer enforce communal ownership and that other forms of ownership institution might become adopted.

3 Command ownership

3.1 The ultimate consequence of a command ownership institution: surplus creation, a division of labour, and social complexity

Low ranked individuals living under a command ownership institution surrender some of what they possess to a more dominant individual. This differs from first possession where individuals maintain possession of the resources they obtain, and almost reverses the egalitarian logic of communal ownership institutions: instead of sharing possessions with others in the group, dominant individuals now receive resources from others. The two most important ultimate consequences of this shift to command ownership institutions are the motivation to create surpluses, and the creation of a division of labour. These are interrelated, and both ultimately derive from the fact that social stratification occurs. The desire to create surpluses is initially motivated by dominant individuals competing for prestige, since it is only by extracting surpluses that they can outcompete others by having more to distribute. Recent genetic analysis suggests that a strong 'bottleneck', particularly in male genetic diversity, occurred around the time of these cultural changes, which implies that some males were far more likely to reproduce than others (Karmin et al. 2015).

The motivation of dominant individuals to compete to accumulate more and more surplus means that a community operating under command ownership is

more likely to obtain more resources from the environment than a less stratified society. Moreover, communities that obtain more surpluses are able to dedicate more resources to both defensive and offensive conflict (an early model is Skaperdas 1992), and together with a division of labour whereby some individuals specialise in acquiring and exercising the necessary skills, this allows communities to develop larger infrastructure projects such as irrigation and eventually innovations such as writing and administrative government that further increase the surpluses that individuals in the community are able to acquire (e.g. Henrich and Boyd 2008, Gowdy and Krall 2015).

3.2 Proximate mechanism: enforcement of status

So why do individuals who find themselves lower down in the hierarchy of stratified societies surrender their possessions to more dominant individuals? Broadly, they do so because they receive sufficient benefits in return or because they are persuaded or coerced into doing so, or some combination of the two. Under command ownership institutions, the benefits of sharing include the familiar benefits of group membership afforded by communal ownership, but instead of the benefits being delivered through the reciprocity of communal ownership, individuals under command ownership institutions receive such benefits due to redistributive decisions made by those who are dominant (e.g. Flannery and Marcus 2012, Searle 1998: 123). As noted above, a benefit may be that the share received is larger due to an increased surplus being obtained by the entire group as a result of a division of labour, investments in infrastructure, or other public goods. Even without coercion, an increase in benefits may be enough for individuals to accept a low status in a stratified society over a precarious existence in a more egalitarian one (Henrich and Boyd 2008). But whilst such a mechanism may help explain why individuals might choose to remain in a group, an additional mechanism is required to account for why low status individuals continue to surrender resources to more dominant individuals within that group, rather than fighting to maintain those possessions. The instinct to maintain social bonds may account for some of this aversion to escape from dominant individuals, but there is little evidence of that these sentiments are felt strongly by hunter-gatherers, who typically escape from or openly attack group members who do attempt to dominate (Boehm and Boehm 2009).

In other words, since command ownership institutions maintain and are maintained by stratified social hierarchies, some further explanation of why lower status individuals accede to such hierarchies is required. Such an explanation involves some account of how dominant individuals use power to maintain command ownership institutions. One element of this is physical force: the ability of dominant individuals to impose costs on those who refuse to surrender their possessions. Direct coercion may be used by dominant individuals to increase the costs of resistance, as well as preventing them from escaping. By threatening and inflicting physical violence, dominant individuals can motivate others to

surrender some of their resources rather than fighting or attempting to flee: in other words, they surrender their possessions because of an aversion to suffering greater losses should they refuse or attempt to escape. Paradigmatic examples of the use of direct coercion include the institutions of slavery and serfdom; slaves and serfs will rarely win fights with their master, and are prevented from escaping, so surrender much of what they initial obtain from the environment to those who exert dominance over them.

