

# THEORETICAL AND SOCIOECOLOGICAL CONSEQUENCES OF FIRE FOODWAYS

Alan P. Sullivan III and Philip B. Mink II

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*Archaeological investigations of the effects of anthropogenic fire on the subsistence economies of small-scale societies, particularly those of the prehispanic northern American Southwest, are embryonic in scope and disciplinary impact. When burning has been mentioned in such studies it typically has been with reference to its alleged effectiveness in clearing land or deforesting areas for maize agriculture. In this article, in contrast, we present the results of our initial efforts to estimate the yield and socioecological consequences of cultivating a common fire-responsive ruderal—amaranth—whose growth is enabled by anthropogenic burning of understory vegetation in the Southwest's pinyon-juniper ecosystems. With data from the Upper Basin (northern Arizona), we show that, in an area that is not environmentally conducive to maize production, populations could be supported with systematic, low-intensity anthropogenic fires that promoted the growth of amaranth and other ruderals, such as chenopodium, which consistently dominate archaeobotanical and pollen assemblages recovered from a variety of archaeological and sedimentary contexts in the region. Based on this evidence, as well as modern fire ecological data, we propose that fire-reliant ruderal agriculture, in contrast to maize agriculture, was a widespread, sustainable, and ecologically sound practice that enhanced food supply security independently of variation in soil fertility and precipitation.*

*Las investigaciones arqueológicas sobre los efectos de los incendios antropogénicos para las economías de subsistencia de las sociedades de pequeña escala, especialmente aquellas de la zona norte del suroeste norteamericano en la época precolombina, se encuentran todavía en un estado naciente y tienen poca influencia en la disciplina. Cuando se mencionan los incendios en tales estudios, es típicamente en referencia a su supuesta eficacia para el desmonte o la deforestación de tierras antes de sembrar maíz. En contraste, en este artículo presentamos la primera estimación del rendimiento y de las consecuencias socio-ecológicas del cultivo de amaranto, una especie ruderal común cuyo crecimiento incrementa en respuesta al incendio antropogénico de la vegetación del sotobosque en el ecosistema piñón-junípero del suroeste norteamericano. Con datos procedentes de la cuenca superior del Río Colorado, en el norte de Arizona, demostramos que en áreas marginales para la cultivación del maíz las comunidades agrícolas pudieron causar incendios de baja intensidad para promover el crecimiento del amaranto y otros ruderales tales como el quenopodio—plantas que dominan las muestras de polen arqueológico en sedimentos encontrados en esta región. Con base en esta evidencia y en datos recientes sobre la ecología del fuego, planteamos que una agricultura ruderal dependiente de los incendios, en contraste con el cultivo del maíz, fue generalizada, sostenible, ecológicamente saludable, e incrementó la seguridad de la provisión de alimentos independientemente de variaciones en la fertilidad de la tierra y precipitación.*

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**C**ross-disciplinary understanding of the transformative effects of anthropogenic landscape fire on ecosystems, their structure, and associated “services” has accelerated dramatically in recent decades (e.g., Bowman et al. 2009). Thinking globally about these developments in the context of human prehistory, it is

rare for modern research regarding human-environment interactions not to mention anthropogenic fire as one of the principal ecosystem-shaping forces during the Pleistocene and Holocene (Supplemental Text 1). Archaeological studies worldwide, ranging from the Upper Paleolithic (Haws 2012:72) and Mesolithic (Mason 2000) in Western

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Europe, to the early Neolithic in Southeast Asia (Hunt and Rabett 2014:26), to the late Holocene in eastern North America (Abrams and Nowacki 2008), indicate that human-controlled fire influenced the nature of social formations and food supply systems of the ancient and modern worlds (Bond and Keeley 2005). These investigations are especially timely in view of the current attention directed at the contributions of fire-induced particulates to climate change (Han et al. 2016) and the continuing controversy over whether the onset and duration of the Anthropocene (Braje 2015) should be defined in terms of atmospheric chemistry (Ruddiman 2013) or domestication processes (Smith and Zeder 2013).

Interestingly, these studies are unified by a topic with deep historical roots and broad interdisciplinary connections—understanding the relation between anthropogenic landscape fire ecology and subsistence economies (Supplemental Text 2). As many environmental historians have remarked, appreciating the ecological dynamics and evolutionary consequences of this entangled relationship intrinsically engages archaeology (e.g., Bonnicksen 2000). However, archaeological data that reflect the extent to which humans persistently employed landscape fire for subsistence purposes are “surprisingly scarce” (Scherjon et al. 2015:321). One complicating factor is that, despite the rich ethnographic, ethnohistoric, and historic accounts of humans igniting landscape fires for a variety of reasons (Supplemental Text 3), including wild plant husbandry, game management, and pest control (Huffman 2013; Roos 2017), such descriptions provide few details that archaeologists can draw upon to inform their investigations of anthropogenic fire and its economic aftermath (Lightfoot et al. 2013:286).

