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DISCUSSION

Fire-reliant subsistence economies and anthropogenic coniferous ecosystems in the Pre-Columbian northern American Southwest

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Abstract Archaeologists working in the vast coniferous uplands of the American Southwest have commonly assumed that the subsistence economies of the prehistoric peoples who dwelt there focused on corn (*Zea mays*) agriculture, the erratic yields of which were supplemented with the unintensive collection of wild plants. In this paper, we develop an alternative to this orthodox view, in which we posit that human-controlled burning of understory biomass was a vegetation-community and successional-stage management strategy intended to propagate wild plants in bulk quantities. By comparing the relative frequencies and ubiquities of macrobotanical remains recovered from a variety of storage and consumption contexts with pollen frequencies from production and processing contexts, we show that the systematic encouragement of ruderals in pyrogenic resource patches ("niches") was a sustainable practice that overcame natural limitations to biomass productivity and corn cultivation in pinyon-juniper (*Pinus edulis* and *Juniperus* sp.) woodlands. Importantly, these analyses indicate that low-intensity burning was a key aspect of fire-reliant subsistence economies that generated anthropogenic ecosystems whose composition and productivity were markedly different from today's.

Keywords Anthropogenic fire · Ruderal agriculture · Pinyon-juniper woodland fire ecology · Prehistoric northern American Southwest · Grand Canyon, Arizona

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"Through fire humans made earth habitable…" (Pyne 2012, p 47).

Introduction

Long considered a securely settled matter in the prehistory of the American Southwest (e.g., Gumerman and Gell-Mann 1994; Schoenwetter and Dittert 1968), the nature of ancient agricultural practices across broad areas of this culturally and environmentally diverse region is being systematically reconsidered as a consequence of new models (Rowley-Conwy and Layton 2011), new data (Powell 2002), and new understandings of the relations between people and plants (Smith 2001). The question as to whether the agricultural economies of prehistoric societies that once occupied upland forests of the northern American Southwest were based on water-dependent domesticated plants, such as *Zea mays* (corn), which is low-moisture intolerant, or fire-conducive wild plants (such as ruderals, which are low-moisture tolerant) has emerged as a pivot point of this rethinking (Sullivan 2014). The conventional, ethnographically inspired and justified view favours the water-dependent model, with its focus on understanding how moisture availability affects the success of maize agriculture and influences, as well, regional variation in population and settlement patterns (e.g., Spielmann et al. 2011). Our intention, however, is to share new archaeological and palaeoecological data that support the fire-reliant model, which focuses on demonstrating the extent to which prehistoric burning and fuel-load ignition-management strategies ensured the sustained propagation of wild plants as the keystone component of prehistoric foodways (Roos et al. 2010).

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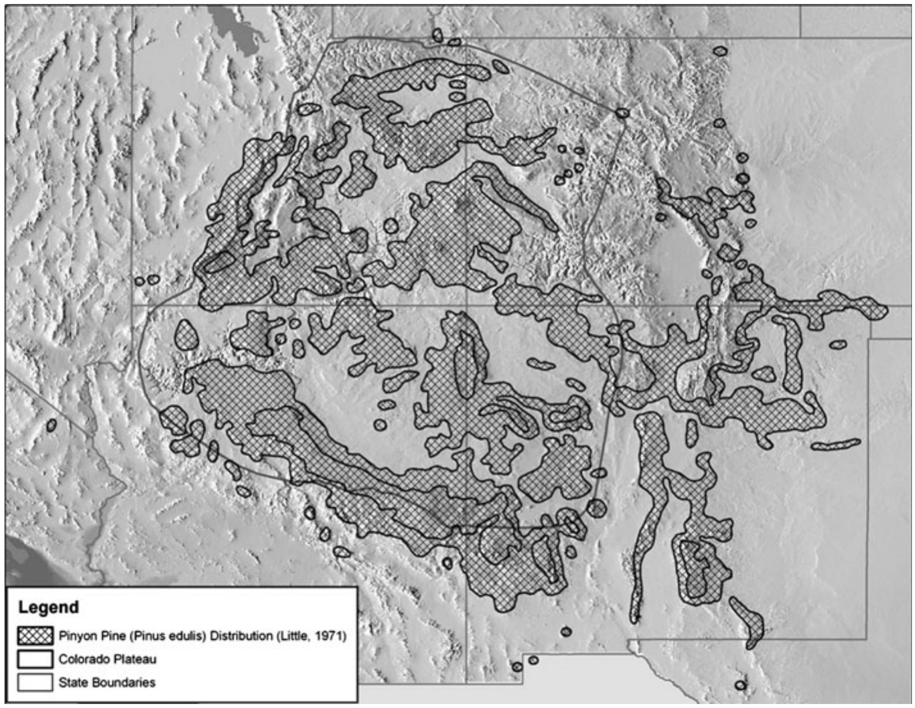


Fig. 1 Modern extent of coniferous uplands, as measured by the distribution of the pinyon pine community, in the American Southwest (adapted from Little 1971)

A smouldering controversy

The upland northern American Southwest is a natural laboratory in which to explore the issues entailed by these disparate points of view because its vast coniferous forests, which cover between 17.4 and 30.4 million ha (West 1983) and range in elevation from 1,372 to 2,287 m a.s.l. (Wright et al. 1979), harbour tens of thousands of archaeological sites (Fig. 1). Moreover, decades of fire-ecology research have demonstrated the profound and known effects that humans can have on these forests in comparatively short periods of time (e.g., Huffman 2008). Inexplicably, however, these well-established ecological relationships between anthropogenic fire and vegetation management have rarely found their way into Southwest archaeology and considerations of prehistoric subsistence practices (Sullivan 1982). Consequently, for the American Southwest, narrowly-drawn ethnographically-based models, focusing principally on water-dependent domesticated plant production, dominate archaeological studies about the nature of prehispanic agricultural economies (e.g., Adams and Fish 2011; Woodbury 1961).

To understand the reasons for this situation, and to appreciate proposed alternatives to it, it is instructive to review synoptically the history of thinking on the topic. Several intertwined elements explain the origins and expansion of this dominant "corn" paradigm (Sullivan 2014). First, working without chronometrically established time relations between prehistoric and modern populations, but assuming they were on the order of only several centuries (Meltzer 1985), mid-to-late 19th century observers interpreted archaeological indicators of agricultural production, such as ground-stone artifacts (Powell 1875) and masonry structures (Morgan 1881), in terms of their first-hand observations of the role of such artifacts and structures in then-contemporary Pueblo populations and practices. Second, early in the 20th century, investigators simply asserted that little change had occurred in subsistence practices between ancient and modern times (Bartlett 1936; Hough 1930; Stewart and Donnelly 1943). Finally, incorporating the legacy of these institutionalized interpretive protocols, modern researchers have focused their work on understanding sociocultural responses, such as settlement relocation, to variable precipitation on maize productivity (Benson 2011), which often entails using "proxy" models of modern soil-type biomass carrying-capacity to estimate corn-crop yields (Kohler et al. 2012; Pool 2013). Supported in large measure by ethnographic analogies with modern populations (e.g., Hegmon 1996), the "corn" paradigm has become so deeply entrenched epistemologically that, even in the absence of what might reasonably be regarded as basic evidence for corn farming, such as *Zea* pollen or macrobotanical remains (Adams and Bohrer 1998), Southwest archaeologists insist that maize agriculture was the focus of the subsistence economies of the region's prehistoric populations (Kohler et al. 2005; Snow 1990, p. 289). Ironically, several leading sociocultural anthropologists (e.g., Bradfield 1971; Eggan 1950), who contributed to the literature that is the basis of the analogies, were themselves ambivalent about the degree to which modern institutions can serve as reliable analogues of their ancient counterparts (Bradfield 1973, p. 217; Bradfield 1995, p. 414; Eggan 1989, pp. 30–33). Nonetheless, despite the absence of direct evidence of *Z. mays* in archaeological assemblages (Hall 1942) or in the face of ambiguous archaeological evidence (Harry and Watson 2010), the ethnographically-based corn paradigm persists as the key interpretive model because no alternative to it is available—a situation that we propose to remedy in this paper.