The persuasive ability of dominant individuals to engender norms that encourage others to surrender their possessions is more subtle. Flannery and Marcus (2012) offer a very clear account of the shift in 'social logic' from communal to command ownership, whereby dominant individuals exploit the very social mechanisms that had evolved to maintain equality among hunter-gatherers in order to actually create inequality instead. Whilst communal ownership institutions are maintained by exerting pressure to be generous and shaming those who selfishly hoard surpluses, the norms sustaining command ownership institutions maintain prestige in sharing but not longer shame those who hoard surpluses. As a result of this shift in social logic, prestigious individuals are able to amass more wealth, which they can then distribute to others, further demonstrating their generosity and increasing their prestige. Flannery and Marcus (2012) give examples of 'affluent foragers' such as the Tlingit as examples of dominant individuals amassing wealth and making gifts to others who are less wealthy and whose attempts to avoid humiliation and to reciprocate such 'generosity' results in their impoverishment and ultimate enslavement.

3.3 Why command ownership institutions are more likely to survive among agriculturalists

The defining characteristic of command ownership is that lower ranking individuals transfer resources to more dominant individuals. Such an institution can therefore only arise in societies with some degree of social stratification. Command ownership is less likely to survive, then, where lower ranked individuals are fairly free to escape from those asserting dominance. It is little surprise, then, that command ownership and social stratification correlate strongly with sedentary groups (Dow and Reed 2013, Bowles, Smith, and Mulder 2010). Some such groups are not agriculturalists but occupy especially rich sites, typically for fishing (Hayden et al. 1981; Barker 2006); others are hunter-gatherers that store food (Testart et al. 1982, though against this view see Pryor 2005: 37 n.13). However, the vast majority of agriculturalists are stratified, and among agriculturalists stratification tends to be more pronounced (Dow and Reed 2013: 610).

There are two important characteristics that rich fishing grounds, agriculture, and stored foods have in common: they are much less variable than hunted foods, and they are more or less fixed in one location. Since these resources are less variable, the incentives to surrender resources to others in the hope

that they will reciprocate in the future is no longer as great as it is for hunter-gatherers. Even after 90,000 years of the hunter-gatherer ethic, the instinct not to share resources strongly reasserts itself once there is no longer such a reliance on reciprocity to motivate the continual social pressure required to maintain communal ownership (e.g. Gurven, Hill, and Jakugi 2004, Bowles and Choi 2013: 8831). Moreover, since these resources are more or less stationary it is much harder for individuals to simply walk away, and individuals who stay on the fringes of a resource rich society more likely to survive than those who try to escape (Dow and Reed 2013). So, we would expect command ownership institutions to be more likely to survive when resources are relatively constant and fixed in one location.

4 Titled property

4.1 The ultimate consequences of titled property institution: growth

Titled property gives an individual possession rights to a precise quantity of future resources, and this right is impersonally enforced. This combination of precision and impersonality distinguishes titled property from the communal and command ownership institutions described above, though the full consequences of the adoption of titled property only really occurs once making profits from resource loans becomes widely accepted.

The ultimate consequences of adopting titled property are that, on aggregate, a far larger quantity of resources are obtained from the environment. This ultimate consequence is attributed to three more immediate effects of the widespread adoption of titled property: more productive resource use; economic rationality; and a growth incentive (perhaps even a growth imperative). Increased efficiency results from the impersonal nature of titled property. Under command ownership, resources are accumulated by individuals as determined by a fairly fixed social hierarchy, whereas with titled property the rights to acquire those resources are much more easily transferred from one individual to another. In particular, resources can more easily be transferred to entrepreneurs, where under command ownership institutions resources for investment in technological innovations are more difficult to acquire, unless the entrepreneur happens to be wealthy or related to wealthy individuals (e.g. see Temin 2004: 718). When combined with a widespread acceptance of making profit by charging interest on loans, the ease with which property titles can be transferred leads to the adoption of a mindset, sometimes termed 'economic rationality', 'monetary rationale', or 'substantive rationality', in which future returns are given a much higher priority in individual decision-making than other considerations (Lau and Smithin 2002: 5; De Soto 2003: 42; Steppacher 2008: 346). Creditors compete to lend to individuals who will provide higher returns and debtors compete

for loans and to make profits that allow those loans to be repaid at interest. The aggregate effect is to produce an incentive, perhaps even an imperative, for exponential economic growthVan Griethuysen 2010. Since exponential growth is impossible to sustain indefinitely, the extent to which political authorities are able to intervene in debt contracts between individuals has important consequences. In some cases, titled property is defined to forbid the charging of compound interest, or to periodically forgive debts that have accumulated; in other cases, titled property titles define rights to exponentially increasing returns and enforceable irrespective of any wider social or political consequences Homer and Sylla 2005. In any case, the incentive to generate profit, and perhaps even an imperative for growth, means that individuals in a society that has adopted titled property are likely to obtain more resources than one that does not.