One approach that has gained considerable attention in the American Southwest, however, is *applied historical ecology* (Swetnam et al. 1999), which infers the effects of landscape burning by examining “paleofire proxies,” such as fire scar, sedimentologic, palynological, and geoanthracological (detrital charcoal) records, and carbon isotope ratios of soil organic matter (French et al. 2009; Roos 2015). The results of these theoretically robust and empirically rich studies demonstrate that anthropogenic landscape burning was indeed a transformative landscape

management and ecosystem-structuring technique (Liebmann et al. 2016; Roos and Swetnam 2012). Nevertheless, the applicability of applied historical ecology is constrained by the “fading record” problem (e.g., most fire scar records in the American Southwest postdate AD 1500; Fulé et al. 2003) and by the likelihood that knowledge of the range of fire regimes may be historically biased because of the “no analogue” problem (Swetnam et al. 1999:1192, 1198).

We see these issues, however, as opportunities to expand the usefulness of applied historical ecology by exploring the possibility that, in regions prone to the record-fading and no-analogue problems, such as the Coconino Plateau and Grand Canyon (Williams and Baker 2013:298), the effects of low-intensity anthropogenic fire would register in archaeobotanical remains recovered from well-dated archaeological contexts (Miller and Tausch 2001:17). Specifically, we posit that people intentionally burned understory vegetation in Southwestern pinyon-juniper woodlands to produce fire-responsive ruderals (Sullivan 2015) that, once harvested, processed, and discarded in a variety of locations, became concentrated in and around now-abandoned settlements (Yarnell 1965). This proposition underscores the centrality of incorporating direct evidence from the archaeobotanical record in establishing the role of fire in economic prehistory (Smith 2014:369), particularly for those periods of occupation in the American Southwest for which there is scant ethnographic documentation for fire-related subsistence practices (Roos 2017; Sullivan and Forste 2014).

Our objective here is to illustrate the explanatory potential of the fire foodway model for the American Southwest’s vast pinyon-juniper woodlands,<sup>1</sup> which, in contrast to maize (*Zea mays*) agriculture, takes advantage of the principles of fire ecology and aligns with the existing archaeobotanical record (Ford 1981:6). We first discuss the key elements of current maize agriculture farming models for pinyon-juniper woodlands, which intrinsically do not consider burning a cultivation method (except for land clearing; Crabtree et al. 2017:125; Wyckoff 1977). Next, adopting the basic structure of maize farming and productivity models (Bocinsky and Varian 2017; Kohler 2012), we determine the per capita

caloric intake needed to sustain one individual on only one ruderal species (amaranth; *Amaranthus* spp.), derive population estimates for one human generation (25 years), and develop productivity estimates for amaranth to support various levels of population during different periods of occupation in the Upper Basin. Then, we introduce the fire foodway model of ruderal cultivation, which is based on two well-secured ethnographic findings: (1) creating anthropogenic niches with burning is a common ecosystem-transforming technique worldwide (Smith 2011), and (2) burn plots established within anthropogenic niches, whose use is rotated on a two- to three-year cycle, take advantage of the invariable appearance of ruderals during the earliest postburn successional cycle (Everett and Ward 1984). Finally, inspired by firsthand contemporary observations of how ruderals predictably respond to a variety of fire types, severity, and origin, we offer some thoughts about how these considerations have the potential to integrate *applied historical ecology* and *niche construction theory* to enrich our narratives of past human-environment interactions and economic prehistory in the American Southwest.

### Maize Farming in Pinyon-Juniper Woodlands

Maize productivity modeling studies for pinyon-juniper woodlands in the upland Southwest are based on the following propositions:

- Pinyon-juniper woodlands were characterized by low primary productivity with “slowly regenerating resources” (Kohler et al. 2012:31) and were inhabitable on a perennial basis only after the introduction of maize agriculture (Ford 1984:128–130).
- Maize production was the principal (if not exclusive) mode of subsistence (Bocinsky and Varien 2017:282–283; Spielmann et al. 2011), and maize consumption accounted for at least 60% to 77% of an average person’s diet per annum (Crabtree et al. 2017:117; Van West and Lipe 1992:112).
- Climatic variation and soil fertility profoundly affected maize production and related cultural dynamics (Kohler et al. 2005).
- Maize farming occurred largely on the surfaces of alluvial deposits (especially floodplains; Dean 1996:37), dunes, or mesa tops (Bellorado and Anderson 2013; Kohler et al. 2000:163).
- Frequent, low-intensity anthropogenic fires in pinyon-juniper woodlands were rare (or did not register unambiguously in paleofire proxy data; Allen 2002; Floyd et al. 2003:268–275), although human populations may have taken advantage of “patchy *natural* openings in the pinyon and juniper forest caused by fire” (Ford 1984:129; emphasis added).

