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Pyrodiversity and the Anthropocene: the Role of Fire in the Broad Spectrum Revolution

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The Anthropocene colloquially refers to a global regime of human-caused environmental modification of earth systems associated with profound changes in patterns of human mobility, as well as settlement and resource use compared with prior eras. Some have argued that the processes generating the Anthropocene are mainly associated with population growth and technological innovation, and thus began only in the late Holocene under conditions of dense sedentism and industrial agriculture. However, it now seems clear that the roots of the Anthropocene lie in complex processes of intensification that significantly predate transitions to agriculture. What intensification is remains less clear. For some it is increasing economic productivity that increases carrying capacity, the drivers of which may be too diverse and too local to generalize. For others using Boserup’s ideas about agrarian intensification, increasing density in hunter-gatherer populations can produce declines in subsistence efficiency that increase incentives for investing labor to boost yield per unit area, which then elevates Malthusian limits on carrying capacity. As Morgan demonstrates in a comprehensive review, the legacy of such Boserupian intensification is alive, well, and controversial in hunter-gatherer archeology. This is a result of its potential for illuminating processes involved in transformations of forager socio-political and economic systems, including those dominated by harvesting more immediate-return resources and high residential mobility as well as those characterized by more delayed-return material economies with reduced residential mobility, a broader spectrum of resources, degrees of storage, and greater social stratification. Here we detail hypotheses about the processes involved in such transitions and explore the way that anthropogenic disturbance of ecosystems, especially the use of landscape fire, could be fundamentally entangled with many broad-spectrum revolutions associated with intensified foraging systems.

Binford was among the first to draw on Boserup to argue that diversification in hunted resources, food processing, and storage facilities may result from an intensified use of the environment that significantly pre-dates agriculture. Flannery’s hypothesis to account for such “broad spectrum revolutions” (BSR) then paved the way for using intensification in an explanatory sense. For Flannery, the BSR was driven by an imbalance between resources and populations, resulting in an increase in labor and a decrease in foraging efficiency. Faced with diminishing returns, Epipaleolithic populations in the Near East spread into less productive environments, which necessitated increased reliance on a wider array of more labor-intensive, but more predictable, plants and animals. Flannery suggested that this set the stage for (or backed hunter-gatherers into) the social and technological processes that eventually lead to domestication and agriculture.
This longstanding explanation for the conditions that lead to the origins of agriculture has been formalized in behavioral ecological (BE) models that allow for the generation and testing of clear predictions tied to the theory of evolution by natural selection. While many tests have been upheld, some have used theoretical and empirical exceptions to challenge both the original formulation and its BE formalizations. Specifically, these critics argue that the classic BE models of resource use ignore the development of social institutions necessary for the transition to delayed return resources and elements of niche construction necessary to account for habitat modification associated with agriculture. After detailing the classic behavioral ecological approach and its critiques, we show how these challenges can be incorporated into behavioral ecological frameworks to provide a comprehensive model for broad-spectrum revolutions that lead to agriculture.

**THE BEHAVIORAL ECOLOGY OF INTENSIFICATION**

In behavioral ecology, such ideas about intensification have been cast in various formal models of prey choice, patch use, central-place foraging, and ideal free distribution, which emphasize the trade-offs organisms face with variability in foraging efficiency and habitat quality. The models can be thought of as tiered solutions to problems a hypothetical forager would face in finding and using resources across different temporal and spatial scales of resource distribution. At the most local (patch scale), potential resource types can be ranked on a scale of utility according to their post-encounter yield and requisite handling costs (for example, energy per unit of time to pursue and process). If an individual is concerned with the opportunity costs of foraging and experiences lower rates of encounter with high-ranked resources in a given patch, the prey choice model predicts that selectivity should broaden to include resources of lower utility in rank order. Scaling up to the habitat as a collection of patches as foraging efficiency declines in a given type of activity or patch, patch-residence time models provide solutions to foraging and traveling trade-offs. These models predict the threshold at which a forager should switch from foraging (searching and handling) for one suite of resources and travel elsewhere to search for and handle other suites of resources. The more foragers are tethered to a central place, the more salient are trade-offs in transporting resources.

Central-place foraging models predict thresholds at which individuals should move resources to their base or their base to the resources. Scaling up to the landscape as a collection of habitats, models of ideal distribution then generate expectations about how foragers should distribute themselves; that is, where they should be based and when they should move depending on the suitability of available habitats in an environment and the density of conspecifics already occupying those habitats. The models predict the order in which habitats will be colonized and relative differences in population density and despotic intensity.

