PROPERTY RIGHTS AND DOMESTICATION[1]

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Abstract This paper combines the property rights approach of Barzel with notions from renewable resources and evolutionary economics to examine the domestication of wild animals. Wild animals are governed by weak property rights to stocks and individuals while domesticated animals are governed by private ownership of stocks and individuals. The complex evolutionary process of domestication can be viewed as a conversion of wild populations into private property as well as a transition from natural selection to economic selection controlled by owners of populations and individuals. In our framework domestication is not the explicit goal of any economic agent, but it rather emerges as the long run outcome of an innovation in hunting strategies in a hunter-gatherer society. Our formal model also suggests that the domestication process moves slowly at first but then proceeds rapidly, aligned with the archeological evidence on domestication events.

Keywords: Domestication, property rights, renewable resources, evolutionary economics.
JEL Classification codes: O130, Q1, Q2

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1. INTRODUCTION

Yoram Barzel's contribution to economics is primarily associated with his analysis of property rights (Barzel 1997). This important work developed a framework for analyzing a wide range of problems by focusing attention to the economics that govern complex assets. In this paper we use this property rights approach to examine the domestication of wild animals.

The domestication of wild animals and plants was a crucial precursor for the development of human civilization (Clutton-Brock 1989 and Diamond 1997). Before domestication, humans depended on their ability to kill or collect wild species for food, shelter, clothing and tools. The great advantages afforded by domestication are obvious. To be able to confine and selectively breed animals and plants -- using them for power, transportation, food and clothing – not only allows a better diet and shelter but also allows the development of markets (for products) and specialized human and physical capital. Domestication is crucial to the development of human societies, but its details are not well understood, particularly from an economic perspective.

Barzel applies his property rights model to a variety of topics from human slavery to the formation of the state, to the allocation of water, but never extends his framework to the domestication of animals. Barzel's approach, however, is applicable because of its recognition of complex assets and how the ownership of those assets can itself be a complex mixture of ownership regimes. For wild and domestic animals there are two complex assets at issue: the population and the habitat (land for the cases we examine). Lueck (1989, 1991) uses Barzel's approach to analyze different systems of governance for wildlife but did not consider the economics of domestication. A property rights approach to domestication is also promising because wild and domesticated animals are governed by different property regimes. Wild animals are governed by weak property rights to stocks and individuals while domesticated animals are governed by private ownership of stocks and individuals. Thus, the complex evolutionary process of domestication can be viewed as a conversion of wild populations into private property.

This article develops an economic approach to the question of human domestication of wild species with a focus on the establishment of property rights to animals and its effect on evolution.[2] We begin by examining literature from archeology-anthropology and genetics to describe the current understanding on the temporal and spatial history of domestication. We briefly discuss theories of domestication from within and outside economics and suggest how the economics of

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[2] Our focus is on animals rather than plants though similar forces are likely at play.

property rights combined with models from renewable resources and evolutionary economics can be used to develop a framework for understanding the domestication of wild populations. We then develop a model in which hunter-gathers have the option of hunting (and killing wild animals) and capturing (and rearing animals for use) to show how economic forces can generate a process consistent with our current understanding of domestication.

2. A SUMMARY OF EVIDENCE ON DOMESTICATION

In this section we summarize the available evidence on the dates, locations and spatial and temporal diffusion of domestication. We then review the main sources and methods that support this evidence.

The domestication of animals – mammals in particular – began between 10,000 and 15,000 years ago (Clutton-Brock 1989, Price 2002, Sauer 1953, and Zuener 1963). Scholars consider domestication ‘dates’ as a point in time when there is strong morphological evidence that a species has become distinct from its wild ancestor. Dogs (*Canis lupus familiarus*) were the first to be domesticated (from wolves or *Canis lupus*) between 14,000 and 15,000 years ago. Dogs were followed by the familiar hoofed mammals – goats and sheep first, (both around 11,000 years ago) and later cattle and pigs (10,000 years ago). Horses were domesticated by 4,000 years ago, while camels, llamas and reindeer are more recently domesticated.[3,4]

Most of the major domestication events are considered to have taken place in just two regions – the Near East (Southwestern Asia) and Asia. Indeed, domestic livestock, sheep, goats, cattle, and pigs, were domesticated between 10,000 and 11,000 years ago in Southwest and Southern Asia. In the Near East domestication seems concentrated in the Fertile Crescent, while in Asia domestication was stretched between many regions and was accomplished by different groups of people.

The Neolithic Package

The suite of plants, animals, and tools originating from Southwest Asia is sometimes referred to as “The Neolithic Package” (Zeder 2008). By 8,000 years ago all the various artifacts,

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[3] Archeologists use the more precise term “calibrated years before present” (cal BP) refers to the correcting of radiocarbon 14 dates with other information. Radiocarbon dating can be off by substantial amounts of time, but can be calibrated with dates from other sources, such as tree ring dates. Cal BP dates are preferred over non-calibrated dates are indicated with YBP, or Years Before Present. In this paper we simply use Years Before Present.

[4] Lueck and Torrens (2019) present more detail on domestication evidence and consider a wider range of species.

demographic changes, and social institutions that collectively make up the Neolithic Package had developed and spread throughout Southwest Asia and had started to appear in other regions such as Southern Asia and the Mediterranean. The Neolithic Package varied regionally and temporally, but plants, animals, certain tools (especially for storage), some religious iconography, and some social organizational principles did diffuse out from Southwestern Asia to surrounding regions in a recognizable and consistent pattern.

Many of the early developments occurred in the Fertile Crescent, a region that stretches in a northward arch from modern day Israel and Jordan, though southern portions of Turkey and Iran, and southward into the northern regions of Iraq. This arch largely follows the eastern coast line of the Mediterranean and the Tigris and Euphrates Rivers.[5] Most of the major livestock animals known today were domesticated in southeastern Turkey and the Zargos Mountains of Iran. Figure 1 shows the regions in which specific domestic animals originated and the dates (cal BP) at which they appear in new regions of Southwestern Asia.

The mechanisms for how the Neolithic Package spread from Southwestern Asia are still debated but the evidence points to a mixture of migrations by Neolithic agriculturalists to new regions and the adoption of the Neolithic Package by other groups of people living in adjacent regions. Migration appears to explain the appearance of the Neolithic around the coastline of the Mediterranean and in southeastern Europe (Edwards et al., 2007, Zeder et al. 2006, and Zeder 2009). The time for the development of the Neolithic Package in China and India is not a settled issue. Some elements of the Neolithic Package appear to have been imported from Southwestern Asia, such as wheat and a portion of the cattle stock (Li et al. 2007, Verhoeven 2004, and Zeder 2009). Other aspects developed independently in Indian and China. The evidence suggests independent domestication events for cattle (Zebu breed) and pigs, and rice was domesticated separately in the Yangtze Basin of China at 7000 YBP (Caramelli 2006, Chen et al. 2009, Jing and Flad 2002, Li 2007, and Li et al. 2007). The Neolithic Package developed independently in Mesoamerica and South America, though at a considerably more recent date than in the Old World. The domestication of corn may have occurred as early as 9,000 cal BP, but the domestication of animals and the full development of similar cultural traits as found in the Old-World Neolithic at 8,000 YBP did not occur in the New World until around 2000 YBP.