### Discussion

The fire foodway model does not rely on any of these assumptions but is informed, instead, by two understandings. First, the production of fire-responsive (or fire-stimulated [Nabhan et al. 2004:18–19]) economic plants, such as amaranth, chenopodium (*Chenopodium* spp.), and various grasses (Bohrer 1975), promotes a secure livelihood in conditions that are considered marginal for maize farming (e.g., Benson et al. 2013; Sullivan 1996). These ruderals, which typically colonize and thrive in human-created disturbances or niches (Smith 2014), have been (1) categorized as weeds or inadvertent by-products of maize farming (e.g., Ford 1984), (2) designated as starvation or famine foods (Minnis 1991), or (3) asserted to have been rarely (if ever) cultivated or the focus of sustained cultivation (e.g., Plog et al. 2015:11) despite widespread archaeological evidence to the contrary (Table 1; Fritz 2007:289–291). In fact, the single plant we focus on here, amaranth, has a history of cultivation and use that is as long as that of maize (Supplemental Text 4), and its yield “per unit of land may be greater than that of corn” (Jones 1953:91; see also Bohrer 1962:108). Ethnographic (Anscheutz 2006) and ethnobotanical (Bye 1981) studies likewise attest to the economic significance of amaranth, as well as chenopodium, in ancient and modern Southwestern subsistence economies (Doolittle 2000:95; Ford 2000:217; Morrow 2006:22). Second, Southwest archaeologists have rarely thought of fire itself as an applied technology for direct food production (e.g., Adams and Fish 2011:167–170), even though such applications

Table 1. Archaeological Studies that Mention Amaranth, Chenopodium, or “Cheno-ams” as Cultivated or Economically Significant Plants in the American Southwest.

| Locality                        | Site                     | Plant Part   | Age/Date               | Reference                   |
|---------------------------------|--------------------------|--------------|------------------------|-----------------------------|
| Southwest Colorado              | Site 22 (La Plata)       | Seeds        | Basketmaker III        | Jones and Fonner (1954)     |
| Southwest Colorado              | Johnson Canyon           | Seeds        | Pueblo III             | Cummings (1995)             |
| West-central New Mexico         | Grants 1 Dune            | Seeds        | 6880 ± 400 BP          | Agogino (1960:46)           |
| Northeast New Mexico            | Cimarron District sites  | Seeds        | Basketmaker II and III | Kirkpatrick and Ford (1977) |
| South-central New Mexico        | High Rolls Cave          | Chaff        | 2640 ± 40 BP           | Bohrer (2007:221)           |
| Northern New Mexico             | Salmon Ruin              | Seeds        | AD 1088–1094           | Doebley (1981)              |
| East-central New Mexico         | Pecos River Valley sites | Pollen       | AD 900–1250            | Jelinek (1966)              |
| Central Arizona (Tonto Basin)   | Tonto Ruins              | Seeds        | AD 1350–1400           | Bohrer (1962)               |
| Central Arizona (Phoenix)       | Los Canopas              | Seeds        | AD 500–1470            | Fritz et al. (2009)         |
| Northern Arizona (Flagstaff)    | Lizard Man Village       | Seeds        | AD 1064–1250           | Hunter (1997)               |
| Northern Arizona (Wupatki)      | Sunset Crater Ashfall    | Pollen       | AD 1150–1250           | Berlin et al. (1990)        |
| Northern Arizona (Grand Canyon) | Upper Basin sites        | Seeds/pollen | AD 1049–1080           | Sullivan and Ruter (2006)   |
| East-central Arizona            | Hay Hollow site          | Seeds/pollen | 300 BC-AD 300          | Bohrer (1972)               |
| East-central Arizona            | Broken K Pueblo          | Pollen       | AD 1150–1280           | Hill and Hevly (1968)       |

Note: Studies presented in this table were selected to maximize spatial and temporal variability and date of publication.

are common worldwide (Dods 2002; Roos et al. 2016:4–5).