4.2 Proximate mechanism: enforcement of contracts

Titled property, as I have defined it above, is the impersonal right to a precise quantity of future resources. Unlike under command ownership, transfers are not determined by the position of individuals in the social hierarchy, and unlike the sharing familiar to hunter-gatherers, transfers are exact and contractually stipulated quantities. As a result, individuals become motivated to make transfers not because of direct coercion or the engendering of attitudinal reciprocity but by the calculated rationality to obtain more in return than has been lent. In the simplest form of titled property, a creditor is initially motivated to surrender some of the resource that they possess because they will receive a greater amount in return, whilst the motivation for a debtor to repay the loan at interest is maintained both through norms that insist that debts must be repaid and through physical coercion sanctioned by law.

As with other forms of ownership, such behaviours survive only if individuals do not excessively harm their chances of survival by behaving in that way: people transfer resources because they accrue benefits in return, or because they are persuaded or coerced. In titled property, the anticipation of reciprocity among hunter-gatherers evolves into a more precise arrangement once the main energy resource becomes less variable, as the prestige attached to generosity and the reciprocating of gifts becomes more easily quantified. Domesticated plants and animals are more reliably obtained and easier to measure more precisely than their wild counterparts, and so it becomes much easier to tell whether an individual's transfers have been adequately reciprocated or not. So titled property often appears alongside command ownership institutions, and often is adopted to govern the transfer of items particularly associated with prestige. In effect, the ability to calculate returns with precision allows reciprocity to be quantified, leading to the use of a more calculating rationality about resource transfers.

Also important is that unlike the gift of a foraged fruit or a hunted animal,

the gift of domesticates bears a future cost to the giver: gifted grain cannot be used as seed, and a gifted sheep cannot be used to breed. The close connection between payment of interest and the productions of domesticated offspring is reflected in ancient languages: Egyptian used *ms* for 'interest' and *msj* for 'to give birth', and Sumerian had just single word, *mas*, for both 'calves' and 'interest' (Homer and Sylla 2005: 20). For those who grow crops and breed animals, the giving of energy resources comes at a future cost: the English word 'interest' itself later derived from the latin *intereo*, meaning 'to be lost' (Homer and Sylla 2005: 73). So arrangements often arise in which interest is paid by the reciprocator to the lender to compensate them for that loss. But even from the earliest times, the charging of interest became problematic: compound interest, in particular, seems to have led to individuals accruing debts that they were unable to repay. Many of the earliest surviving written texts are legal and religious codes that limit and specify the institution of titled property by stipulating what may be loaned, to and by whom, at what rate of interest, what may be used as collateral, in what circumstances debtors may default, and what the permitted consequences of default may be. Such texts include the Babylonian Code of Hammurabi in the 19th century BC, the Greek Laws of Solon in the 6th century BC, the Roman Twelve Tables in the 5th century BC, and the Indian Laws of Manu in the 2nd century BC - texts that in many ways are the foundation documents for the civilisations that are subsequently built upon them; laws defining titled property and regulating lending contracts have been a feature of legal systems ever since (Homer and Sylla 2005).

4.3 Why titled property institutions are more likely to survive among fossil fuelled societies

Titled property, including the practice of making loans at interest, predates the large-scale adoption of fossil fuels by several millennia. Nevertheless, there is a strong relationship between titled property and fossil fuels, for two reasons: firstly, because the development of fossil fuel technologies require large amounts of initial investment, and secondly because titled property tends to encourage an economic expansion that reaches a limit much sooner under the energy constraints that exist in agricultural societies.