Fanning the flames

Despite the global prevalence of burning for subsistence purposes—across space and through time (Bowman et al. 2011; Mellars 1976; Pyne 2012)—ethnographic accounts of economic fire are virtually absent in the anthropological literature of the American Southwest (Roos 2008; for an exception, see Dobyns 1981). In fact, the most thorough accounts of indigenous subsistence burning for the region have been written by environmental historians (Pyne 1982) and forest scientists (Bonnicksen 2000; see also Vale 2002). The thin scholarship on the economic significance of fire is attributable to several factors. First, by the time ethnographers had begun to study many reservation-based tribal communities, particularly in the American Southwest, the federal government was strongly advocating that Native American farmers grow water-dependent crops in addition to *Z. mays* (Fig. 2; Minnis 1991, p. 246; Soleri and Cleveland 1993; see Schroeder 2013 for a wide-ranging discussion of this complicated topic). Second, government agencies were encouraged to restrain Native Americans from igniting landscape fires in order to reduce federal liability exposure if "Indian" fires escaped reservation boundaries, as well as to protect grasslands for cattle ranching (Pyne 1982, p. 80; see also Minnis and Elisens 2000, p. 4). Third, in view of the settlement history of late prehistoric and historic populations on the Colorado Plateaus, it is clear that the rise of geographically isolated clusters, beginning in the 14th century (Wilcox et al. 2007), contributed to the development of widespread abandoned landscapes where anthropogenic burning did not figure in ecosystem dynamics, thereby substantially altering regional fire regimes (particularly with respect to fuel loads and their management by humans; Roos and Swetnam 2011). Fourth, in aboriginally occupied territory, pre-reservation burning may have been widespread but there are no ethnographic accounts of its subsistence implications, although anecdotes abound (Allen 2002; Bonnicksen 2000, pp. 236–240); conversely, because landscape burning had been discontinued on Native American reservations, or was under strict management by federal authorities (Austin and Wolf 2001), ethnographers had no reason to inquire about it and its role in food provisioning (Cooper 1960, p. 138; Woodbury 1966, p. 225; see also Maxwell and Anschuetz 1992, pp. 38–39). It is little wonder, then, that Southwest archaeologists, who historically have followed the lead of their sociocultural colleagues in conceptualizing how aspects of ancient society are registered in the archaeological record (Longacre 2010), have developed models of ancient subsistence that rarely incorporate considerations of anthropogenic fire ecology (Adams 2004).

Coniferous upland subsistence economies in ecological perspective

The behavioural consequences of the water-dependent and fire-reliant subsistence models can best be appreciated by considering them within their relevant ecological theoretical

Fig. 2 Irrigated farmland in the vicinity of Moenkopi Pueblo, northern Arizona

frameworks. For instance, the orthodox water-dependent model, with its focus on the propagation of low-moisture-intolerant domesticated plants with inflexible growing requirements (Muenchrath and Salvador 1995), is an example of an obligate ecological model. In this case, humans in pre-industrial settings have little or no control over the variables that affect plant production. Hence, given the demonstrable unpredictable variability in palaeo-precipitation patterns (Benson 2011; Dean 1988; Euler et al. 1979) and its effect on ground-water levels, floodplain aggradation, and erosion cycles (Damp 2007), *Z. mays* agriculture is an inherently risky practice (Wills 1992), with high socioeconomic destabilization potential (Gumerman and Gell-Mann 1994) because humans cannot directly influence when, where, and in what quantities precipitation materializes (Dean et al. 1985; Gaines and Gaines 2000, p. 111). Also, given the nature of the region's prehistoric agricultural technology (Maxwell and Anschuetz 1992), populations were constrained in their capacity to capture, control/redirect, and store water or to enhance soil properties in response to the planting depth and soil nutrient growing requirements of *Z. mays*, particularly in upland coniferous forests where soils are thin and rocky (Homburg and Sandor 2011; Kohler et al. 2000, p. 149; compare Matson 1991, p. 86). Moreover, it is difficult to reconcile the outcomes of palaeoeconomic investigations in production and consumption contexts, such as "agricultural" terraces (Berlin et al. 1990; Homburg 1992) and mummified human colon contents (Reinhard et al. 1992), where direct indications of *Z. mays* agriculture should be clear and unambiguous, with what is actually recovered—evidence of maize is non-existent or occurs in extremely low frequencies (<1 % of pollen or macrobotanical remains), whereas evidence of wild plants is abundant (Sullivan 1996).

Facultative ecological models, in contrast, focus on the transformative consequences of disturbances created by anthropogenic fire (Sullivan 1982). As Pyne (1982, p. 71) has remarked, "It is hard now to recapture the degree to which Indian economies were dependent on fire." A truism that no doubt resonates with many Old World archaeologists, particularly economic prehistorians (Jelinek 1977, p. 25; Mason 2000; Rösch et al. 2002), Pyne's observation challenges ethnographically-inspired obligate models of ancient subsistence in the American Southwest in several significant respects. For instance, by focusing on the production of abundant seed-producing ruderals, i.e., wild (undomesticated) plants that thrive in pyro-disturbances (Grime 2001, p. 80; Kramp et al. 1983, p. 2), humans directly control the location and potential yield of their food supply that is constituted by low-moisture-tolerant plants (Table 1). Importantly, understory fire reduces competition around the bases of nut-bearing *Pinus edulis* (pinyon pine), thereby enhancing the productivity and predictability of this highly nutritious food (Lanner 1981; Madsen 1986). Further, by unbinding the constraints of food production that are typically associated with corn agriculture, such as soil depth and nutrients, humans enhance predictability and reduce risk and potential interruptions in their food supply, thereby stabilizing the entire subsistence economy (Smith 2011). Moreover, the by-products of ruderal agriculture not only align with the content variation of the archaeo-economic record, i.e., high abundances of wild plant pollen and macro-botanical remains (Cummings 1995), but also with respect to the distributions of Southwestern archaeological sites that, with few exceptions, do not occur adjacent to alluvial floodplains and, hence, could only have served as locales for food production by virtue of their surroundings having been transformed by the application of fire (Pyne 2012, p. 66).