Taken together, foraging models frame testable hypotheses about the potential processes of intensification. They generate expectations about the direction of economic transformation with shifts toward a reliance on a broader spectrum of resources characterized by higher handling costs, how resource depression may link with patterns of mobility and residence, how human populations are likely to spread and increase with greater reliance on more costly but abundant resources, and how resulting circumscription and the colonization of less suitable habitat may result in declining residential mobility and increased socio-political stratification. There are common patterns in relationships between reduced residential mobility, increasing investment in processing technology, and shifts to lower-ranked resources. As foragers spend proportionally more time handling lower-ranked resources and face associated declines in the benefits of moving elsewhere when neighboring habitats are more densely settled, it becomes more worthwhile to invest in technologies to reduce handling costs.

Foraging models have thus provided a set of generic tools to explore economic and socio-political intensification and changing patterns of mobility and colonization under a broad range of circumstances. Recent examples illustrate how tests of model predictions give new insight into classic archeological problems. We suspect that processes of intensification illustrated in the logic of foraging theory are important in many transitions to domestication and the requisite social institutions of farming that have radically transformed earth systems.

**THE PROBLEM: PROPERTY AND ANTHROPOGENIC HABITAT CONSTRUCTION**

Models in behavioral ecology have proven useful in unveiling many of the dynamics that likely accompany intensification. However, recent work has highlighted two issues. First, straightforward ideas about how decreasing subsistence efficiency leads to intensification need to grapple with understanding the development of the social institutions implicit in the transition from immediate-return or public-goods to delayed-return or private-goods based economies.

Bowles and Choi have recently developed a model suggesting that shifts to a delayed-return economy depend on the number of individuals in any social group who act on the link between labor and product in such a way that those who labor have priority in controlling the distribution of material associated with their labor. Norms and institutions that manage private property and storage are thus critical components in the maintenance of a delayed-return material economy. Along with these shifts toward delays in material return are institutions such as households as units of economic production, more centralized governance to police ownership and redistribution, specialized scaled labor, and inequalities based on the accumulation of material wealth. If one individual stores her harvest instead of sharing it, she inevitably produces inequalities between producers, increasing the social costs of hoarding that we argue shape nonreciprocal sharing in many immediate
However, if everyone is storing and not sharing, the social costs are minimal. What Bowles and Choi show is that the maintenance of a delayed-return economy characteristic of farming requires cultural institutions to manage material property for storage and redistribution. The question they pose but do not address is how societies get to the threshold at which it pays for individuals to invest in maintaining institutions that manage material storage as opposed to sharing?

The second issue centers on presumptions about the direction of environmental change and human behavior. As opposed to farming, in which environments are engineered for food production, foraging is often portrayed as a merely extractive activity in which food is harvested from a nonanthropogenic environment. Variability in foraging strategies is thus often modeled as a static, linear relationship: Either environmental change results in behavioral change or behavioral change results in environmental change. We know that, even among foragers, the process is more dynamic. Patterns of embodied foraging practices and values emerge in complex, nonlinear interactions of anthropogenic construction, cognition, and material engagement.1–36

Along these lines, Zeder5 and Smith37–39 have recently pointed out that in some archeological contexts it is not clear that a BSR in foraging economies is preceded by population pressure or evidence of declines in foraging productivity. In response, they have developed an approach that calls on niche construction and complex systems theory40 to propose that anthropogenic construction and management of ecosystems to improve subsistence lie at the heart of the BSR. While offering a more nuanced perspective on human-environment interaction, this approach introduces additional problems. Perhaps most importantly, it provides no framework for developing hypotheses about decision-making with regard to resource use beyond notions of intentionality in innovation. Actors who intentionally modify habitats gain via future, delayed payoffs. This delay sets up a collective action problem: How can individuals in immediate-return societies, which typically operate under forms of common property tenure regimes, ensure that their labor to improve future resource availability will not induce free-riders to take advantage of their forethought, leaving them with little future benefit to show for their trouble?