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[5] The term “Levant” refers to the western region of the Fertile Crescent (Verhoeven 2004).

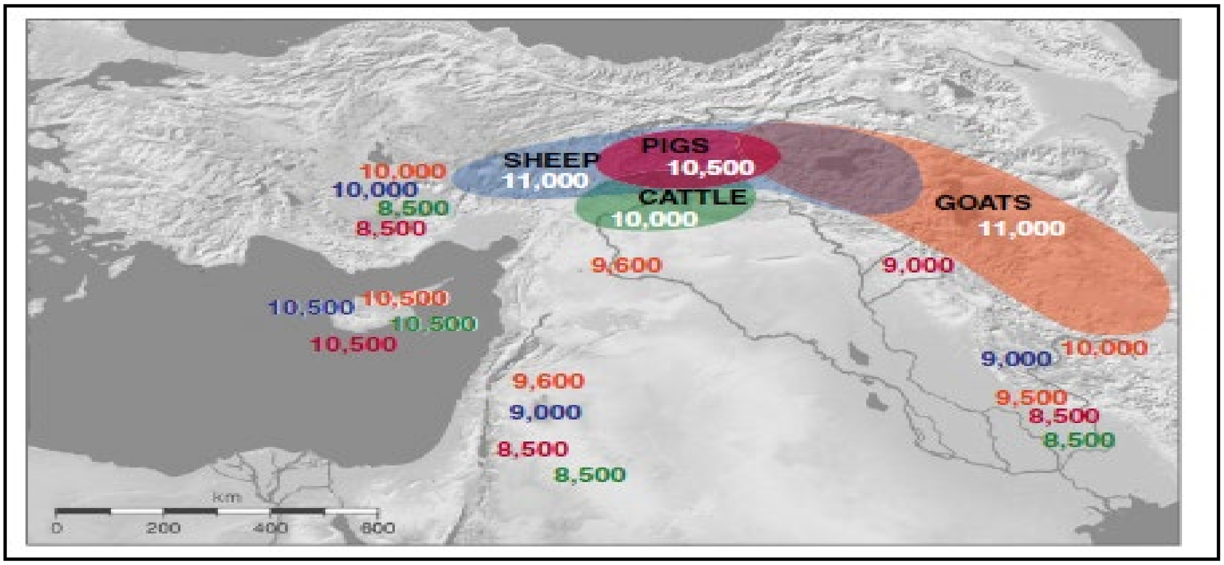

Figure 1. Origins and early movement of livestock in Southwestern Asia

Note: Names, geographic regions, and dates (cal BP) for the origins of major livestock animals are shown as colored polygons. The colored numbers indicate the locations and dates at which domesticates are found outside of their points of origins – the colors are the same as the polygons.
Source: Image from Zeder (2008).

Sources of evidence: genetics and archaeology

The most comprehensive empirical works on the origins and spread of domesticated animals come from interdisciplinary efforts between archaeologists and geneticists (see Edwards et al. 2007 Gotherstrom et al. 2005, and Zeder et al. 2006).[6] Archaeologists use skeletal morphology (the shape and size of bones) to establish similarities and differences between populations of animals, and various signs of muscle alteration and bone damage to understand the life-history, death, and butchering processes of animals. Dating methods (especially radiocarbon dating and stratigraphic analysis) and geographic relation of archaeological sites are also used by archaeologists to identify the origin and spread of domesticates (Reitz and Wing 1999). Geneticists use a variety of chemical methods, computerized analyzers, and statistical methods to analyze the relationship between non-coding sections of DNA to establish the genetic similarity or distance between populations of a species.

Genetic comparisons can be used to determine how related modern sub-populations of a species are to each other, and how related modern populations are to ancient specimens of the

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[6] New evidence is continually changing the agreed upon dates and specific location but for this paper the evidence presented is sufficiently precise.

species found in archaeological sites. These comparisons between modern and ancient specimens can be used to pinpoint the original archaeological populations from which modern domestic populations descended. In some cases, such as domestic cattle and pigs, there seem to have been multiple points of at different times.[7] Related analysis can be conducted to determine the degree to which domestic sub-populations have been interbred with other domestic sub-populations or related wild populations.[8]

The primary data used by geneticists studying the origins and spread of domesticates are similarities and variances within the genetic code (Reitz and Wing 1997). In studying the origins of domesticates, and their subsequent spread, one of two comparative approaches are used. In the first method, the DNA of domestic populations are compared to the DNA of wild species from which they are thought to have descended, if that wild species is still extant. In the second method, the DNA of domesticates is compared to Ancient DNA (aDNA) extracted from archaeological specimens of the presumed wild ancestor. If possible, both methods are used to assure the connection between domesticates and both modern and ancient conspecifics.[9]

There are three primary means by which archaeologist can determine when an animal species has been domesticated (Reitz and Wing 1999). The first, and most traditional, method is to examine the appearance of distinct morphological (the physical shapes and characteristics) traits in the skeleton that distinguish domesticates from their wild relatives. The second technique, developed recently, is to calculate mortality profiles of the animal remains from archaeological sites to examine if animals killed there were done so in accord with the standard culling profile of domestic food animals. The third approach is to determine when a species starts appearing in regions outside its native habitat. This last method is particularly useful when the wild ancestor species had a limited range, or when the regions being investigated are separated by major geographical features such as oceans or mountain ranges. Though this discussion pertains mostly to domesticated animals, these techniques are used, in modified ways, to also address the domestication of plants.

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[7] Also see Larson et al. (2007); Edwards et al. (2007); and Loftus et al (1994).

[8] For example, domestic cattle were apparently allowed to interbreed, occasionally, with aurochs, their wild ancestor. This appears to be also true for pigs, dogs, chickens and most likely other domesticates.

[9] Conspecifics refers to two or more varieties of one species, particularly when these varieties exist in distinct or isolated populations, or for other reasons are distinct enough from each other that it worth noting that the two or more sub-populations are actually of the same species.

Morphological changes

There are several morphological difference that signal the appearance of a domesticated version of a wild species. These differences include changes in body size, changes in cranial morphology, and related features such as horn size and shape, or greater or lesser uniformity in several characteristics (Zeder 2008, Zeder et al 2006). Changes in cranial morphology is considered one of the more universal characteristics signaling the appearance of a domestic species, particularly changes that are related to neoteny – the retention of juvenile characteristics. Retained juvenile characteristics of the skull include a shortened snout or face, crowding of the teeth, simplification of the cusps on teeth, the deduction or smoothing of muscle attachment ridges, and changes in the overall dimensions of the skull that suggest selection for particularly traits or an easing of selective pressures.[10]

The appearance of greater uniformity or greater variance in other biological traits can also signal domestication. Greater uniformity can occur because the whole domestic population was derived from a relatively small sub-group of the wild population. Greater variance can occur either because new traits are being actively selected for, or because in reducing the pressures of natural selection, through controlled breeding and by providing protection, humans allow variations to appear in domesticate populations that would not have been able to survive naturally. Some morphological changes occur well into the domestication process, or towards the end of the initial domestication event.[11] As such, the appearance of a morphologically distinct domestic species may signal the final product of a domestication event and not the beginning of the process.