Fire power: ecological consequences of burning pinyon-juniper woodland understory vegetation

To illustrate the advantages of thinking about ancient subsistence in facultative rather than obligate ecological frameworks, we explore how anthropogenic fire enabled ancient populations to provision themselves on a sustainable and largely risk-resistant basis (Sullivan 1996). Specifically, the three transformative effects of burning in *P. edulis* and *Juniperus* sp. (pinyon–juniper) woodlands that we discuss are focused on understory vegetation, which is composed principally of "duff" (i.e., unburned accumulations of dead branches, pine cones, and other organic forest debris; Fig. 3), herbs, forbs, and grasses, after it is set ablaze by human-controlled ignition (Dieterich 1983, p. 29). First, combustion rapidly reduces the above-ground biomass into fertile ash, thereby thickening (or, in many cases creating) a cultivable A-horizon and releasing nutrients that are essential for plant growth, such as potassium, nitrogen, and phosphorous (Donkin 1979, p. 27; Weaver 1974, p. 293). Second, the fertile growing conditions created by the disturbances caused by anthropogenic ground-fires (Herrmann et al. 2007), including the albedo effects of the darkened ground surface (which absorbs solar radiation; Viro 1974, p. 4; Fig. 3) and the greater moisture infiltration (caused by the elimination of competing plants for water; Lewis 1972, p. 210), encourage the propagation of seed-bearing ruderal plants. Some studies suggest that the dormant but viable seed bed of fire-tolerant ruderals is actually activated by the heat of the passing fire, thereby contributing to the emergence of dense concentrations of these plants after such pyrogenic disturbances occur (Biswell 1972, p. 71; McCulloch 1969, p. 783). Third, with human-controlled ignition, not only is the production location dictated by human intentionality, it is independent of prevailing soil conditions (Pyne 1982, p. 74). Further, with relatively constant understory fuel

Table 1 Ecological characteristics of plant categories and representative taxa that comprise them. Multiple entries indicate characteristic variation at the species level (data from USDA PLANTS database 2013 and Epple 1995)

			Fire Tolerance				Drought Tolerance			
Category and Taxa	Common Name	Growth Duration	none	low	med	high	none	low	med	high
Herbs and Forbs										
Achillea sp.	yarrow	perennial				X			X	
Amaranthus sp.	pigweed	annual					*no data*			
Brassica sp.	mustard	annual	X	X				X		
Chenopodium sp.	goosefoot	annual					*no data*			
Cleome sp.	spider plant	annual	X	X				X		X
Helianthus annuus	common sunflower	annual	X						X	
Mentzelia sp.	blazingstar	annual or perennial					*no data*			
Plantago sp.	plantain	perennial		X		X			X	X
Portulaca sp.	purselane	annual					*no data*			
Sphaeralcea sp.	globemallow	perennial				X				X
Shrubs										
Artemisia sp.	sagebrush	perennial		X	X	X		X		X
Atriplex sp.	saltbrush	perennial	X	X		X			X	X
Ephedra sp.	joint-fir	perennial	X		X	X	X			X
Prunus virginiana	chokecherry	perennial				X			X	
Grasses										
Achnatherum/ Oryzopsis hymenoides	Indian ricegrass	perennial				X				X
Alopecurus sp.	foxtail	annual	X	X		X	X	X	X	
Bromus sp.	brome grass	annual	X	X	X	X	X		X	X
Poa sp.	bluegrass	annual or perennial		X	X	X		X	X	X
Cacti and Succulents										
Agave sp.	agave	perennial	X	X						X
Opuntia sp.	prickly pear	perennial	X							X
Yucca sp.	yucca	perennial	X							X
Trees										
Juniperus monosperma	one-seed juniper	perennial	X							X
Juniperus osteosperma	Utah juniper	perennial		X						X
Pinus edulis	two-needle pinyon	perennial		X						X
Zea mays	maize, corn	annual		X				X		

regeneration ("duff" accumulations), fire can be returned to the same "burn plot" (Sullivan 1982) after several years—estimates range from annual burns for grasses to 2–3 years for forbs (Barney and Frischknecht 1974, p. 94; Kramp et al. 1983, pp. 2–6; Wright et al. 1979, pp. 18, 28–29)—without a significant decline in yields (Arno 1985, pp. 81–82). Generalizing from the vast literature on the fire ecology of pinyon–juniper woodlands, it is reasonable to conclude that anthropogenic ignition management of understory fuel loads creates a predictable and sustainable successional mosaic (Bonnicksen 2000, pp. 238–240) of drought-tolerant ruderal plant species (Everett and Ward 1984, p. 67; Wright and Bailey 1982, pp. 204–205), which are keystone components of aboriginal food supply systems (Bohrer 1975; Cummings 1995; Doebley 1984; also Fowler and Rhode 2011).

Study area

Variation in modern and ancient vegetation

We now discuss the results of recent investigations that were designed specifically to understand the role of fire in the economies of those societies that once inhabited the sprawling conifer forests of northern Arizona near the Grand Canyon (Schwartz 1990). An official World Heritage Site (Morehouse 1996), the Grand Canyon is known for its spectacular vistas and extravagant landscapes (Pyne 1998). Far less appreciated is the fact that, despite the attention it receives from onlookers and hikers, the Inner Canyon was barely inhabited (Fairley 2005). In reality, the bulk of the prehistoric occupation of the Grand Canyon was restricted to its densely forested rims, with the South

Fig. 3 *Left*: Unburned understory accumulation (ca. 20 cm thick) of grass, needles, and pine cones near the Tusayan Ruin, Grand Canyon National Park, northern Arizona. *Right*: Aftermath of controlled burn that consumed understory fuels in Kaibab National Forest, northern Arizona

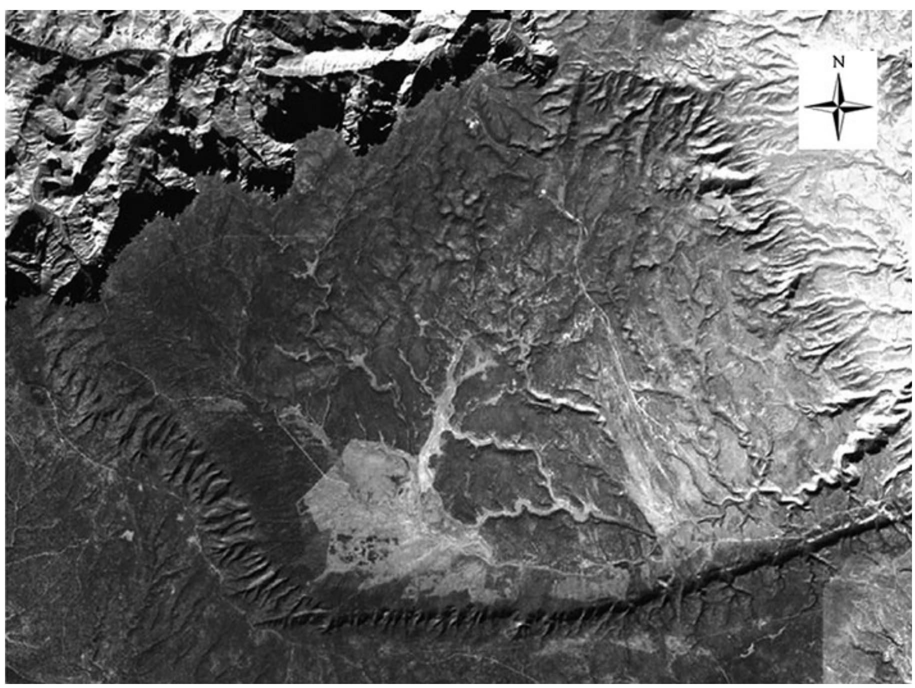


Fig. 4 IKONOS satellite image of the Upper Basin of northern Arizona, showing the South Rim of the Grand Canyon (diagonal running from *upper left* to *top center*) and the Coconino Rim of the Coconino Plateau (*left center* to *bottom*). Dark areas are dense pinyon–juniper woodlands and *Pinus ponderosa* woodland. Navajo Indian Reservation is the light-colored terrain on the right of the image. Distance from *top* to *bottom* of image is ca. 16 km (10 miles)

Rim/Upper Basin area sustaining the heaviest concentration of settlements (e.g., more than 2,000 prehistoric sites have been discovered in 23.8 km^2, all of which have been abandoned for at least 800 years) in an upland (>2,000 m) conifer ecosystem dominated by pinyon pines and junipers (Brewer et al. 1991; Sullivan et al. 2002; Vankat 2013; Fig. 4).