The co-evolution and niche construction approaches are both incomplete solutions to the problems with existing intensification models. While Bowles and Choi argue a necessary co-evolution between subsistence and social institutions governing property and ownership rights, Zeder and Smith’s approach presupposes such property rights in the design or management of ecosystems for sustainable benefit. Likewise, while Zeder and Smith’s model includes a focus on the ecological dynamics of human-environment interactions, the absence of ecological dynamics in the Bowles and Choi model does not allow for the incorporation of processes that shift property norms. Neither model addresses issues of fundamental conflicts of interest inherent in individual decision-making and the collective action required to sustain property regimes that govern storage and delayed material return.41

In what follows, we suggest that both of these modifications to the classic intensification explanation of the BSR can be integrated by understanding how the behavioral ecology of individual decision-making interacts with the ecological dynamics of anthropogenic disturbance that structure how resources are distributed in space and time. These dynamics affect the patchiness and predictability of some types of resources, in some cases reducing the cost of acquisition so that asserting ownership over them becomes worthwhile (Fig. 1). Whether or not resources are worth acquiring and then defending depends to a great extent on the history and practice of forager-environment interactions. Ecology shifts the relative costs of sharing versus storing in ways that affect most individuals within a social group, thereby setting the benefits for resource defense and reduced mobility. Both the marginal valuation of defense at the scale of the individual harvest42,43 and the marginal valuation of defense at the scale of the patch or landscape44 are predicted to affect the benefits of staying put and defending claims to exclusive use rights over a resource. Individuals are predicted to share more and store less when there is high intertemporal variation in foraging success (stochasticity), package size and perishability is high,
and the degree of interforager correlation in harvest success is low.45
Both empirical observations of sharing among hunter-gatherers and experimental work on the links between sharing norms and unpredictable rewards support these predictions. More synchronously and predictably acquired resources, such as small game, tend to be characterized by a greater percentage kept for the consumption of acquirers and their families.46,47 Experiments in industrialized societies (Japan and the U.S.), corroborate this pattern, suggesting that the links between expectations about sharing versus keeping can be manipulated by providing resources that are associated with an unpredictable link between labor and reward. Windfall (stochastic) resources are commonly shared more widely than are resources with strong links between labor and production,48 suggesting similar processes behind such norm development. This suggests that when everyone has access to economically defendable resources (when resources are spatially and temporally predictable, with patchy distribution decreasing the costs of defense), and when the amount of time invested predicts harvest size, ownership may be likely to emerge and spread in a population. We argue that such conditions, with profoundly dynamic networks of nonlinear interaction, are more likely to emerge when foragers regularly and systematically disturb landscapes in ways that increase patchiness and habitat heterogeneity. We can think of no anthropogenic disturbance in human foraging more salient than landscape burning.

DISTURBANCE AND THE ECOLOGICAL DYNAMICS OF MOBILITY AND OWNERSHIP

The notion that the BSR can be explained by either resource depression or intentional strategies to manage it emerges from an ecological focus on simple (dyadic) negative interactions between species, mainly involving competition for resources, predation, and the direct effect of one species on another. New ecological (“nonequilibrium”) perspectives consider interacting networks of species and include the study of indirect and positive effects and how they are involved in the persistence and stability of entire ecological communities. Considered at the scale of the ecological community, negative effects like predation are a form of disturbance that can result in positive outcomes for the community as a whole. These positive effects come about indirectly, without agent intent or management, when one organism has an effect on another via a third organism (for example, wolves shape riparian dynamics by reducing elk populations). These effects also can include direct interactions, like mutualism and commensalism. Positive effects, whether direct or indirect, are increasingly viewed as a significant force in the assembly of ecological communities and may be critical in sustaining population stability in a complex food web.49,50 These positive effects are often associated with “keystone species,” those that have a high number of trophic connections,51 construct niches for other organisms, or provide disturbance at intermediate temporal and spatial scales.52 Such species can have positive effects on a wide range of other species, so that their removal can cause extensive population extinctions.53 Keystone species tend to be top predators,54 super-generalist omnivores with many weak links to other species.55 They also tend to be large-bodied56 or to modify the physical environment in significant ways.57 When such species modify environments with disturbance at intermediate temporal and spatial scales, it tends to produce more positive ecological effects, often increasing species diversity or the stability of ecological communities.58

Disturbing vegetation at an intermediate scale would theoretically have two potential effects: it might increase in-patch species diversity (alpha-diversity) by interrupting processes of plant succession that result in domination by a few competitive species and might increase diversity at larger scales by increasing the heterogeneity of patch types across the landscape (beta-diversity). Intermediate levels of landscape heterogeneity may stabilize species interactions58–60 and provide rescaling and habitat protection effects for species that require a variety of habitats for both food and shelter.61–63 This, in turn, may increase food web stability, allowing more species to persist with more stable populations than in the absence of such disturbance.64 and, particularly, affect the composition of animal communities by increasing patch density and habitat edges. This would favor populations of dietary or habitat generalists, which would see their foraging returns increase through reductions in the cost of travel between patches or encounters with prey.65 This would make it easier for such species to switch to alternative prey when high-ranked prey became scarce, facilitating the persistence of prey populations.66 Reducing the cost of accessing a wider range of resources and increasing the number of encounters with any one species would also reduce dietary variability and the possibility of harvest failure across individuals.