As noted above, the charging of interest on loans has been problematic since the beginning of recorded history. Not only does the payment of interest tend to transfer money from those who don't have resources towards those who do, but interest compounds exponentially; the social consequences of this were sometimes so severe that many of the earliest legal and religious texts simply prohibit loans at interest. Where interest was permitted, it was regulated closely (Homer and Sylla 2005). When interest is relatively unrestricted, historically there have been broadly three outcomes: the chronically indebted become slaves; or the debts are periodically forgiven; or there is a period of exponential growth. If individuals are enslaved, the system reverts to a form of command ownership

in which slaves transfer what they obtain to their masters. If debts are periodically forgiven, such as during jubilees, then the institution ceases to be titled property, since the right to a precise quantity of future resources no longer exists if the creditor no longer has a right to the resource transfers they expected to receive; moreover, such jubilees are only possible when a political authority is sufficiently strong to The third outcome is that there is a period of economic expansion, in which titled property is maintained during periods of economic growth which allows compound interest repayments to be maintained, at least for a period of time. Territorial expansion can be exponential, for a while, as more territory supplies more soldiers for more conquests. Similarly, fossil fuels can supply more energy for exploration and extraction of ever more fossil fuels, and so too can grow exponentially for a time (Georgescu-Roegen 1976 [1965]: 98, Steppacher 2008).

5 Summary and conclusion

A short answer to the question 'why do ownership institutions change when energy systems change?' is 'because in different energy systems, individuals with some behaviours are more likely to survive than others'. Possessive behaviours evolve and are maintained through an individuals aversion to loss, and tends to survive amongst foragers who obtain most of their energy from small resources, and where possessiveness reduces wasteful conflict and allows groups to grow in size. Communal ownership institutions are maintained by continual social pressure on the individual to adopt an attitude of reciprocity, and tend to survive amongst hunter-gatherers who obtain most of their energy from larger and more variable resources where communal ownership has the effect of reducing the variance in the energy supply. Command ownership institutions are maintained by social hierarchies, and tend to survive among agriculturalists who obtain most of their energy from resources that are less variable and are fixed in a given locality, and these institutions result in a division of labour and an increase in surplus. Titled property institutions are maintained by contract, and are more likely to survive in societies whose energy systems are capable of exponential growth, such as expanding colonial societies and societies that can rely on increasing amounts of fossil fuels.

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A Appendix: a simple formal model of the evolution of four ownership institutions

A.1 The intuition

Every individual needs energy resources to survive. There are energy costs to obtaining these resources, and if the costs of obtaining them exceed the returns on their acquisition then the individual will eventually die. There are two ways in which an energy resource can be obtained for consumption: it can be obtained by the individual from the environment, or it can be taken from another individual. This leads to two kinds of cost: the costs of obtaining a resource from the environment, and the costs of fighting with others for the resource. Some individuals are more likely to win fights over resources than others. Finally, sometimes, there may be additional benefits to sharing a resource with others, perhaps particularly the benefit of future reciprocity. Depending on the relative value of the resources, benefits, and costs, and depending on the strategies adopted by others, different strategies are more likely to allow an individual to capture more energy and so are more likely to survive.

A.2 The strategies

There are three ways in which an individual can obtain a resource: demand it from others and fight if necessary (Demand); obtain it themselves and fight if necessary (Resist); or obtain it themselves and surrender it if demanded (Share). Interactions are random pairings, strategy choice is simultaneous, and populations are of unlimited size. (Note that Demand is similar to the strategy sometimes called Aggrandiser or Gangster, Resist is similar to Bourgeois, and Share similar to Dove; see supplement to Bowles and Choi 2013).

Demand (D): Demands a resource of value v from the other player. If the other player resists then there is a fight where D incurs a cost f. Demand wins the fight a proportion P of the time and gains v when it wins.

Resist (R): Obtains a resource of value v at a cost c. Incurs a cost f if fought by a Demander; wins the fight and retains the resource $1 - P$ of the time.

Share (S): Obtains a resource of value v at a cost c. Surrenders the resource if demanded by a Demander and neither Share nor Demand suffers any cost of fighting. Some additional benefit b is gained by the Sharer; this b could be the benefits of reciprocation that reduces variance or of being part of a larger group, for example.

A.3 The variables

v Value of the resource possessed by the individual.
c Cost of obtaining the resource from the environment; $0 < c$.
f Cost of fighting over the resource; $0 < f$.
b Additional benefit of sharing the resource.
P Proportion of fights that a Demander wins the resource; $0 \leq P \leq 1$.