Based on the analysis of pack-rat middens (Cole 1990; see also West 1984, pp. 1309–1310), the Grand Canyon's pinyon-juniper woodland has been in place for at least the last six millennia, which is the era that correlates with the earliest evidence of sustained human occupation in the area (Davis et al. 2000; Emslie et al. 1995). The composition of the modern woodland community, however, is a complex historical precipitate that has been affected by the cessation of perennial aboriginal occupation at the end of the 13th century A.D. (Euler 1992), the suppression of natural fire (Pyne 1989), and the introduction of intensive cattle and sheep grazing (Huffman 2008, p. 2099; Miller 1921). Combined, these factors have altered the fire regime of the pinyon-juniper woodland from fire-tolerant (high frequencies of non-lethal surface fires) to fire-vulnerable (low frequencies of lethal crown fires; Fulé et al. 2003, p. 142; but see Huffman et al. 2009 for an alternative view), thereby facilitating the expansion of sagebrush and juniper at the expense of pinyon trees and grasslands (Arno 1985, p. 82). This ecological dynamic has contributed to the dramatic decline in frequency of economically important "semi-domesticated" (Spoerl and Ravesloot 1995, p. 496; Bohrer 1983) plants, such as Indian rice-grass (*Oryzopsis hymenoides*), chenopodium (*Chenopodium* sp.), and amaranth (*Amaranthus* sp.) (Phillips et al. 1987; Schwinning et al. 2008).

Discussion

Studies of pinyon-juniper woodland fire history often refer to "pre-settlement" or "pre-Euro-American" burning, a designation that excludes prehistoric occupation periods (e.g., Floyd 2000; Moore et al. 2004, p. 166), thereby constraining consideration of fire use during the prehispanic era with which we are concerned (Vankat 2011). Compounding the problem is the likelihood that anthropogenic fires "have probably always been a factor in Grand Canyon ecosystems, but the extent and ecological importance of native burning remains uncertain" (Fulé et al. 2003, p. 142). In addition, fire histories typically are based on the analysis of fire scars, which are usually produced by fires of sufficiently high-intensity and severity to register only on trees of a certain age or size (Allen 2002, pp. 165–166). Therefore, the fire-scar record has a low probability of documenting the frequency of low-intensity surface fires, particularly in managed woodlands (Bunting 1987; Grissino-Mayer et al. 2004; Huffman et al. 2012; Romme et al. 2009; see also Keeley 2009); also, it is generally understood that "historical pinyon-juniper fires were of limited extent and lethal only in patches" (Huffman 2008, p. 2103). It is fair to say that the effects of these "disturbances" on local pinyon–juniper ecosystem structure are just beginning to be studied and understood (Baker and Shinneman 2004; Hood and Miller 2007). Nonetheless, there is broad agreement that in the "very remote past (many hundreds or thousands of years ago)" (Romme et al. 2009, p. 211), these woodlands would have had sufficient understory fuels, which have been eradicated during the last 150 years because of grazing, and inter-tree distances to carry low-intensity surface fires without jeopardizing the health of the ecosystem (see Roos and Swetnam 2011, p. 8).

Variation in modern and ancient precipitation

Examination of the area's historic precipitation records reveals that two periods of low rainfall can be expected yearly (Fig. 5). One develops in late Spring and another in the Fall (Sullivan et al. 2002, pp. 51–53), precisely bracketing the traditional growing season for *Z. mays* (Muenchrath and Salvador 1995), which is about 141 days long in the Grand Canyon area (Merkle 1952, p. 376). Based on dendro-climatological records from across the Southwest (Dean 1996), this bi-seasonal pattern was in place when the area was occupied prehistorically (Euler 1988).

If we focus on tree-ring reconstructed precipitation (Fig. 6), two attributes stand out: (1) the record is characterized by multi-year periods of above-average or below-average precipitation and (2) it always rains and snows (even the "worst" years, e.g., 1067, 1073 and 1093, still registered at least 255 mm/10 inches of precipitation). This highly variable precipitation pattern, however, is largely

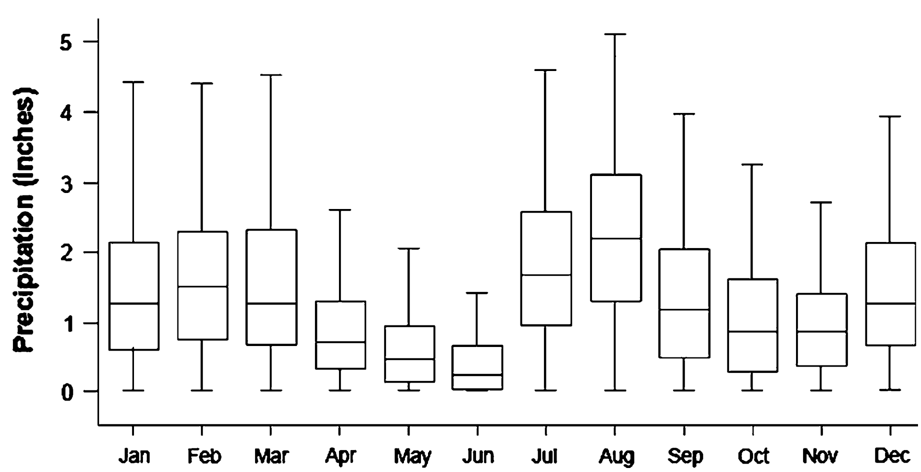


Fig. 5 Box plots of monthly precipitation in the Grand Canyon area based on meteorological records from 1904 to 1983 (adapted from Sullivan and Ruter 2006, p. 186)

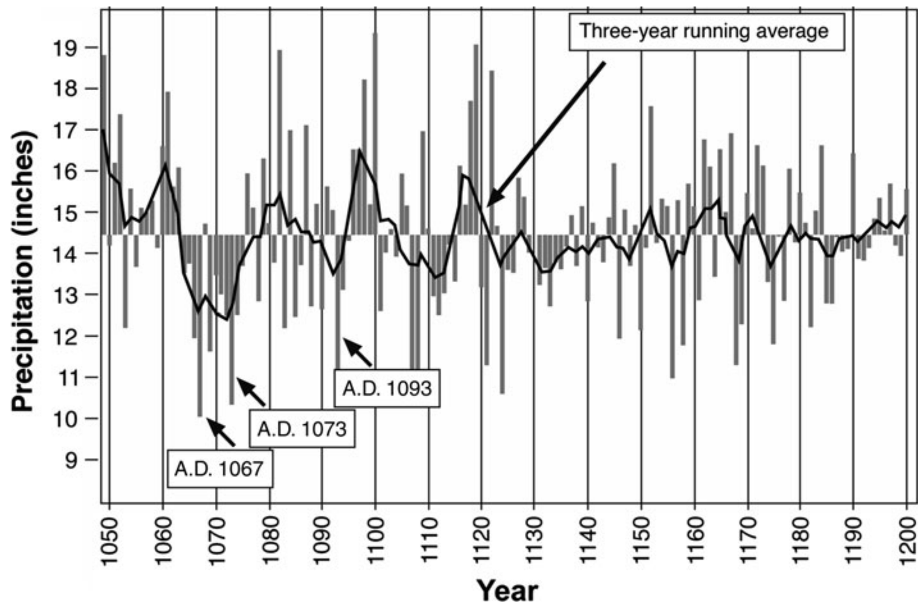


Fig. 6 Annual amounts of tree-ring reconstructed precipitation showing variation from the overall average [mean = 366.8 mm (14.44 inches), standard deviation = 46.7 mm (1.84 inches)] for the Coconino Plateau between A.D. 1049 to 1200 (data courtesy of J.S. Dean, Laboratory of Tree-Ring Research, University of Arizona; adapted from Sullivan and Ruter 2006, p. 187)