The co-evolutionary ecological model we explore here suggests that the emergent properties of human-environment interaction, with intermediate levels of ecosystem disturbance, shape landscapes and ecological communities in ways that cause shifts in species distributions, which in turn shape human social organization in ways that favor greater benefits of ownership and producer control over resource distribution. The model (Fig. 1) links ecological disturbance creating patchiness and predictability in certain resources with social processes of sharing and cooperation. We propose that shifts in ecological conditions that increase production of small prey, reduce variability in acquisition, increase group size, reduce mobility, and thus favor storing over sharing can be an emergent property of the way hunter-gatherers interact with plant and animal communities.67 This would be so especially in savannahs and grasslands, where applications of fire at a patch scale can dramatically improve immediate subsistence returns.

FIRE AS A SOURCE OF DISTURBANCE

The idea that landscape fire as a source of environmental disturbance...
might be fundamentally involved in subsistence intensification is not new. Lewis68 explored the idea in an often overlooked but important paper. What he was not able to articulate was the process by which fire affected the immediate returns from foraging and how this affects the likelihood of intensified production and all of its concomitant social structures.

In seasonally dry forests, woodlands, savannahs, and grasslands, the use of broadcast fire at a patch or stand scale is widespread among foragers. Indeed, it probably is the principal form of anthropogenic ecosystem disturbance with a deep evolutionary history in our lineage.69,70 In 1963, Stewart71 argued that application of fire to landscapes in traditional subsistence systems was a fundamental component of processes shaping over a quarter of the world’s ecosystems. He criticized both anthropologists and ecologist for not considering indigenous practice and knowledge with regard to landscape burning as fundamental in understanding widespread social and ecological interactions.71 Stewart’s argument was largely ignored and his full treatise on indigenous fire remained unpublished until long after his death.72

Stewart, however, was right, and his proposal has been especially relevant to understanding the nature of indigenous social and ecological integration in California73,74 and Australia. Unlike elsewhere, in Australia it has been difficult to ignore the central role of fire in Aboriginal economic, social, and ecological systems. The immediacy of contact among ecologically bent anthropologists, historians, archeologists, and traditional owners who maintain their burning practices forces our attention away from the destructive side of fire and toward the way in which intentionally applied fire constructs anthropogenic landscapes. Such landscapes comprise the “landscape capital” of classic Aboriginal estates.75–78 The distinctive institutions that manage property, regulate resource distribution, shape mobility, and facilitate social exchange are fundamentally linked to the nature of an anthropogenic niche that emerges from regular practices of firing the landscape. These are bound in co-evolutionary processes, so that where Aboriginal burning was interrupted by colonial forces the result was an abrupt ecological collapse.79,80

**BROAD SPECTRUM INSTITUTIONS IN AUSTRALIA’S WESTERN DESERT**

There is now considerable archeological support for the view that while people have occupied greater Australia for at least 45k years, something important happened in many Aboriginal societies during the Holocene and that the mid- to Late-Holocene in particular was a turning point in Australian prehistory, with diverse signatures of social and economic intensification in many locales.78,81,82 In the Central and Western deserts, Codding,83,84 Edwards and O’Connell,85 Smith,78 and Veth86 have shown that the latter half of the Holocene, especially the last 2,000 years, was marked by a dramatic increase in reliance on plants, especially grass seeds, that require significant processing, and a proportional increase in small game, especially monitor lizards and small mammals. These shifts occurred in association with the archeological appearance of distinctive elements of ethnographic desert tool kits, specifically woodworking adzes, seed-grinding implements, and composite weaponry. Late Holocene and ethnographic technology are more “curated” tool kits, with implements purpose-built for specific functions, more suited to logistical than residential mobility. Smith78 argues that these indicate clear signatures of mobility reorganization in the Late Holocene, with key sites occupied more often by groups with reduced residential mobility and increased investments in logistical mobility (more frequent and longer subsistence trips out from a residential base, sensu Binford87). That these “broad-spectrum revolutions” in the desert occurred independent of the reorganization often associated with the adoption and spread of classically defined farming points to the dramatic diversity of human social and economic systems during the Holocene.100 Work with contemporary Aboriginal foragers suggests that broad-spectrum desert economies are fundamentally associated with anthropogenic fire, which fragments landscapes, shapes species distributions, and facilitates ecological interactions that support distinctive habitats and landscapes.