In archeology, the term "domestication event" refers to the period during which a wild species evolves into a relatively genetically, biologically, and behaviorally stable domesticated species.[12] Since a domestication event can take several hundred to several thousand years the appearance of a morphologically distinct domesticate species does not necessarily tell us much about the

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[10] For example, domestic dogs have short snouts and floppy ears, which are present only among juveniles in wolves. These characteristics are documented in the fox study (Trut and Dugatkin 2017).

[11] For example, the shape of horns in both goats and sheep changed drastically from their wild ancestors, however the appearance of this distinct physical difference did not occur until well after the domestication process had begun (Zeder et al 2006). Similarly, in recent domestication experiments with silver foxes, physical traits comparable to domesticated dogs did not occur until later in the experiment and after behavioral traits associated with domesticity had already begun to appear (Belyaev 1959, Trut and Dugatkin 2017).

[12] The term however is an abstract term without reference to set amounts of times, specific events, nor does it mean that no further alterations are made to the species through further selective breading – it only means the appearance of a genetically distinct sub-species which serves as the basic form of the domesticated variety of a species (Zeder et al. 2006; Gotherstrom et al. 2005; Price 1984).

conditions of the process itself, it only tells us that it has already occurred. It does give, however, an end point from which to look further back in time for evidence of the domestication process itself. The search for this evidence often focuses on the environmental, social conditions, and human behaviors, such as species management, which likely caused or aided in the domestication process. In the model we develop below a domestication event is an outcome of a path of rational decisions by groups.

Herd management

Another useful method for understanding the origins of domesticated herd animals has been to collect evidence of herd management since most of the major domesticated species are social (herd) mammals such as cattle, dogs, and sheep (Zeder 2008).[13] Herd management can include selective culling, or killing, of certain animals within a population so as to achieve human objectives such as meat production while still maintaining herd size and the breeding potential of a population. In general, males are preferentially killed relatively young, while females are allowed to survive until their prime reproductive years have ended. This differs from the way that hunter-gatherers typically kill the social mammals. This management strategy also closely resembles the typical mortality profile for modern domesticated animals, though it seemed to have taken some amount of time for it to develop fully.

Archaeological evidence for herd management is a demographic shift in collections of animal remains recovered from kill sites. Hunter-gather sites typically show a fairly indiscriminate killing of all members of species regardless of sex or age, or with only a slight preference for large adult males. As ancient peoples shifted toward herd management the demography of animals killed started to more resemble that of more modern domesticated animal kill profiles. In this profile most males are killed just after they reach adulthood, but before they become sexually mature, while females are kept alive until after their reproductive prime. This management approach (correlated with this demographic profile) allowed humans to maintain, if not increase, the size of a herd while still obtaining a substantial amount of meat from it. Zeder (2008) and Zeder et al (2006) have argued that a shift from the kill profiles of hunter-gathers to the herd culling profiles of pastoralists occurred some 500 to 1,000[14] years before the appearance of morphologically

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[13] Indeed, scholars can measure the deviation from ancestral demographic distributions by comparing measures of central tendency and dispersion.

[14] This time frame might be taken as the time needed for a domestication process to occur.

distinct sheep and goats.[15] At around 10,900 YBP these demographic changes appear in goat remains in Iraq, while morphological changes in goats do not appear until 9,900 YB. Similarly, demographic changes appear in sheep populations at 10,500 YBP, with other signs of domestication (translocation from original habitat) do not appear until 10,200 YBP. There is further evidence that manipulation of herd demographics began as early as 12,000 YBP for sheep, though these appear to be a first attempt as the culling profile had not yet fully come to parallel that of fully domesticated animals. In particular, it seems that males were allowed to get into adulthood, but females were being preserved until late in life (Zeder 2008).[16]

Appearance of a species in a non-native habitat

The final form of evidence of domestication is the appearance of a plant or animal species in a non-native habitat. Once it has been established that the animals within an archaeological site are non-local species this can provide further evidence of human control over a species. This form of evidence has also been used as an index of the domestication of plants. In cases in which there were local varieties of the same species, or closely related species, so it is still necessary to establish that animals at archaeological sites are indeed domesticates through either morphology or genetics – or both.

In summary, the combination of archaeological and genetic data has both increased the precision of our knowledge of domestication and has also generated greater certainty about the origins and spread of domestic animals. In some cases, the two sources verify each other while in other cases they contradict each other. Genetic analysis allows researchers to determine which specimens found at archaeological sites truly are the ancestors of modern domesticates. In addition, genetic evidence has been used to unravel the history of domestic species as they spread out from their point of origin and are interbreed with domestic or wild conspecifics (animals or plants of the same species, but of different sub-populations, such as different varieties or breeds). The dating of

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[15] Morphological changes are well documented in the fox domestication study (Trut and Dugatkin 2017).

[16] This empirical analysis is possible because the age and sex of animals can be determined from the osteological (bones) remains of animals found in archaeological sites (Reitz and Wing 1999). By carefully reconstructing the demographics of the animals slaughtered at a particular site it has become possible to see the emergence and evolution of management strategies within the regions in which some domestic animals first appeared. Management appears to have occurred in the domestication process of sheep, goats, and cattle. This method, to date, has not been used to examine the origins of other domesticates, such as pigs and horses, and it is currently thought that it did not play a part in the domestication of either dogs or cats which are currently thought to have largely "self-domesticated" themselves.

archaeological sites gives a chronology to the history of domestication that genetic analysis is still not capable of providing. Also, archaeology continues to provide morphological, demographic (animal, plant, and human), and cultural evidence that attests to the biological changes that occurred as plants and animals were domesticated, domestic management strategies and uses, and socio-cultural changes that coincided with the advent of agriculture and pastoralism.

3. PROPERTY RIGHTS ECONOMICS AND DOMESTICATION

Despite using the best evidence available from archeology-anthropology and biology-genetics, the current domestication literature does not have a governing theoretical framework within which to offer explanations and develop the implications needed to further our understanding of the domestication process. For economics the key questions are: What are the social and economic interactions that produced domestication of wild animals? What determines which species were domesticated? What determines where and when were these species domesticated? In this section, we discuss basic economic issues of property rights, renewable resources and evolutionary economics pertinent to building an economic theory of domestication. In the following section we illustrate the economic approach to domestication with a formal model.