inconsequential for wild plants (perennials and annuals; Schwinning et al. 2008) but highly problematic for low-moisture-intolerant domesticated annuals, such as *Z. mays*, with inflexible growing seasons and water requirements (a minimum of 50 mm or 2 inches of rain per month for three consecutive months is needed for *Z. mays* to germinate; Muenchrath and Salvador 1995). In view of these constraints on maize production and the likelihood of crop failure, it is no surprise that direct evidence for *Z. mays* agriculture has been difficult to come by in the Grand Canyon region (Sullivan 2014).

Materials and methods: evidence of burning

Sedimentary pollen evidence

Working within this environmental framework, we present the results of recent geoarchaeological and palaeoenvironmental studies of an alluvial deposit, known as Simkins Flat, which is located south of the Grand Canyon's South Rim in Kaibab National Forest (Fig. 7; McNamee 2003). Analysis of pollen samples recovered from this axial alluvial fan revealed elevated frequencies of cheno-am (chenopod and amaranth) pollen that are correlated with the principal period of aboriginal occupation in the surrounding watershed (Roos et al. 2010; Fig. 8). The prevalence of non-arboreal pollen is replaced by arboreal pollen, a pattern that is attributable to re-colonization of the drainage catchment by trees and shrubs following the cessation of persistent understory burning as the area became abandoned (Sullivan and Ruter 2006; see also Wyckoff 1977). These patterns of pollen co-variation are consistent with the proposition that the people who ignited understory fuels intentionally influenced the yield and predictability of ruderals (see Adams and Dockter 2013), which thrive in disturbed habitats (Jelinek 1966; cf. Rösch et al. 2002). Furthermore, these patterns of pollen fluctuations cannot be explained by the incidence of wildfires, which are too infrequent to have created "opportunistic" resource patches (Huffman et al. 2009, p. 632). In fact, Huffman et al. (2008, p. 2101) conclude that the MFI (Mean Fire Interval) for a nearby study area (Tusayan) was 10.9 years with a large range (1–64 years; see also Baker and Shinneman 2004, p. 9), which is far too lengthy to provide the degree of resource reliability and economic sustainability that is reflected in the abundant macrobotanical and pollen remains we have recovered (Sullivan 1987; Sullivan and Ruter 2006). In support of this hypothesis, we now discuss the implications of data from several types of primary archaeological contexts in the area, each involving different constellations of surfaces, features, and artifact assemblages.

Archaeological evidence

Archaeological investigations of several in situ arrays of fire-cracked-rock piles and ground-stone artifacts (Cook 1995), which repose directly on prehistoric occupation surfaces, have revealed macrobotanical remains and pollen of the aforementioned ruderal species that thrive in fire-disturbed habitats (Fig. 9). Our interpretation is that the artifacts and the thermal features with which these increased frequencies are associated are the remains of extramural activity areas that were used to process chenopod, amaranth, and grass seeds, as well as pinyon nuts (*P. edulis*) in bulk quantities

Fig. 7 *Left*: Upstream panoramic view of Simkins Flat, a typical axial alluvial fan of upland areas in the northern American Southwest, bordered by pinyon–juniper woodland. *Right*: Palaeoenvironmental sample recovery from alluvial sediments at Simkins Flat

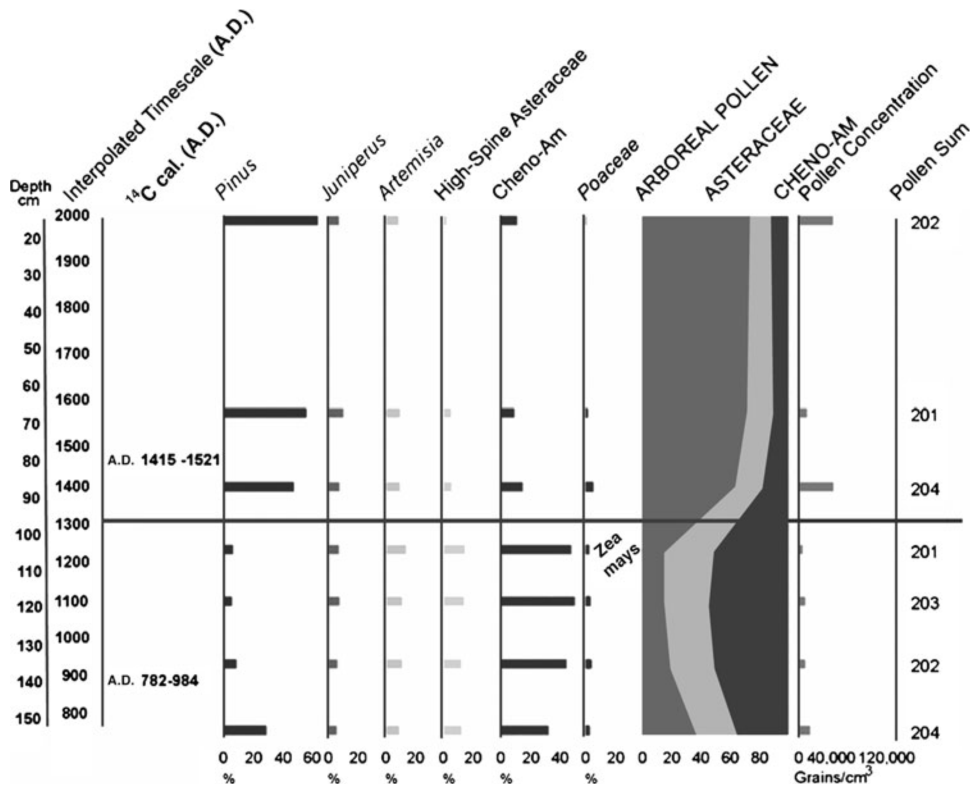


Fig. 8 Pollen diagram of Simkins Flat showing variation in non-arboreal/arboreal pollen and the relative abundance of encouraged ruderals (cheno-ams)

(Sullivan 1992); the resulting by-products were then transported to nearby settlements to be stored, and subsequently consumed (Sullivan et al. 2003). The abundance of these features across the landscape (Fig. 10) also testifies to the importance of fire-reliant ruderal-plant and pinyon-nut production and processing in the subsistence economies of these forest-dwelling populations (Greenberg 2013).

Equally compelling evidence for these inferences comes from archaeological investigations of perennial and seasonal settlements located in the same area. Excavations conducted at multi-room and multi-structure sites (Fugate 2003; Sullivan 1986), each occupied for at least a decade during the 11th century AD, yield the same picture (Fig. 11). That is, macrobotanical assemblages from storage and consumption contexts in these ruins are dominated by economically important ruderals, such as chenopod, amaranth, and grasses, as well as pinyon nuts. In contrast, little or no *Z. mays* pollen and few (if any) *Z. mays* macrobotanical remains were recovered (Sullivan 1987). Similarly, excavations of four seasonal one-room structures, considered by many Southwest archaeologists to be the remains of agricultural "field houses," have revealed no *Z. mays* pollen, and the macrobotanical and pollen assemblages are dominated by the remains of the same suite of ruderal plants (Fig. 12; Huckell 1992).