Many Australian Aboriginal groups have maintained or re instituted customary burning practices in their homelands. Despite dramatic changes, critical components of their ecosystems remain intact and contiguous, and fundamental cultural institutions continue to be supported by their treatment of landscapes with fire. Figure 2 is a map of all anthropogenic fires from April through August 2014, along with the location and usual population of discrete Aboriginal communities across the Western and Central Deserts of Australia. We produced the map by outlining the footprint of every new fire visible in Landsat imagery across the entire region during the season (cool-dry) when there are no sources of ignition other than people. The vast majority of these fires that dominate the remote region are lit in the course of daily hunting trips out from the remote communities, on travel between communities through the region, and in prescribed burning in communities with ranger programs. The remote region — the vast interior with no rural centers and only small Aboriginal communities — is dominated by desert hummock grasslands and comprised almost entirely of contiguous Native Title, Indigenous Protected Areas, and Aboriginal Reserve Lands.88 Hunting-fires beyond this remote region are restricted by administration of non-Aboriginal land and by woodland/shrubland dominated habitats where the use of fire for hunting is less common.

Here we explore the contingent social and ecological processes of fire among Martu foragers in the Western Desert (see Fig. 2 for the Martu Native Title). Previously, we have shown that Martu mosaic burning strategies are maintained in support of immediate foraging efficiency.89,90 From simple rules to increase immediate hunting returns with fire, anthropogenic systems emerge with radically rescaled fire regimes. The emergent landscapes are buffered from climate-driven cycles of drought and wildfire,
and are characterized by increased density of habitat heterogeneity, compressed cycles of vegetative succession, and modified distribution and density of animal populations, all of which feed back to improve hunting and gathering return rates and the predictability of key subsistence resources. Here, we examine Martu use of fire as an important source of disturbance to investigate whether habitats shaped by human fires produce higher hunting return rates for small animals, reduce interforager harvest variability, reduce mobility, and increase an acquirer’s ability to control distribution in ways that could facilitate ownership. We argue that these are conditions common across broad-spectrum foraging economies and shape emergent properties of interactions requisite for farming and conditions that led to the Anthropocene.

CONTEMPORARY MARTU

In the remote desert regions of Western Australia, many Aboriginal foragers, including but not exclusively people who refer to themselves as Martu, continue to maintain fundamental aspects of their customary life ways and livelihoods. These practices include economic pursuits focused on hunting, gathering, and patch mosaic burning, as well as pursuits that are fundamentally intertwined with the maintenance of social relations and ritual obligations. In the mid-1980s, many Martu returned to their homelands after a 20-year exile in missions and settlements on the desert fringe, establishing three remote communities, Parnngurr, Punmu, and Kunawarritji (Fig. 2). Among the more recently contacted were Martu who took up permanent residence at the site of a uranium lease at Parnngurr rockhole, owned then by an Australian subsidiary of Rio Tinto, an international mining company. This group of about 70 people included several families from the Kartujarra, Manyjiljarra, and Warman estate owners, who felt that their claim to the area was quite strong. Most in this group were full-time foragers until the mid-to late-1960s. Today, families based out of Parnngurr maintain a mixed economy based on hunting and gathering, social security, and craft income from painting and traditional arts.

On and off for the last 15 years, our research team has been living with Martu based out of Parnngurr. Over that time, we have amassed a large quantitative observational dataset on contemporary foraging, including more than 4,500 observation hours of foraging during more than 1,900 individual foraging bouts. Martu spend 25%-30% of their days hunting or gathering; they rely on foraged food for 35%-50% of their daily diet, depending on the season. While they continue to collect a wide array of plant and insect resources (especially Solanum spp. fruit, Hakea spp. and Gevillea spp. nectar, and Endoxyla spp. grubs), men and women are primarily hunters. The main prey, especially of women, are several species of monitor lizards. Bustards (Ardeotis australis) and hill kangaroo (Macropus robustus), mostly hunted by
men, make up the bulk of the remainder.\textsuperscript{32,95,96}

In the following analysis, we combine previously reported metrics on differences between Martu modified landscapes and those that emerge from a nonanthropogenic fire regime\textsuperscript{79} with spatial variability in foraging intensity and efficiency.\textsuperscript{90} Details on methods are provided in those publications but, briefly, we use a composite of 10 years of vegetative patch heterogeneity (interpatch variability in succession following fire) measured from satellite imagery between 2000-2010. We then map spatial differences in foraging return rates and variability in foraging time onto the composite heterogeneity map. Time allocation and return rates from different foraging activities were recorded in systematic observations of 1,831 adult foraging bouts between 2000-2010.\textsuperscript{32} A foraging bout consists of measures of time per day an individual spent searching for, pursuing, capturing, and processing resources from a given foraging activity, and associated yield by resource type.