Economics offers a framework in which individual and groups make decisions that can be studied as a social equilibrium. The economic approach makes explicit the benefits and costs of domestication which will put some structure on the topic by separating parameters (e.g., habitat, alternative food sources) from the economic choices made by prehistoric, and sometimes more modern, peoples. The benefits of domestication are both obvious and important. Domestication results in increases in food production (e.g., meat, grains, milk) and reduced the temporal variance in this production.[17] Domestication results in increases in the production of shelter and clothing (e.g., hides, furs) and tools (e.g., bone). Domestication lowers the cost of power (e.g., cattle pull carts, plows and logs) and transportation (e.g., horses allow long distance travel). Taken together domestication allows a move away from a hunter-gatherer economy to an agricultural economy with increased specialization and greater wealth.[18]

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[17] More indirectly dogs protect livestock and cats kill rodents that feed on stored crops.

[18] Some authors argue that the transition to an agricultural economy caused a reduction in the quality of life of humans because cereals and other food-based domesticated plants cannot replace the nutrients in meat. See, for example, Hermanussen and Poustka (2003) and Sands et al. (2009). In the long run, there is little doubt that agriculture lead to greater income per capita. In any case, the argument does not immediately apply to the domestication of animals.

The costs of domestication have several components. Initially there are costs of capture and rearing and control, as well as the opportunity cost of hunting-gathering activities foregone. The costs of capture, confinement, and control of wild populations (or individuals from such populations) are likely to be key to understanding the origins and spread of domestic animals. For example, is it cheaper to capture juveniles and rear them in small groups? Or is it cheaper to capture a small group with a mix of sexes and ages to keep the social structure in place? The cost of confining and controlling wild animals is likely to vary across species and across habitat as well. Knowledge about the variation of characteristics within a species or within population of a species can also lead to insight about the cost of capture and control.

In economic terms, a domesticated animal is distinguished from a wild animal by ownership and by the time path of ownership (Lueck 1989, 2002). Domestication itself can be viewed as an economic process by which the forces of natural selection are (largely at least) replaced by the forces of human selection by owners of populations.[19] This process ultimately results in individuals that become dependent on human control and will be unlikely to survive (or certainly thrive) in a setting solely governed by natural forces.

Barzel's (1997) approach, which focuses on property rights to attributes of assets, is important in our framework. In this case, for wild populations or animals generally, it is useful to consider property rights to the habitat (land) and animals (stocks or populations). Figure 2 shows some possible property rights regimes (for details on this characterization, see Lueck and Miceli 2007). Open access, common property and private property are considered as possibilities for both land and animals resulting nine possible regimes. The upper left cell is the simplest regime common to the earliest hunter gatherers, while the lower right cell shows the fully developed private property regime for both land and animals. The case in the middle of the matrix in which both land and animals are governed by common property is the prototypical case of a hunter-gather society that controls a hunting territory and, thereby, implicit access to a wild population.

The economic theory of property rights states that the equilibrium level of ownership of an asset (or an attribute of an asset in Barzel's approach) is determined by maximizing the net present value of the rent stream derived from the asset given the relative costs and benefits associated with

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[19] Selection can take place over the quality of the animals for draft, hides, and meat as well as for docility or other handling characteristics. Indeed, the Siberian fox study by suggests that selecting for docility might be the dominant force (Balyeav 1979, Trut and Dugatkin 2017).

the definition and enforcement of those property rights. Moreover, the theory suggests a pathway from open access to common or private ownership (Demsetz 1967, Anderson and Hill 1975, Field 1989, Libecap 1990, and Lueck 1995, 2002). The same logic most likely also applies to domesticates (i.e., species that came to be domesticated).[20]

Habitat \ Animals	Open access	Common property	Private property
Open access land	Simplest hunting society for wild species.	Cattle on open range (share herds).	Cattle on open range.
Common (group) land	Wild species on a common pasture.	Hunter-gatherers. Pastoralists – sheep, cattle, goats, reindeer.	Typical of European common for cattle, sheep, goats.
Private land	Wild species on private land with open access for hunting.		Typical modern livestock setting (e.g., cattle on ranch).

Figure 2. Possible property regimes for habitat and animals

The property rights framework can be merged with models of renewable resources to examine how the incentives for ownership of a population change as parameters change (Gordon 1954, and Clark 1990).[21] To illustrate this consider a hunter-gatherer group that controls a territory with a population of wild animals.[22] Suppose that the evolution of the stock of wild animals is described by the following difference equation $W_{t+1} = W_t + \gamma W_t \left(1 - \frac{W_t}{W_K}\right) - hW_t$, where W_t is the stock of animals in period t, W_K is the environmental (habitat) carrying capacity, $\gamma > 0$ is the intrinsic growth rate, and $h \in (0, \gamma)$ is the proportion of animals hunted by the group in each period.[23] Given W_K and γ, the hunting rate h induces a steady state stock of $W^{SS} = \frac{(\gamma - h)W_K}{\gamma}$ animals. Suppose that the payoff of the group is given by $v_H = hW^{SS} - c_h h$, where c_h is the marginal cost of hunting for the group and $c_h h$ is the total cost of hunting. Then, the level of h that maximizes v_H is $h^* = \frac{\gamma(W_K - c_h)}{2W_K}$, which induces a steady state stock of $W^* = \frac{W_K + c_h}{2}$ wild animals, a steady

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[20] Original ownership of domesticates was held by groups (Baker 2003, Bailey 1992, Ostrom 1990, Sethi and Somanathan 1996, and Smith 2000).

[21] Gordon (1954) was the first to link property rights to renewable resources while Clark (1990) is an important theoretical development in renewable resources.

[22] We assume the stock has no significant interaction with other stocks, so it can be viewed as a single resource. We also assume the group is acting as a sole owner of the stock and not treating the stock as common property (Caputo and Lueck 2003). Under common property groups hold exclusive access to the stock and allocate its use among members subject to the costs of policing those members. Several models show that common property may be a cheaper alternative than private property because of economies of enforcement and use of a relatively large-scale resource (Bailey 1992, Lueck 1994, Ostrom 1990).

[23] The harvest rate is constrained to be lower than the intrinsic growth rate, so the stock is not fully depleted.

state harvest of $h^*W^* = \frac{\gamma[(W_K)^2-(c_h)^2]}{4W_K}$ animals, and a payoff for the hunter-gatherer group of $v_H = \frac{\gamma(W_K-c_h)^3}{4W_K}$. Note h^*W^* and v_H^* are both increasing in the environmental carrying capacity and the population growth rate and decreasing in the marginal cost of hunting.[24]

Using the notation above imagine a population of wild cattle with a carrying capacity of $W_K = 25{,}000$ and realistic intrinsic 20% growth rate ($\gamma = 0.20$). In the simplest case in which there is no hunting cost ($c_h = 0$) there would be a harvest of $h^*W^* = 1{,}250$ and a sustainable population of $W^* = 12{,}500$ wild cattle.[25] This means that this wild cattle herd could provide a harvest of 1,250 cattle per period in perpetuity (what biologists call the maximum sustainable yield/harvest). More generally, as hunting costs increase, the optimal harvest decreases and, hence, the size of the population increases.