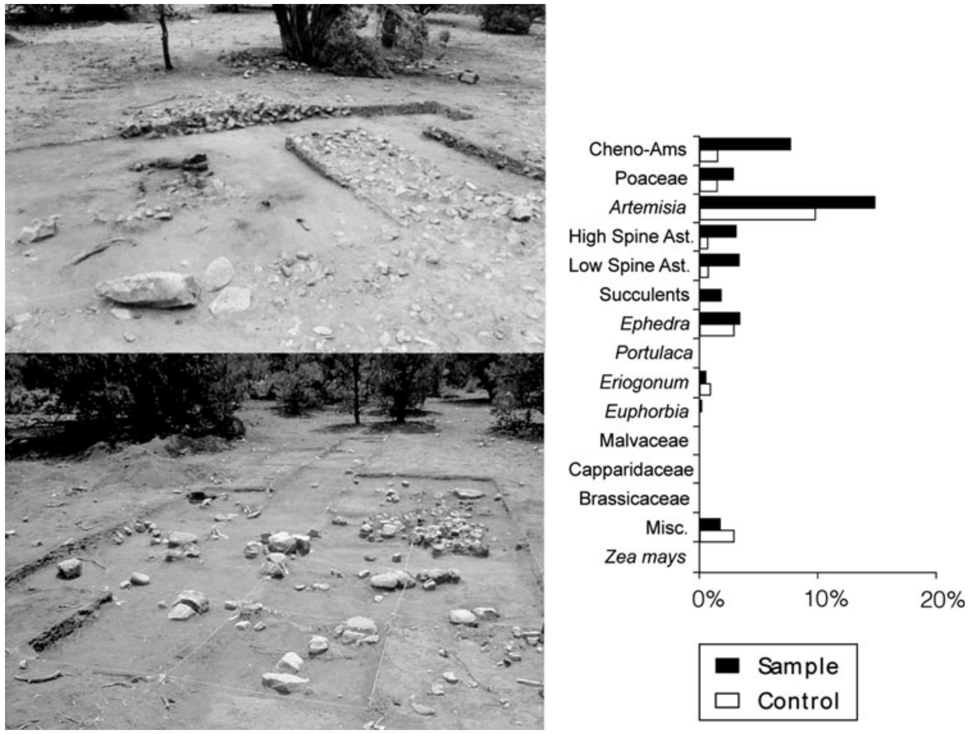


Fig. 9 *Top left*: Cross-section of fire-cracked-rock pile showing variation in the size and distribution of unsorted clasts, contact with prehistoric occupation surface, and adjacent thermal feature. *Bottom left*: View of array of ground-stone artifacts (manos and metates) and other tools on prehistoric occupation surface that were used to process seeds and pinyon nuts that had been roasted on nearby fire-cracked-rock piles. *Right*: Diagram of non-arboreal pollen recovered from sediments surrounding the processing tools in a nearby artifact array

One final strand of supporting evidence for the "ruderal" fire-farming argument comes from archaeological investigations of a series of rock alignments located near the settlements mentioned above. Analysis of pollen samples recovered from buried surfaces that had accumulated behind the alignments, typically interpreted as features designed and used for the production of *Z. mays*, revealed an abundance of "ruderal" plant pollen (Fig. 13; Bozarth 1992; Sullivan 2000). Although some would argue that ruderal pollen is attributable to the tolerance of these "weedy" disturbance plants by *Z. mays* farmers (Fish 1994), the recovery of both macrobotanical remains and pollen from these species, and not of *Z. mays*, in the domestic contexts described above, argues that they were the principal objects of production (Sullivan and Ruter 2006).

Discussion

Our focus on anthropogenic burning and it subsistence consequences reasonably leads to a consideration of some general hypotheses and embedded assumptions regarding the resource productivity and depletion potential of pinyon-juniper woodlands. From an obligate ecological perspective, it has long been assumed that the natural productivity of pinyon–juniper woodlands was limited—pinyon nut crop yields were erratic and unpredictable and concentrations of low-yielding and unreliable annuals were restricted to small patches created by environmental (non-anthropogenic) disturbances (Ford 1984, p. 129)—and that pinyon–juniper woodlands actually were rendered perennially inhabitable only because of the ecological transformations that followed the introduction of *Z. mays* agriculture (Wagner et al. 1984, p. 616). In addition, it has been argued that pinyon-juniper woodlands, once occupied perennially, were susceptible to rapid resource depletion by virtue of the need for suitably-sized trees for construction timber (Kohler 1992), fuel for domestic fires (Floyd and Kohler 1990), and the requirements of "mesa-top dry farming" where "plots cleared by burning …were quickly depleted of nutrients, water, and topsoil reserves" (Kohler et al. 2000, p. 163).

With a facultative ecological framework and the results presented above, these generalizations can be challenged, as follows. Adopting a Great Basin perspective, the advantages of which Eggan (1989) convincingly illustrated, pinyon nuts can be considered a reliable resource whose yields could be intensified with fire, among other technological solutions (Anderson 2005), and that pinyon trees do not have to be large or old to produce nuts in abundance (Lanner 1981); hence, even in the face of stand-replacing fires, younger pinyon trees that mature afterwards will contribute to the nut crop. Interestingly, Floyd and Kohler (1990, p. 154) hypothesized that, for the northern American Southwest, the economic importance of pinyon nuts could have been