A.4 The payoffs

The payoffs are calculated as follows. If a Demander interacts with another Demander then neither increases in fitness; if a Demander interacts with a Resister then a fight over the resource ensues and the Demander wins the resource with a probability P; and if a Demander interacts with a Sharer then no fight ensues and the Demander receives the entire resource. If a Resister interacts with a Demander then a fight ensues and the Resister retains the resource with a probability $1 - P$, though has suffered the costs of fighting and of having obtained the resource in the first place; if a Resister meets another Resister or a Sharer then no fight ensues and each retains the resource, minus the costs of having obtained it. If a Sharer meets a Demander then they surrender the resource and suffer the costs of having obtained it, but also receive a gain from having shared with the Demander; if a Sharer meets a Resister or another Sharer then they each retain the resources, minus the costs of having obtained it. As a payoff matrix, this is:

Table 1: Payoff matrix for Demander-Resister-Sharer game. Payoffs are to the row player (on the left)

	Demand	Resist	Share
Demand	0	$Pv - f$	v
Resist	$(1 - P)v - f - c$	$v - c$	$v - c$
Share	$-c + b$	$v - c$	$v - c$

A.5 Proportions and average fitnesses of strategies in mixed populations

This simple model shows how different values for these variables leads to different mixes of strategies in the population. These are represented by the proportion p in a population that adopts Demand, the proportion q that adopts Resist, and the proportion $1 - p - q$ that adopts Share. For calculating the way these proportions increase or decrease in a population, $V(X|Y)$ denotes the increase in fitness that results from an interaction between strategy X and strategy Y, and $W(X)$ denotes the average change in fitness across all of strategy X's interactions, which in turn depends upon the proportion of each of the

other strategies in the population. These symbols are listed here:

p Proportion of D in the population.
q Proportion of R in the population.
$1 - p - q$ Proportion of S in the population.
$V(X|Y)$ The change in fitness of X when X interacts with Y.
$W(X)$ The average change in fitness across all of X's interactions.

So the outcome of each interaction can be listed as:

$V(D\|D) = 0$	$V(R\|D) = (1-P)v - f - c$	$V(S\|D) = -c + b$
$V(D\|R) = Pv - f$	$V(R\|R) = v - c$	$V(S\|R) = v - c$
$V(D\|S) = v$	$V(R\|S) = v - c$	$V(S\|S) = v - c$

The payoffs for an individual playing each strategy is the result in terms of increased fitness that accrues to that individual when they interacts with another player. That is, the average fitness is the sum of the fitness increases that result from the interactions with individuals adopting different strategies multiplied by the frequency with which those strategies occur in the population. So, for example, the average increase in fitness for a Demander is the sum of the payoff an individual receives from interacting with another Demander multiplied by the chances of it meeting another Demander, plus the payoff from interacting with a Resister multiplied by the chances of it meeting a Resister, plus the payoff from interacting with a Sharer multiplied by the chances of it meeting a Sharer. So, for each of the three strategies:

$$\begin{aligned} W(D) &= pV(D|D) + qV(D|R) + (1-p-q)(D|S) \\ &= q(Pv - f) + (1-p-q)v. \end{aligned} \tag{1}$$

$$\begin{aligned} W(R) &= pV(R|D) + qV(R|R) + (1-p-q)V(R|S) \\ &= v(1-pP) - pf - c. \end{aligned} \tag{2}$$

$$\begin{aligned} W(S) &= pV(S|D) + qV(S|R) + (1-p-q)V(S|S) \\ &= (1-p)v + pb - c. \end{aligned} \tag{3}$$

A.6 Replicator dynamic and difference equation

The replicator dynamic is used to calculate the strategy mix in a population based upon the proportions in the preceding population and the relative fitness

of the strategies. In this model, the replicator dynamic for a two strategy game between Demanders and Sharers, where p' denotes the proportion of D in the succeeding population, is:

$$p' = \frac{pV(D)}{pV(D) + (1-p)V(S)} \tag{4}$$

from which the difference equation can be derived (see McElreath and Boyd 2008: 26):

$$\Delta p = p(1-p)\frac{W(D) - W(S)}{pW(D) - (1-p)W(S)}. \tag{5}$$

A.7 Outcomes and their interpretation

In the model, the possible stable outcomes of these interactions are a population entirely composed of one of the three strategies (in which one strategy dominates), or a population in which two or more of these strategies are mixed (in which there is coexistence). These different outcomes are interpreted to correspond with the different ownership institutions adopted by a population

Importantly, in this a model, a population composed entirely of Demanders obtains no resources from their environment, so individuals in such a population would not survive. As a result of the risk of Demander takeover leading to population collapse, an intuitive way of interpreting the role of ownership institutions in different societies is that they prevent a situation in which Demand is the best unique strategy, since if that were to occur then such a population would collapse.