This population growth model can be used in harvest models or in models of optimal crop rotation, both of which might be applicable to the question of domestication, depending on the mechanism of initial domestication.[26] If hunter-gatherer groups live-captured small groups (i.e., populations) and managed them as pastoral herds as with goats and sheep, then the optimal harvest model is more appropriate because the herd is maintained intact and harvest is more or less continuous. If, however, just a small number of juveniles were captured to start a new herd, then the rotation model is more appropriate because the population is allowed to grow and then be harvested as a cohort. In either case these biological parameters will depend on the natural environment and vary across space and time.[27]

The forces of evolution also can be used to examine how economic selection can in turn affect population characteristics.[28] Ownership of a wild population effectively substitutes natural

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[24] To keep the example as simple as possible we have assumed that the hunter-gatherer group selects h to maximize its steady state payoff. Qualitatively similar conclusions can be obtained if the group selects h_t in each period to maximize its discounted payoff. Formally, we must solve the following dynamic programing problem: $\max_{\{h_t\}} \sum_{t=0}^{t=\infty} \beta^t h_t(W_t - c)$, subject to $W_{t+1} = W_t + \gamma W_t\left(1 - \frac{W_t}{W_K}\right) - h_t W_t$ and $W_0 > 0$ given. In such case the steady state level of W^* is given by the unique solution to $W^* - c = \frac{\beta\gamma(W_K - W^*)W^*}{(1-\beta)W_K + \beta(2-\gamma)W^*}$ and $h^* = \gamma\left(1 - \frac{W^*}{W_K}\right)$. Also note that focusing our attention on steady state values, we ignore transitional dynamics; that is, we do not explore the path to the steady state.

[25] In this symmetric growth function the stock at the maximum sustainable yield is half the carrying capacity (Clark 1990).

[26] Continual harvest models are typical of fishery analysis and cropping models are typical of forest analysis.

[27] For example, caribou are found in tundra and forest habitat and the populations have distinct characteristics in these distinct environments (Ingold 1980).

[28] See, for example, Friedman (1998), Maynard Smith (1982), and Sigmund and Young (1995).

selection for artificial (Clutton-Brock 1989) or what we call economic selection. This economic selection changes the parameters of the evolutionary process (Geist 1971, Trut 1999, Trut and Dugatkin 2017). This process can be incorporated into evolutionary models. For example, assume that a portion of the individuals are 'docile' and a portion are 'aggressive'. Then, economic selection over time for docile (which should reduce capture and confinement costs) will lead to a population of domestic animals distinct from the wild ancestor. Indeed, in the following section we formally develop such an approach.

4. AN ECONOMIC MODEL OF DOMESTICATION

In this section we illustrate the economic approach to domestication with an evolutionary model of a hunter-gatherer group that interacts with a wild population that provides products (e.g., meat or clothing).[29] In the model, the group begins indiscriminatingly hunting animals from the wild population, which contains docile and aggressive individuals. At some point the group gains access to a new hunting technology that gives the group the ability of capturing and confining a subgroup of the wild population and identifying docile and aggressive individuals within the confined population. This allows the group to selectively slaughter animals based on their aggressiveness or cost of economic control. Being able to control live animals is the beginning of ownership and the domestication process. This economic selection under ownership and control changes the confined populations and over time (and many generations) creates domesticated populations. Because this economic selection takes place over a long time frame no single economic actor has domestication as an explicit goal.[30] The group simply slaughters more aggressive animals because it is cheaper to confine more docile individuals. The model includes a dynamic link in which the cost of confining animals and extracting products from docile animals decreases in the future because the captured docile animals generate relatively more docile individuals in the future. From this connection the model generates path dependence.

The basic model

Consider again a hunter-gatherer group that controls an exclusive hunting territory populated by a stock of wild animals. The territory has a carrying capacity of $W_K > 0$ animals, which allows

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[29] This model does not distinguish between species used for protection, power, food, clothing, or transportation. These distinctions are examined in a companion paper (Lueck and Torrens 2019).

[30] In the Siberian fox experiment, however, domestication was the explicit goal.

the group to hunt a steady-state level of $h^* W^*$ animals that maintains the population at $W^* < W_K$. As noted above the associated payoff of the group is given by:

$$v_H = h^* W^* - c_h h^*, \tag{1}$$

where c_h measures the marginal cost of hunting. The wild population contains a mix of aggressive and docile individuals, which a proportion $a_w \in (0,1)$ are aggressive, or naturally more difficult to control. We assume that the vast majority of individuals in a wild population are aggressive and hunting does not affect the distribution of aggressiveness in the population. Before period $t = \tau_C$, hunting is the only technology available to the group and, hence, the size of the population of wild animals, the distribution of aggressiveness and the payoff obtained by the hunter-gatherer group remain constant over time. Formally, $W_t = W^*$, $a_t = a_w$, $v_t = v_H$, respectively, for all $t < \tau_C$. This outcome is the pure hunter-gatherer equilibrium for a group exploiting a single wild population.

In the absence of any technological change the group remains in the hunter-gatherer equilibrium shown above. One way to introduce a change that can lead to domestication is to assume the group innovates in a manner that allows the hunter-gatherer group to confine wild animals. We assume that such innovation occurs in period $t = \tau_C$.[31] The innovation creates a technology that gives the group the ability to confine a group of animals and identify aggressive and docile animals within the confined population. Specifically, after the innovation, the group can confine a proportion $y \in (h^*, 1)$ of the wild population and selectively slaughter a steady-state level of $h^* W^*$ animals.[32] Note that this technology allows the group to harvest $h^* W^*$ animals from a confined population of yW^*, while hunting requires a population of W^* wild animals to generate the same steady-state level of output.

Keeping animals confined is costly for the group. Moreover, we assume that the cost of confinement is higher for aggressive than docile animals. Specifically, when the group uses the confinement technology its payoff is $v_{C,t} = s_{a,t} A_t + s_{d,t} D_t - c_C (1 - s_{a,t}) A_t$, where A_t (D_t) denotes the stock of aggressive (docile) animals in the confined population at the beginning of

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[31] The origins of such an innovation might be taking advantage of a geographical location or some other unique situation. We do not distinguish between adults and juveniles in the wild population, though it seems likely that the capture and control costs of juveniles will be lower than for adults.