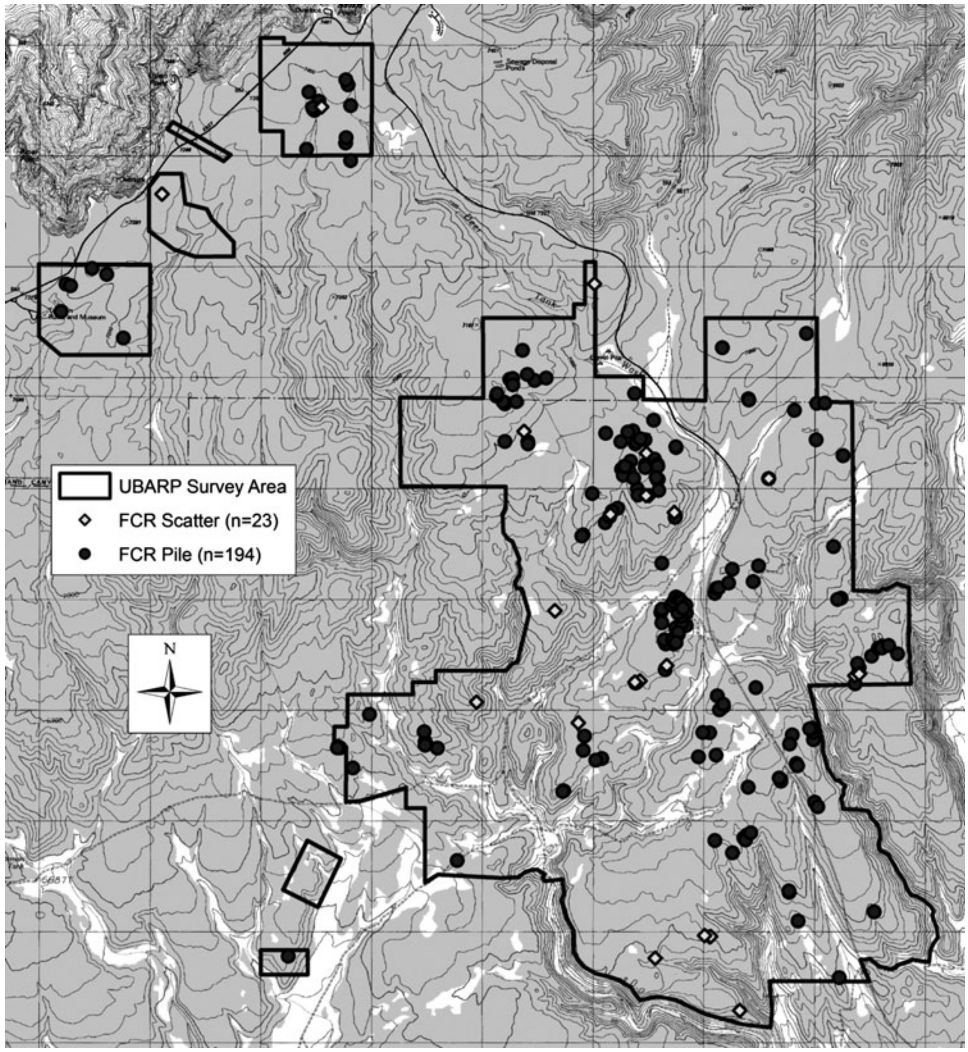


Fig. 10 Map of the regional distribution of fire-cracked-rock (FCR) piles and scatters discovered by intensive survey in the Upper Basin, northern Arizona. For geographic reference, the South Rim of the Grand Canyon runs diagonally from *upper left* to *top center* of the figure

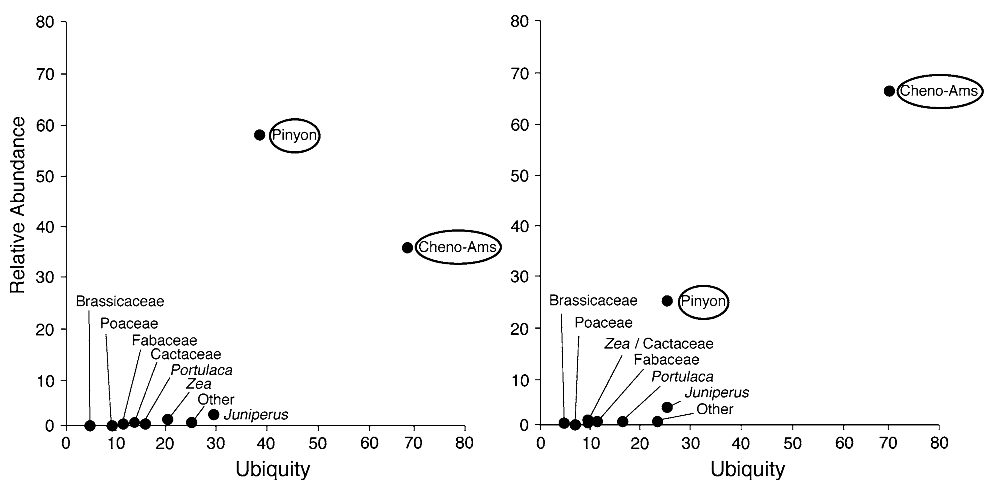
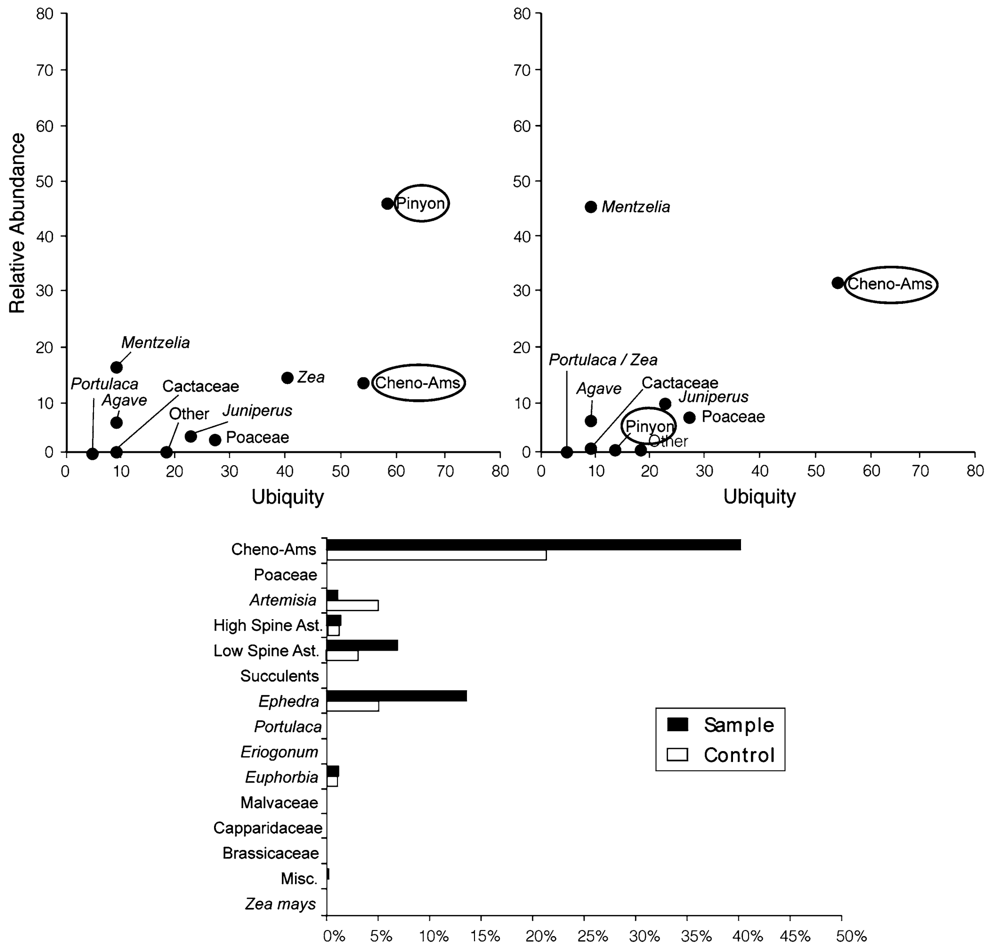


Fig. 11 *Scatterplots* of the ubiquity and relative abundance of macrobotanical remains from two perennial sites in the Upper Basin, northern Arizona. *Left scatterplot* displays variation among all macrobotanical remains (edible and nonedible, charred and uncharred), whereas the *right scatterplot* displays variation in only charred, edible plant parts

dramatically and systemically underestimated if their production and processing transpired away from perennial habitations, which is exactly what our multi-contextual evidence, described above, has confirmed (Sullivan et al. 2003; see also Fowler and Rhode 2011, pp. 242–246; Sutton 1984). As well, our data support Gaines and Gaines (2000,

Fig. 12 Macrobotanical and pollen variation of three seasonal sites in the Upper Basin, northern Arizona. *Top left*: Scatterplot of the ubiquity and relative abundance among all macrobotanical remains (edible and nonedible, charred and uncharred). *Top right*: *scatterplot* of variation among only charred, edible plants. *Bottom*: Diagram of non-arboreal pollen from a seasonal site in the Upper Basin



p. 120) contention that subsistence economies that incorporate more wild resources, such as fire-conducive ruderals that are propagated independently of *Z. mays* agriculture (cf. Ford 1984), are "less sensitive to drought" and other "random environmental impacts on food supplies" and, hence, more likely to be sustainable on an inter-annual basis (Schwinning et al. 2008). In this context, it is worth reiterating that the fire sensitivity of pinyon–juniper woodlands is dependent on fuel loads and the effects of stand management (e.g., Keeley 2002). Trees whose bases are kept free of combustible material, and whose low-hanging limbs are either pruned or removed for firewood, are essentially invulnerable to low-intensity surface fires (Anderson 2005; Ford 2000) and, hence, unlikely to register fire scars. The anthropogenic management of pinyon–juniper woodlands with repeated low-intensity burning of understory fine fuels plausibly explains the fact that only a handful of fire scars have been reported from thousands of tree-ring specimens recovered from prehistoric sites in the American Southwest (personal communication, J. S. Dean, Laboratory of Tree-Ring Research, University of Arizona, 2011).