**MARTU FIRE, FORAGING, AND MOBILITY**

The immediate function of Martu burning operates at the scale of the patch and is designed to clear off large stands of hummock grass (spiningex, *Triodia* spp.) in order to increase the efficiency of searching for and tracking small animals, primarily burrowed ones. Today, the major prey hunted with fire is the sand monitor lizard (*Varanus gouldii*). However, while searching for these lizards, hunters often pursue a range of resources on encounter (mostly other species of monitor, as well as *Tiliqua* spp. skink, snakes, and *Solanum* spp. fruit). Resources acquired in this foraging activity make up more than half of all hunting time and provide nearly half of all the bush food people consume.\textsuperscript{32}

Sand monitors burrow during the cold winter months and live off stored fat. The lizards are hunted with fire in the winter and tracked in recently burned ground in the summer. Hunts in winter target old-growth spinifex grasslands last burned more than 5 to 10 years ago, which provide shelter to monitor lizards. Also, only past this stage is vegetation thick enough carry a fire. Sand-monitor hunting returns are high in both winter and summer, averaging between 1,500-2,000 kcal/forager hr until about one year after fire (given rain). Hunting returns then decline rapidly as the burned patch is revegetated.\textsuperscript{90} Hunting without burning in patches older than about 5–7 years is inefficient, averaging only between 25–100 kcal/forager hr.

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**Figure 3.** The effect of fire on the mosaic of vegetative succession in the Martu homelands. The stand ignition map shows the cumulative effect of both Martu and lightning fires between 2000 and 2010. Fires were visually detected and hand-digitized using a ratio of Landsat 7 Infrared bands 7 and 5. Light colors indicate more recent fires; dark shades indicate older fires. Regions across the study area are stratified into four categories of foraging intensity from 4,106 adult foraging hours observed between 2000 and 2010: Category 1 includes regions with 0-0.05 forager days/km$^2$, 2 = 0.06-0.25 forager days/km$^2$, 3 = 0.26-2 forager days/km$^2$, 4 = >2 forager hrs. A) The number of patches at different stages of vegetative succession/km$^2$ regressed by foraging intensity. B) shows the number of old-growth patches (patches that remained unburned)/km$^2$ regressed by foraging intensity.
When iterated across the landscape, the aggregate effect of burning to hunt has a large effect on the scale of landscape patchiness. Figure 3 shows a stand ignition map of the region: the cumulative effect of both Martu and lightning fires between 2000 and 2010. Patches of different time since fire, or successional stage, are associated with different plant communities. It takes about ten years to cycle through to the final successional stage in which spinifex grass will completely dominate the patch. In this analysis, we classify the composite stand ignition map into four regions according to the intensity of foraging use across all adult foraging hours (4,106) observed between 2000 and 2010, where intensity is measured as forager days per square km. As shown in Figure 3a, more foraging produces significantly greater density of different patch types (patches of different successional communities) across the landscape. Fires are dramatically smaller where Martu hunt more often, leading to a higher density of diverse patches.\(^{79,92}\) Particularly, as shown in Figure 3b, the density of unburned patches increases significantly with more use, meaning the distance one has to travel to reach a suitable hunting patch for burning is shorter.

![Proportion time in travel and search](image)

**Figure 4.** Martu foraging mobility is significantly lower in anthropogenically modified regions. The graph shows a subsample of pedestrian sand monitor hunting focal individual tracks in which GPS tracks were recorded (n = 35) comparing the proportion of foraging time individuals spent in travel between patches and search within patches in remote regions (use category 1, see Fig. 3) versus anthropogenic regions (use categories 2-4, see Figure 4). Errors are 95% confidence intervals.

If resource patches are closer together in anthropogenic landscapes, this implies that mobility should decline in landscapes with increased use. Figure 4 illustrates this with a subsample of winter foraging bouts for sand-monitor lizards where GPS tracks were recorded. When people forage on foot in anthropogenic landscapes, they spend about 10% less time in mobile search and travel.