[32] Slaughter is simply harvesting in confinement. It is clear that hunting and slaughtering are differentiated by ownership of the live animals. In this concept of confinement, aggressive and docile are not identified until after separation from the main population.

period t, $s_{a,t}$ ($s_{d,t}$) $\in [0,1]$ the proportion of aggressive (docile) animals slaughtered in period t, and $c_C(1 - s_{a,t})A_t$ is the cost of confining aggressive animals (to simplify things we assume that the cost of confining docile animals as well as the cost of slaughtering animals in a confined population are both zero). Thus, the new problem for a hunter-gather group choosing capture and confinement in period t is given by:

$$\max_{s_{a,t}, s_{d,t}} \{v_{C,t} = s_{a,t}A_t + s_{d,t}D_t - c_C(1 - s_{a,t})A_t\} \quad (2)$$

$$\text{subject to: } s_{a,t}A_t + s_{d,t}D_t \leq h^* W^*$$

The constraint indicates that the total number of animals slaughered in period t (a mix of aggressive and docile individuals) cannot excess $h^* W^*$, the maximum number that the group can slaugher maintaining the population at W^*. It is easy to verify that, if $A_t > h^* W^*$, then solution to (2) is $s_{a,t}A_t = h^* W^*$ and $s_{d,t} = 0$, while if $A_t \leq h^* W^*$, then the solution is $s_{a,t} = 1$ and $s_{d,t}D_t = hW_0 - A_t$. Because the cost of confinement is higher for aggressive animals, the group will slaughter as many aggressive animals as possible, allowing them to confine relatively more docile individuals. As a consequence, while the stock of aggressive animals is greater than the steady state level that can be slaughtered ($A_t \geq h^* W^*$), the group only slaughters aggressive animals. Alternatively, when $A_t < h^* W^*$, the group completely wipes out all the aggressive animals and starts slaughtering docile animals.

After the group makes the slaughtering decisions in period t, the proportion of aggressive animals remaining in the confined population is $(1 - s_{a,t})A_t / [(1 - s_{a,t})A_t + (1 - s_{d,t})D_t]$, which implies that at the beginning of period $t + 1$ the stock of aggressive (docile) animals in the confined population will be given by:

$$A_{t+1} = \frac{(1 - s_{a,t})A_t}{(1 - s_{a,t})A_t + (1 - s_{d,t})D_t} yW^*, \quad (3)$$

and

$$D_{t+1} = \frac{(1 - s_{d,t})D_t}{(1 - s_{a,t})A_t + (1 - s_{d,t})D_t} yW^*, \quad (4)$$

respectively. If in period $t = \tau_C$, the group adopts the new technology, then yW^* wild animals are captured and confined, a proportion a_w $(1 - a_w)$ of which are aggressive (docile). Thus, $A_{\tau_C} = a_w yW^*$ and $D_{\tau_C} = (1 - a_w)yW^*$. Introducing the slaughtering decisions of the group into (3) and (4) and solving the corresponding difference equations we obtain the following proposition.

Proposition 1 *Suppose that in period τ_C the group adopts the new technology. Then, the paths of A_t and D_t for all $t \geq \tau_C$ are given by:*

$$A_t = \begin{cases} yW^* \left[1 - (1 - a_w)\left(\frac{y}{y-h}\right)^{t-\tau_C}\right] \text{if } t \leq \tau_D \\ 0 \text{ if } t > \tau_D \end{cases}, \tag{5}$$

and

$$D_t = \begin{cases} yW^*(1 - a_w)\left(\frac{y}{y-h}\right)^{t-\tau_C} \text{ if } t \leq \tau_D \\ yW^* \text{ if } t > \tau_D \end{cases}, \tag{6}$$

where $\tau_D = \tau_C - 1 + \left[\frac{ln(1-a_w)}{[ln\, y/(y-h)]}\right]$.[33]

Figure 3 illustrates Proposition 1 for specific parameters. In period τ_C the group captures and confine a population of $A_{\tau_C} = a_w yW^*$ aggressive animals and $D_{\tau_C} = (1 - a_w)yW^*$ docile animals. For many periods the group selectively slaughter only aggressive animals in order to make the confinement cost as low as possible. As a consequence, the population of aggressive animals slowly but steadily decline until it reaches $A_t \leq h^* W^*$. At this moment (formally, when $t = \tau_D$) all the remaining aggressive animals are slaughtered and, thereafter, the population only have docile animals. The domestication process has been completed and this would be a 'domestication event'.[34] In the long run only docile individuals are maintained as property. Figure 3 also shows that the domestication process moves slowly at first but then proceeds rapidly.[35] This could explain the archeological evidence on domestication events. Although obtaining a population of fully docile animals could take many periods[36], at some point the process will gain momentum and the proportion of docile and aggressive aninals in the confined population will experience significant changes in relatively short time.

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[33] $[x]$ denotes the integer part of x.

[34] Note that our model does not examine morphological and hormonal changes that arise from domestication.

[35] This is generally consistent with the findings of the Siberian fox study (Trut and Dugatkin 2017).

[36] For example, if we interpret a period as 30 years (approximately, one human generation), the domestication process depicted in Figure 3 would take 480 years.

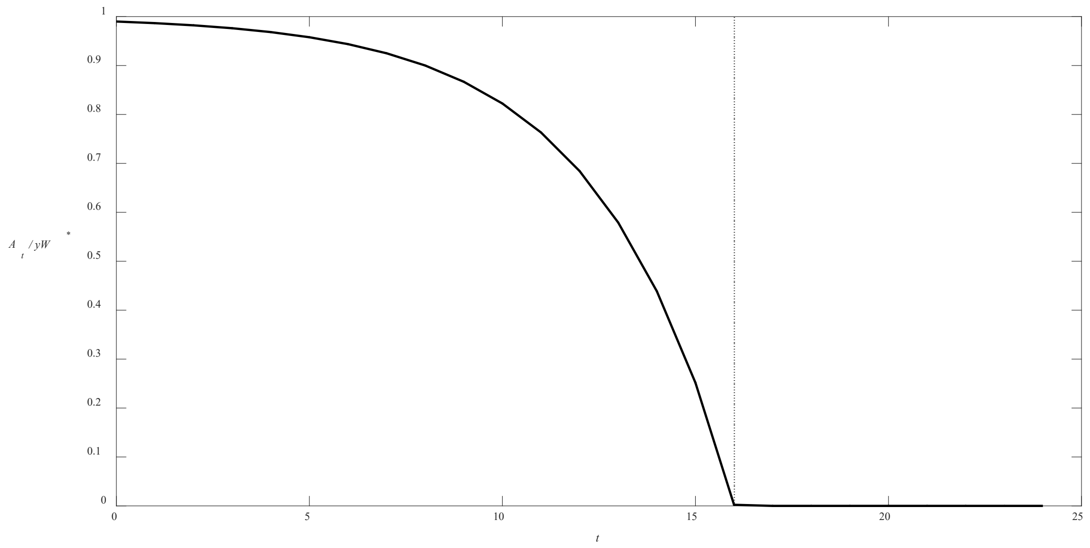

Figure 3. Proportion of aggressive animals in the confined population

Notes: Example using the following parameters: $a_w = 0.99$ (proportion of aggressive animals in the wild population), $W^* = 1000$ (size of the wild population), $y = 0.2$ (proportion of W^* captured) and $h^* = 0.05$ (proportion of W^* harvested).