Finally, as we have noted, the fire ecology literature and our studies do not support assertions that *Z. mays* or ruderal agriculture invariably depletes soil nutrients or other resources in pinyon-juniper woodlands (Sullivan 2000; note that Homburg and Sandor 2011 have concluded that this under-studied phenomenon currently expresses great variability inter-regionally). In addition, widespread deforestation (Kohler et al. 2005; Minnis 2000, pp. 279–280) also seems unlikely because such a practice would have decreased the potential supply of nutritious pinyon nuts; hence, it would be more reasonable to infer that pinyon-juniper woodlands were selectively thinned by cutting younger trees for construction timber. Moreover, with respect to archaeological evidence for deforestation, our intensive regional surveys, conducted during the last 25 years, have located only a handful of what generously might be regarded as stone axes or axe fragments, even

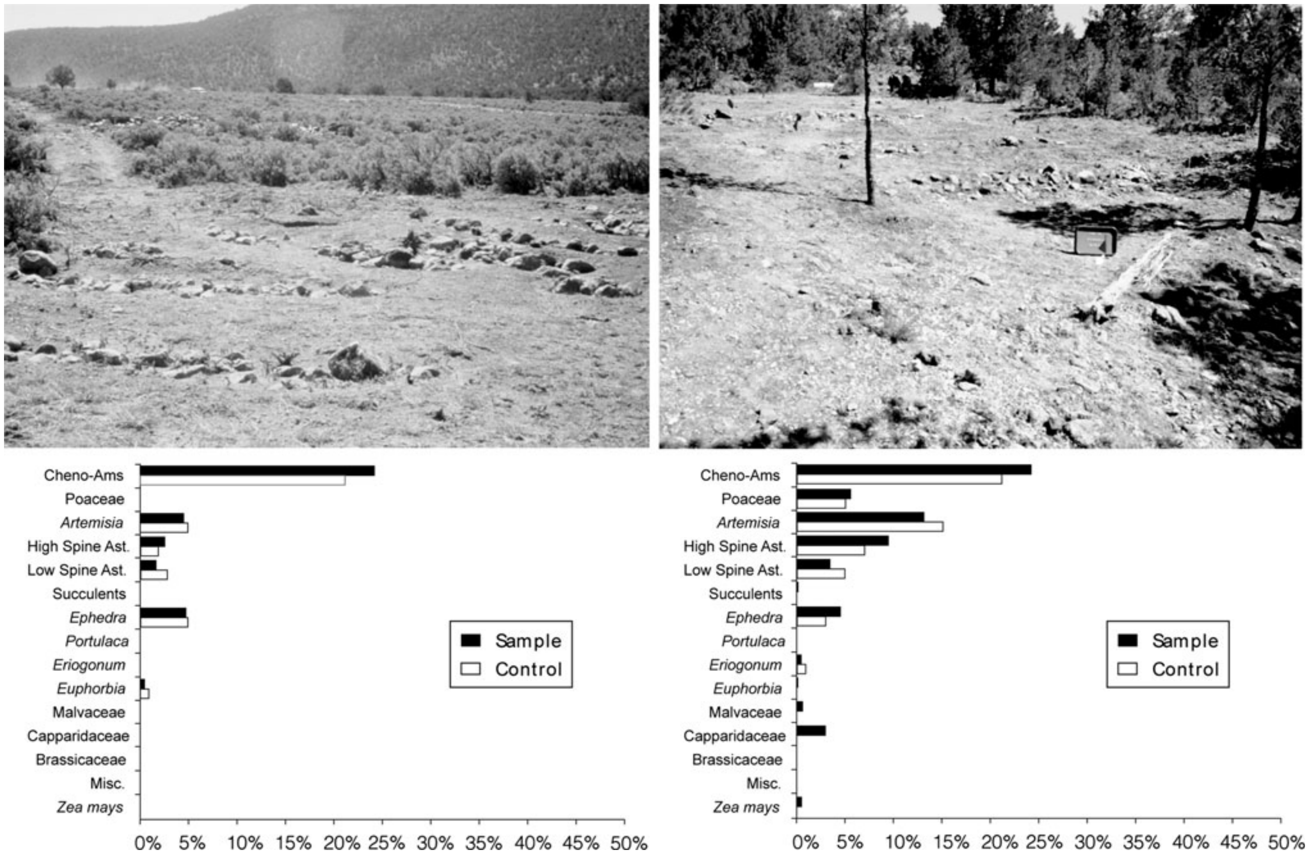


Fig. 13 Two rock-alignment complexes in the Upper Basin, northern Arizona, which are generally interpreted as agricultural terraces designed and used for corn production, and associated non-arboreal pollen diagrams

though we have found hundreds of much smaller projectile points and projectile-point fragments (Thompson 2003).

Conclusions

No matter how the data—recovered from a wide variety of independently sampled and well-dated sedimentary and archaeological contexts—are examined, the most reasonable inference regarding how ancient societies of the Southwest's pinyon-juniper woodlands sustained themselves is that they managed the successional effects of surface fires on herbaceous understory vegetation (Roos et al. 2010). Such economic burning in pinyon-juniper woodlands—applied anthropogenic fire ecology—focused on the production of ruderal species (herbs, forbs, and grasses) in pyrogenic disturbances. Not surprisingly, these inferences and supporting evidence are inconsistent with the vast bulk of ethnographic information from the American Southwest about subsistence economies that has focused on strategies for successfully propagating low-moisture-intolerant domesticated plants, such as *Z. mays*, in unforested ecosystems (alluvial fans, in this case; Bradfield 1971; Kennard 1979). The data-driven inferences we have presented align strongly with the hypothesis that, by engineering the structure of conifer vegetation communities with fire, people influenced the growth of ruderals and, with repeated burning, advantaged these species, particularly in times of drought, over domesticates (Sullivan 1996). Hence, these fire-reliant food-supply systems were largely buffered from the destabilizing effects of variable precipitation patterns, which plague the propagation of low-moisture-intolerant domesticated plants (Gaines and Gaines 2000, p. 110).

In summary, by considering regional patterns of pollen, macrobotanical, and artifact assemblage co-variation, we have established an empirical foundation that serves to broaden theoretical models about subsistence practices in coniferous ecosystems, principally by expanding the range of possibilities beyond what ethnographers have recorded and what archaeologists have proposed concerning the cultivation of low-moisture-intolerant domesticated plants based on obligate ecological models (Kehoe 1981). At the least, by building strong archaeological arguments that focus on the facultative role of fire in the production of ruderal plants, we can profitably investigate the options that ancient societies deployed to increase the security of their food supply, and thereby understand the degree to which human history has been forged by fuel-load and ignition-management strategies.

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