This scaling of patch density not only reduces the costs of foraging for Martu, it also increases habitat quality for certain species. As we have shown elsewhere,\(^{90}\) Martu use of a region increases the density of their major prey, the sand monitor lizard. Density is higher in anthropogenic regions despite the fact that hunting pressure is also higher. This is likely because sand monitors are edge-loving generalists, who do better in anthropogenic environments. Other species show different responses to anthropogenic patchiness. Larger animals such as kangaroo also benefit from the landscape diversity that Martu fires create: areas that are most heavily hunted have lower kangaroo densities, but so do areas with no hunting or very limited hunting.

Regions of intermediate use have significantly higher kangaroo populations, likely because the benefits of an anthropogenic fire regime include increased access to patches of high-quality forage and a net increase in kangaroo at intermediate distances from Martu communities.\(^{91}\)

The patchy landscapes created through the accumulation of several years of winter hunting fires have long-term effects on the distribution of plants and animals. Landscapes where hunting is most intense also have more patches of mid-successional grassland, which has a significantly high density of high-ranked seed grasses such as *Eragrostis* spp., which were a precontact staple, and fruits such as *Solanum*.\(^{92}\) Again, just as with hunting patches, this higher density minimizes the likelihood of having no seed-bearing patches available within a reasonable travel distance from any camp. The anthropogenic landscape thus rescales resource patch density to reduce the cost of accessing a wider range of resources.

Figure 5 shows the overall foraging return rates (kcal/forager hr) for both collected and hunted resources, including both small and large game, according to regional differences in intensity of foraging use. Returns are highest in areas under intermediate use, where the negative effects of anthropogenic resource depression are outweighed by the positive effects of human fire. Even in the most used regions, Martu achieve significantly better returns than they do in more remote regions. This is not a result of foragers simply targeting areas that have higher inherent successional diversity because, as we have previously demonstrated, without anthropogenic burning heterogeneity dramatically declines.\(^{79}\)

Because resource patch heterogeneity increases with foraging use intensity, at the level of the camp, each forager has better access to high-quality resource patches in anthropogenic landscapes. Also, there is less variability in returns across individuals per day (Fig. 6). Everyone in a camp is roughly equally successful in an anthropogenic environment, leading to a lower daily coefficient of variation in daily food production in anthropogenic landscapes compared
to unmodified landscapes. Furthermore, the increase in small game productivity and the reduction in the cost of accessing patches for hunting small game and plants increase the proportion of overall camp production comprised of small game in more anthropogenic habitats. Small animals and collected resources, relative to large animals, increase from 37% of camp harvest in remote regions to more than 80% in the most intensively used regions (Fig. 7). Previously, we have shown that, relative to large game (hill kangaroo), small game (sand monitor) is associated with increased producer control over distribution.93,95,97

The effects of decreased mobility also have a strong influence on the costs of claiming the benefits of ownership. In the small bush camps that Martu form on a daily basis, comprising from 5-20 adults from various residential camps within the permanent community, members do not segregate into separate households but, instead, act as a single food-pooling unit. Acquirers of small game keep a smaller average portion for consumption than that given to others. However, when sharing occurs in larger, long-term camps where people have segregated into multiple residential groupings, the average portion that acquirers keep for distribution to their own dependents is greater than that given to others. The Martu data indicate that people operating in anthropogenic fire regimes experience increased returns from small-game hunting at the immediate scale, which supports long-term increases in subsistence returns over longer periods. Long-term small-game returns are higher because human fire increases patchiness and fine-scale habitat heterogeneity, which increases the predictability and density of generalist and staple animal prey near central places. This tends to reduce mobility, increase reliance on small prey, and reduce variability across individuals, which decreases sharing and increases the benefits to hunters of controlling distribution. Critically, fire is not being used deliberately as a habitat management tool; rather, the use of fire is maintained by its immediate benefits to hunting burrowed animals. Complex systems then emerge from these interactions.

**SYNTHESIS: ON THE BROAD SPECTRUM REVOLUTION**

These results are directly relevant to the central question regarding the social and ecological processes surrounding mobility and subsistence shifts in hunter gatherer economies: How do such societies shift from the more immediate-return economy of mobile hunter gatherers to a more delayed return economy focused on sedentism, storage, and greater social hierarchy based on material wealth? This question gets at the heart of ubiquitous shifts toward increasingly broad-spectrum economies, reduced residential mobility and, ultimately, the origins of agriculture.