Comparative statics analysis

The model can also generate implications about how the time required to fully domesticate a population changes with the parameters of the model. $\tau_D - \tau_C$ is decreasing in a_w. Thus, as the proportion of aggressive animals in the wild population is higher, it takes more time to completely wipe out the aggressive individuals from the confined population. $\tau_D - \tau_C$ is increasing in y. Thus, as the new technology requires the group to confine a higher fraction of the wild population prior to selectively killing the aggressive animals, it takes more time to eliminate all the aggressive ones. Finally, $\tau_D - \tau_C$ is decreasing in h^*. Thus, as the proportion of animals that the group can slaughter increases, it takes less time to obtains a domesticated confined population.

Endogenous adoption of domestication technology

Until now, we have assumed that the group exogenously switches to the new technology in period τ_C but the adoption decision can be made a choice of the group. We consider two possible cases. First, suppose that the group is completely short-sighted, i.e., it only takes into account its payoff in period t. Second, consider a group that takes into account the payoff in the current and future period and has a discount factor $\beta \in (0,1)$, so the group maximizes $V_t = v_t + \beta v_{t+1}$, where

$v_t = v_{C,t}$ ($v_t = v_H$) if the group has (not) adopted the capturing technology. The following proposition summarizes the adoption decision in each case:

Proposition 2[37]

1. *Suppose that the group is completely short-sighted. Then, it adopts the new technology if and only if* $c_C < \frac{c_h h^*}{(a_w y - h^*)W^*}$.
2. *Suppose that the group maximizes* $V_t = v_t + \beta v_{t+1}$. *Then, it adopts the new technology if and only if* $c_C \leq \frac{(1+\beta)c_h h^*}{W^*\left[(a_w y - h^*) + \beta(y - h^*) - \beta y(1 - a_w)\left(\frac{y}{y - h^*}\right)\right]}$.

Proposition 2 simple states that the domestication process begins only if the cost of confinement is below some threshold. Intutitively, the cost of obtaining $h^* W^*$ animals hunting from the wild population is $c_h h^*$, while the cost of obtaining the same level of output using the new technology is $c_C(a_w y - h^*)W^*$. The most important implication of Proposition 2 is that it is possible that some hunter-gatherer groups never transitioned to a domestication path simply because the initial costs of confining and selectively slaughtering animals was not low enough relative to the costs of hunting from a wild population. If somehow the hunter-gatherer group found a way of partially internalizing the future cost reductions associated with the domestication path, then adoptions was easier. Formally, the threshold in Proposition 2.2 is higher than the threshold in Proposition 2.1. This suggests that not only environmental, but also social and organizational factors could have played a role in the path followed by different groups.

5. CONCLUSIONS

The domestication of wild animals and plants is undoubtedly an important innovation in human history. Domestication is fundamental to the transformation from hunter-gatherer societies to agricultural and ultimately industrial societies. Archeologists, anthropologists, biologist, historians and others have studied and continue to study domestication. Economists have been curious bystanders so far, but they need not be. Data on domestication is accumulating and economic models of property rights, renewable resources and evolutionary games provide tools of analysis.

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[37] The proof of Proposition 2 is provided in the appendix.

It is our view that economics has great potential to illuminate our understanding of the human domestication of wild species.

Yoram Barzel's approach to economics has been to focus on the property rights to assets and how those rights shape incentives and ultimately economic decisions. Our application to the domestication of wild animals relies on his framework to examine the incentives inherent in human decisions to move from hunting and gathering to a property rights-based system of using and managing animals. This paper has started this application but has by no means finished. Among other things our analysis ignored the differences between animals domesticated for meat (cattle, sheep, pigs) and those domesticated for transportation or protection (dogs and horses). The mechanism of ownership and economic selection is likely different across such species. The emergence of property rights to animals and creation of markets and the expansion of trade is also left for future work. It is noteworthy that '*chatel*' the Old Norman term for personal property has its origins in ancient word for cattle.

REFERENCES

Anderson, T. L., and P. J. Hill. 1975. The Evolution of Property Rights: A Study of the American West. *Journal of Law and Economics* 18 (1): 163-179.

Bailey, M. J. 1992. Approximate Optimality of Aboriginal Property Rights. *Journal of Law and Economics* 35: 183-198.

Baker, M. J. 2003. An Equilibrium Conflict Model of Land Tenure in Hunter-Gatherer Societies. *Journal of Political Economy* 111: 124-173.

Barzel, Y. 2007. *Economic Analysis of Property Rights.* 2nd Edition. Cambridge University Press: New York, NY.

Belyaev, D. K. 1979. Destabilizing Selection as a Factor in Domestication. *The Journal of Heredity* 70: 301-308.

Belyaev, D. K., A. O. Ruvinsky, and L. N. Trut. 1981. Inherited Activation-Inactivation of the Star Gene in Foxes. *The Journal of Heredity* 72: 267-274.

Brander, J., and S. Talyor. 1998. The Simple Economics of Easter Island: A Ricardo-Malthus Model of Renewable Resource Use. *American Economic Review* 88: 119-138.

Budiansky, S. 1992. *Covenant of the Wild: Why Animals Chose Domestication*. William Morrow and Company: New York, NY.

Caramelli, D. 2006. The Origins of Domesticated Cattle. *Human Evolution* 21: 107-122.

Caputo, M., and D. Lueck. 2003. Natural Resource Exploitation Under Common Property Rights. *Natural Resources Modeling* 16(1): 39-67.

Clutton-Brock. 1989. *A Natural History of Domesticated Mammals.* University of Texas Press: Austin, TX.

Coase, R. 1960. The Problem of Social Cost. *Journal of Law and Economics* 3: 1-44.

Demsetz, H. 1967. Toward a Theory of Property Rights. *American Economic Review* 57: 347-359.

Diamond, J. 1997. *Guns, Germs, and Steel: The Fates of Human Societies*. W. W. Norton & Co., Inc.: New York, NY.

Dugatkin, L., and L. Trut. 2017. *How to Tame a Fox: And Build a Dog.* University of Chicago Press: Chicago, IL.

Friedman, D. 1998. On Economic Applications of Evolutionary Game Theory. *Journal of Evolutionary Economics* 8:15-43.

Geist, V. 1971. *Mountain Sheep, a Study in Behavior and Evolution.* University of Chicago Press: Chicago, IL.

Gotherstrom, A., C. Anderung, and L.Hellborg. 2005. Cattle Domestication in the Near East Was Followed by Hybridization with Aurochs Bulls in Europe. *Proceedings: Biological Sciences* 272(1579): 2345-2350.

Hard, R. J., A. C. MacWilliams, J. R. Roney, K. Adams, and W. Merrill. 2006. Early Agriculture in Chihuahua, Mexico. In *Histories of Maize: Multidisciplinary Approaches to the Prehistory, Linguistics, Biogeography, Domestication, and Evolution of Maize,* edited by J. E. Staller, R. H. Tykot, and B. F. Benz, 109-121. Elsevier Academic Press: Boston, MA.