There are, then, four different outcomes which correspond to four different ownership institutions. First, a first possession institution exists when a population is largely composed of Resisters who are able to prevent invasion by Demanders. Second, a communal ownership institution exists in a mixed Demander-Sharer population where the invasion of Resisters is prevented by sufficiently high additional benefits accruing to Sharers. Third, a command ownership institution exists in a mixed Demander-Sharer population in which the invasion of Resisters is prevented by the increased likelihood of Demanders winning fights. Fourth, titled property is similar to communal ownership in this model in that it is composed of a mixed Demander-Sharer population, but differs in that the invasion of Resisters is prevented by increasing values of v to allow sufficiently high additional benefits to accrue to Sharers. (In the terminology of Acemoglu

and Robinson, it may be useful to think of titled property institutions as corresponding to an 'inclusive' ownership institution, in contrast to the 'extractive' character of command ownership.)

It is worth noting that a mixed Demander-Resister population represents the absence of an ownership institution: Resisters obtain resources from the environment and then fight over them with Demanders. It is intuitive to expect that populations observing some form of ownership institution engage in less wasteful conflict, and that individuals in those populations are more likely to survive; it is that insight that motivated the modelling of the origins of first possession institutions as coordination games in the first place (Maynard Smith 1979, 1982).

A.8 First possession: Resisters dominate Demanders

A situation in which a population of Resisters can repel invasion by Demanders can be found by examining the two-by-two payoff table for interactions between Demanders and Resisters:

Table 2: Payoff matrix for Demander-Resister game. Payoffs are to the row player

	Demand	Resist
Demand	0	$Pv - f$
Resist	$(1 - P)v - f - c$	$v - c$

If the payoffs to Resisters are always greater than payoffs to Demanders, Resisters will dominate and repel any invading Demanders. This occurs when $(1-P)v - f - c > 0$, and when $v - c > Pv - f$. The second of these inequalities can be rewritten $(1-P)v + f - c > 0$; since $f > 0$, Resisters can repel Demanders as long as $(1 - P)v - f - c > 0$. Solving for v:

$$\begin{aligned} v &> Pv + f + c \\ v &> \frac{f + c}{1 - P}. \end{aligned} \tag{6}$$

A.9 Communal ownership: a Demander-Sharer mix repels Resisters through high additional benefits accruing to Sharers

After the transition to hunter-gathering, the inequality $v > \frac{f+c}{1-P}$ no longer holds: whilst the relative power P of Demanders decreases, the costs of fighting over resources f increases due to the use of hunting tools as weapons, and the costs

of obtaining resources c increases due to the increased energy expenditure in hunting and processing those resources. It is also worth nothing that although in the short term the value v of the resource possessed by an individual is large - a single large animal can provide much more energy than can be consumed by an individual - the meat quickly declines in value through spoilage. Interpreted over the short term, this rapid decline in value also means that very soon $v > \frac{f+c}{1-P}$ no longer holds.

In terms of the model, a mixed Demander-Sharer population can avoid collapse into a Demander dominated population as long as Demand and Share can coexist and converge upon a mixture of the two strategies. The two-by-two table gives these conditions:

Table 3: Payoff matrix for Demander-Sharer game. Payoffs are to the row player

	Demand	Share
Demand	0	v
Share	$-c+b$	$v-c$

For there to be bistability around a convergence point, the two inequalities $v > v - c$ and $-c + b > 0$ must hold. Since $c > 0$, the first of these inequalities always holds, so for Demander-Sharer bistability, the benefits of sharing must be greater than the costs of obtaining the resource in the first place, that is, when $b > c$.