The standard model of the broad-spectrum revolution is one of intensification. An increase in human population density causes reductions in mobility and a decline in high ranked resources, particularly large-bodied, slowly renewing prey. This then shifts foraging toward a wider array of low-ranked resources (smaller prey and handling-intensive plant foods), which spurs investment in technologies to reduce associated handling costs, which are the roots of processes associated with plant or animal domestication and agriculture.

Issues with the standard model are highlighted in arguments about whether population increases or declines in efficiency precede shifts to broad-spectrum economies, where it appears, in some cases, that there are no detectable declines in high-ranked resources.23 Whether or not the resources of concern are “high-ranked” (high yield for time spent pursuing and processing) needs to be demonstrated. The assumption that large bodied, slowly renewing prey are always ranked higher than smaller, more quickly renewing prey, depends on the probability that pursuits will be successful.32,95 Equally important, however, the standard model needs to account for the necessary development of norms of ownership, which make possible shifts to a delayed return economy more dependent on food storage.30

Our analysis suggests that the emergent properties of human-environment interaction can shape landscapes and ecological communities in ways that cause shifts in species distributions, which, in turn, shape human social organization in ways that favor the benefits of reduced mobility and producer control over resource distribution. The model links ecological conditions creating patchiness and predictability in certain resources with the social processes of sharing and cooperation. The shifts in ecological conditions that increase production of small prey,
reduce variability in acquisition, and increase group size and reduce mobility, and thus favor storing over sharing, can be an emergent property of the way hunter-gatherers interact with plant and animal communities in woodlands and grasslands: They use fire at a landscape scale to reshape their environments.

Combining the results discussed, which show how certain subsistence resources increase in density with fire, we show that these anthropogenic landscapes shape subsistence and mobility patterns in ways that presage the increasing sedentism of a broad-spectrum economy. The finer-grained habitats shape the scale at which foragers experience resource patchiness. Travel time between patches is reduced, lowering the overall cost of foraging and reducing the total distance traveled.

The final piece of the model brings together the ecological shifts in small animal density that increase average returns and reduce variability in those returns, with the social relationships and norms that are created through sharing. The cost of making claims to ownership decreases when variability among individuals is lower, with the prediction that the degree to which acquirers bias sharing in ways that produce greater material benefit for their own dependents (producer priority) increases positively with the daily production of others in camp. As others produce more, one should keep more of one's own production, a necessary step toward being able to accumulate and defend access to food stores. This is the case for small animals but not larger ones. Harvests of small animals show substantial contingency of harvest size on foraging time, leading to a stronger link between labor and the products of that labor, while harvests of larger animals do not.95

In this model, short-term foraging returns under conditions of reduced mobility are sustained through the application of broadcast fire. This potentially illuminates a wide range of diachronic subsistence shifts, particularly the common trend in the Late-Pleistocene and Holocene toward broad-spectrum economies, especially in seasonal habitats where lightning fires is a common occurrence. Indeed, the origins of broad-spectrum economies across much of Asia co-occurred with increased fire frequency as shrublands of the late Pleistocene gave way to the warmer and patchier grasslands and woodlands of the Holocene.35,98 The common increase in the proportional representation of small animals in the archaeological record suggests that in many environments occupied by modern humans, co-evolutionary dynamics may have caused shifts in ecological communities, with an increase in species that are resilient to human environmental impacts or even dependent on human disturbance.99 We suggest that broad-spectrum economies may be shaped through co-evolutionary processes involving habitat modification, which can result in increased populations of some species (often smaller or disturbance-dependent) and reduce variability in acquisition, shifting sharing norms toward increasing private ownership and reducing mobility.

We propose that Aboriginal landscapes in Australia, which have characterized much of the desert since the mid- to late-Holocene, are emergent
ecological systems. Codding suggests that anthropogenic fire mosaics are an epiphenomenon of foraging economies based on small marsupials and reptiles, requirements for foragers with reduced incentives to maintain especially high residential mobility. Bliege Bird and coworkers and Smith argue that mid- to late-Holocene reorganization in technology and mobility, as well as the emergence of the ethnocritically documented estate-based system of land ownership, closely corresponds with establishment of anthropogenic fire mosaics. Efficient exploitation of small game and seed resources, core characteristics of the social-economics of desert broad-spectrum institutions, may thus be bound to creation of the small-scale sequential mosaics created by anthropogenic burning. Similar processes elsewhere, where intensification will continue to amplify in feedbacks that increase Malthusian limits of carrying capacity, probably are the roots of domestication, dense sedentism and, ultimately, the Anthropocene.

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