Harris, D. 1989. An Evolutinary Continuum. In *Foraging and Farming: The Evolution of Plant Exploitation*, edited by D. Harris and G. Hillman, 11-26. Unwin Hyman: London, UK.

Hermanussen, M., and F. Poustka. 2003. Stature of Early Europeans. *Hormones* 2(3): 175-178.

Hildebrand, E. A. 2003. Motives and Opportunities for Domestication: an Ethnoarchaeological Study in Southwest Ethiopia. *Journal of Anthropological Archaeology* 22: 358-375.

Hole, F. 1981. A Two-Part, Two-Stage Model of Domestication. In *The Walking Larder:Patterns of Domestication Pastoralism and Predation (One World Archaeology)*, edited by J. Clutton-Brock. Unwin Hyman: London, UK.

Ingold, T. 1980. *Hunters, Pastoralists, and Ranchers: Reindeer Economies and their Transformations*. Cambridge University Press: New York, NY.

Kavar, T., and P. Dovc. 2008. Domestication of the Horse: Genetic Relationships between Domestic and Wild Horses. *Livestock Science* 116: 1-14.

Larson, G., U. Albarella, K. Dobney, and Rowley-Conwy. 2007. Ancient DNA. Pig Domestication, and the Spread of the Neolithic into Europe. *Proceedings of the National Academy of Sciences of the United States of America* 104(39): 15276-15281.

Libecap, G. D. 1989. *Contracting for Property Rights.* Cambridge University Press: New York, NY.

Lueck, D. 1989. The Economic Nature of Wildlife Law. *Journal of Legal Studies* 18: 291-323.

Lueck, D. 1995. The Rule of First Possession and the Design of the Law. *Journal of Law and Economics* 38: 393-436.

Lueck, D. 2002. The Extermination and Conservation of the American Bison. *Journal of Legal Studies* S609-S652.

Lueck. D, and T. Miceli. 2007. Property Law. In *Handbook of Law and Economics*, edited by A. Mitchell Polinsky and S. Shavell. Elsevier: Academic Press: Boston, MA.

Lueck D., and G. Torrens. 2019. An Economic Analysis of Domestication of Wild Animals. Working Paper.

Maynard Smith, J. 1982. *Evolution and the Theory of Games*. Cambridge University Press: New York, NY.

Ostrom, E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press: New York, NY.

Olsson, O., and C. Paik. 2016. Long-run Cultural Divergence: Evidence from the Neolithic Revolution. *Journal of Development Economics* 122: 197-213

Price, E. O. 2002. *Animal Domestication and Behavior*. CABI Publishing. New York: NY.

Reitz, E. J., and E. S. Wing. 1999. Zooarchaeology. Cambridge Manuals in Archaeology. Cambridge University Press: New York, NY.

Sands, D. C., C.E. Morris, E.A. Dratz, and A. Pilgeram. 2009. Elevating Optimal Human Nutrition to a Central Goal of Plant Breeding and Production of Plant-based Foods. *Plant Science Review* 177(5): 377–389.

Sauer, C. O. 1953. *Agricultural Origins and Dispersals*. American Geographic Society - MIT Press: Cambridge, MA.

Sethi R., and E. Somanathan. 1996. The Evolution of Social Norms in Common Property Resource Use. *American Economic Review* 86: 766-788.

Sigmund, K., and H. Peyton Young. 1995. Evolutionary Game Theory in Biology and Economics: Introduction. *Games and Economic Behavior* 11:103-110.

Smith, H. E. 2000). Semi-common Property Rights and Scattering in the Open Fields. *Journal of Legal Studies* 29: 131-169.

Stiner, M. C. 2002. Carnivory, Coevolution, and the Geographic Spread of the Genus Homo. *Journal of Archaeological Research* 10 (1): 1-63.

Trut, L. N. 1999. Early Canid Domestication: The Farm Fox Experiment. *American Scientist* 87 (2): 160.

Van Gelder, R. G. 1979. *Biology of Mammals*. Scribner and Sons: New York, NY.

Verhoeven, M. 2004. Beyond Boundaries: Nature, Culture and a Holistic Approach to Domestication in the Levant. *Journal of World Prehistory* 18(3): 179-282.

Zeder, M. A. 2009. The Neolithic Macro-(R)evolution: Macroevolutionary Theory and the Study of Culture Change. *Journal of Archaeological Research* 17: 1-63.

Zeder, M. A., E. Emshwiller, B. D. Smith, and D. G. Bradley. 2006. Documenting Domestication: The Intersection of Genetics and Archaeology. *Trends in Genetics* 22(3): 139-155.

Zuener, F. E. 1963. *History of Domesticated Animals*. Harper and Row, Publishers: New York, NY.

APPENDIX – PROOF OF PROPOSITION 2.

Suppose that the group is completely short-sighted. If the group does not adopt, its payoff is given by $v_H = h^* W^* - c_h h^*$. On the contrary, if the group adopts, its payoff is given by $v_C = h^* W^* - c_C(a_w y - h^*) W^*$, where we have used that $A_{\tau_C} = a_w y W^*$, $s_{a,\tau_C} A_{\tau_C} = h^* W^*$ and $s_{d,\tau_C} = 0$. Therefore, the group adopts if and only if $c_C < c_h h^* / (a_w y - h^*) W^*$.

Suppose that the group maximizes $V_t = v_t + \beta v_{t+1}$. If the group does not adopt, its payoff is given by $V_H = (1+\beta) v_H = (1+\beta)(h^* W^* - c_h h^*)$. On the contrary, if the group adopts, its payoff is given by $v_{C,\tau_C} = h^* W^* - c_C(a_w y W^* - h^* W^*)$ and $v_{C,\tau_C+1} = h^* W^* - c_C W^* \left[y - h^* - y(1-a_w)\left(\frac{y}{y-h^*}\right)\right]$, where we have used that $A_{\tau_C} = a_w y W^*$, $s_{a,\tau_C} A_{\tau_C} = h^* W^*$, $s_{d,\tau_C} = 0$, $A_{\tau_C+1} = y W^* \left[1 - (1-a_w)\left(\frac{y}{y-h^*}\right)\right]$,

$s_{a,\tau_C+1}A_{\tau_C+1} = h^* W^*$ and $s_{d,\tau_C+1} = 0$. Therefore, $V_C = h^* W^* - c_C(a_w y - h^*)W^* + \beta W^* \left\{h^* - c_C \left[y - h^* - y(1 - a_w)\left(\frac{y}{y-h^*}\right)\right]\right\}$. Hence, the group adopts if and only if $c_C \leq \frac{(1+\beta)c_h h^*}{W^*\left[(a_w y - h^*) + \beta(y - h^*) - \beta y(1 - a_w)\left(\frac{y}{y-h^*}\right)\right]}$. **QED**