Moreover, such a mixed Demander-Sharer population must be able to repel Resisters who fight to prevent their resources being taken; that is, at the point where Demanders and Sharers are in a stable equilibrium, both strategies must be fitter than Resisters. To find the conditions in which a mixed Demander-Sharer population can repel invading Resisters, the equilibrium point of the Demander-Sharer strategy must first be found. This is where $\Delta p = 0$, with that equilibrium point denoted by $\hat{p}$. To find $\hat{p}$, we set $p = \hat{p}$ and $W(D) = W(S)$ and solve for $\hat{p}$ (remembering that $q = 0$):

$$\begin{aligned} W(D) &= W(S) \\ q(Pv - f) + (1 - \hat{p} - q)v &= (1 - \hat{p})v + \hat{p}b - c \\ \frac{c}{b} &= \hat{p}. \end{aligned} \tag{7}$$

So, a mixed Demander-Sharer population has a stable internal equilibrium when $b > c$, where the proportion of Demanders in the population is c/b. At that point, a rare Resister can invade if it is fitter than the Demanders and Sharers in the population. Since Demanders and Sharers are equally fit at that point, Resisters can be prevented from invading as long as $W(D) = W(S) > W(R)$, when $q = 0$, and $p = c/b$. This occurs when:

$$\begin{aligned} W(D) &> W(R) \\ (1-p)v &> v(1-pP) - pf - c. \end{aligned} \tag{8}$$

Among hunter-gatherers this inequality is maintained because b is sufficiently large: the benefits of variance reduction and continuing membership of the group are sufficiently fitness enhancing. To find the level at which b is sufficiently large to for the communal ownership institution to survive, we first solve for p:

$$\begin{aligned} (1-p)v &> v(1-pP) - pf - c \\ p &< \frac{c}{v - Pv - f} \end{aligned} \tag{9}$$

the substitute c/b for p:

$$\frac{c}{b} < \frac{c}{v - Pv - f} \tag{10}$$

and then solve for b:

$$\begin{aligned} cb &> c(v - Pv - f) \\ b &> (1-P)v - f. \end{aligned} \tag{11}$$

So, to repel invasion by Resisters, the additional benefits accruing to Sharers must be larger than $(1-P)v - f$. So, taken together, the conditions in which hunter-gathers maintain a mixed Demander-Sharer population is when $b > c$ and $b > (1-P)v - f$.

A.10 Command ownership: To prevent Resisters dominating a mixed Demander-Sharer population is maintained through increased Demander power

After the transition to agriculture, the ability to store reduces the benefits of sharing resources, and at least initially, the tending of domesticates increases the costs of obtaining the resources in the first place. If b falls below $(1-P)v-f$, the mixed Demander-Sharer population no longer repels invasion by Resisters. A return to a population dominated by Resisters is possible, as long as there are conditions in which a population of Resisters can repel Demanders; as above, that is when $v > \frac{f+c}{1-P}$ (an instance of this turn from communal to possessive behaviours is the Siniori; see Holmberg 1950, Stearman 1987).

An alternative possibility is that an agricultural society may maintain a Demander-Sharer mix by the suppression of Resisters by more powerful Demanders. This

can occur when P is sufficiently large to make Demanders and Sharers fitter than Resisters. Again, the conditions for a stable Demander-Sharer population are that $c > b$ and $b > (1 - P)v - f$. Solving for P:

$$\begin{aligned} b &> (1 - P)v - f \\ P &> 1 - \frac{f + b}{v}. \end{aligned} \tag{12}$$

So as long as P remains high relative to the costs of fighting and the benefits of sharing, this represents the conditions in which a mixed Demander-Sharer population can prevent the invasion of Resisters through asymmetries in the ability to win resource conflicts. This can be interpreted as the condition in which extractive command ownership institutions arise, whereby powerful individuals are able to Demand resources from the Sharers who obtain them from the environment whilst repelling Resisters willing to fight to try to retain the resources they have obtained.

A.11 Titled property: To prevent Resisters dominating, a mixed Demander-Sharer population is maintained by again increasing the benefits of Sharing

A further possibility for suppressing Resisters is to increase the benefits of Sharing. In terms of the model, this works by making b sufficiently large to make Sharers fitter, and so prevent Resisters invading the mixed Demander-Sharer population. This mechanism may operate in conjunction with Demanders increased chances of winning conflicts to repel them, since the condition in which Resisters are repelled is $P > 1 - \frac{f+b}{v}$, if b increases then the value of P need not be as high to ensure that invasion by Resisters is prevented. This can be interpreted as representing the way that mutually beneficial contracts begin to replace direct coercion as the means by which Resisting is prevented and Sharing encouraged.