### Suitability of the Upper Basin for Maize-Based Foodways

Our study area is the Upper Basin, which is a downfaulted and tilted graben of the Coconino Plateau that extends south of the eastern South Rim of the Grand Canyon (2,256 m asl at Desert View) to the base of the Coconino Rim (1,859 m asl at Lee Canyon; Figure 1). Today, the Upper Basin is blanketed by a dense pinyon-juniper woodland (Vankat 2013) that becomes intermixed with ponderosa pine on its western edge but grades to grassland farther south (Darling 1967). Like so many areas in the upland Southwest occupied between AD 875 and 1200 (Euler 1988), the Upper Basin is thickly stocked with abandoned one- to two-room structures and other features, such as rock alignments and terraces (Sullivan et al. 2015), which conventionally have been interpreted as landscape signatures of maize production (e.g., Effland et al. 1981; Stewart and Donnelly 1943). However, these appearances are deceiving when we examine the area’s modern and ancient environmental characteristics and its archaeo-economic record and evaluate the extent to which they align with the attributes of maize-based foodways.

### Soils

Pinyon-juniper woodlands are notorious for establishing themselves on nutrient-poor soils (West 1999:289), and the Upper Basin is no exception. Surface material ranges from bedrock and very cobbly/very gravelly loams in the Upper Basin’s upper and central reaches (considered “agriculturally unsuitable” according to the Natural Resources Conservation Service; Lindsay et al. 2003; Merkle 1952:377) to very gravelly/gravelly sandy loams in its lower reaches (suitable only for rangeland after “conversion;” Figure 2; Brewer et al. 1991). Soil chemical and texture analyses of archaeological terrace sediments (Homburg 1992; Sullivan 2000) attest to the Upper Basin’s thin and rocky soils (Hendricks 1985). Pollen analyses of these anthropogenic terrace sediments yielded only a dozen or so *Zea mays* pollen grains (<0.5%) out of thousands examined, and two sets of samples contained no maize pollen whatsoever (Bozarth 1992; Davis 1986).

### Precipitation

With respect to the other major constraint on maize production—water availability during the frost-free growing season—hydrologic studies in the Upper Basin confirm that runoff from rainfall or snowmelt is negligible (Rand 1965:13–14), which means that water cannot be directed

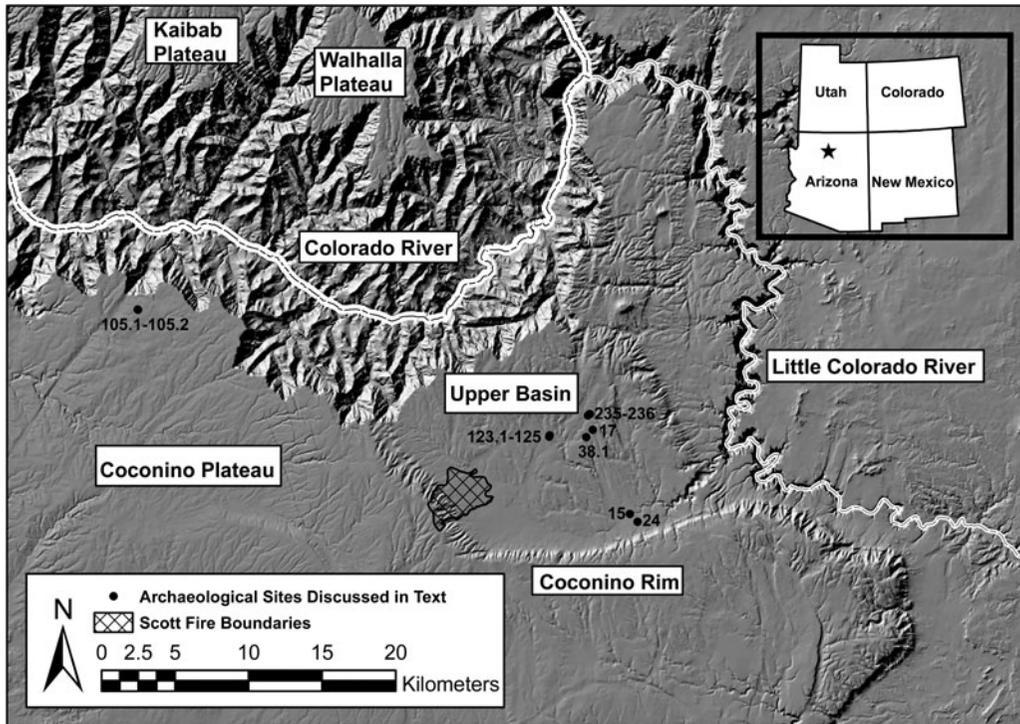


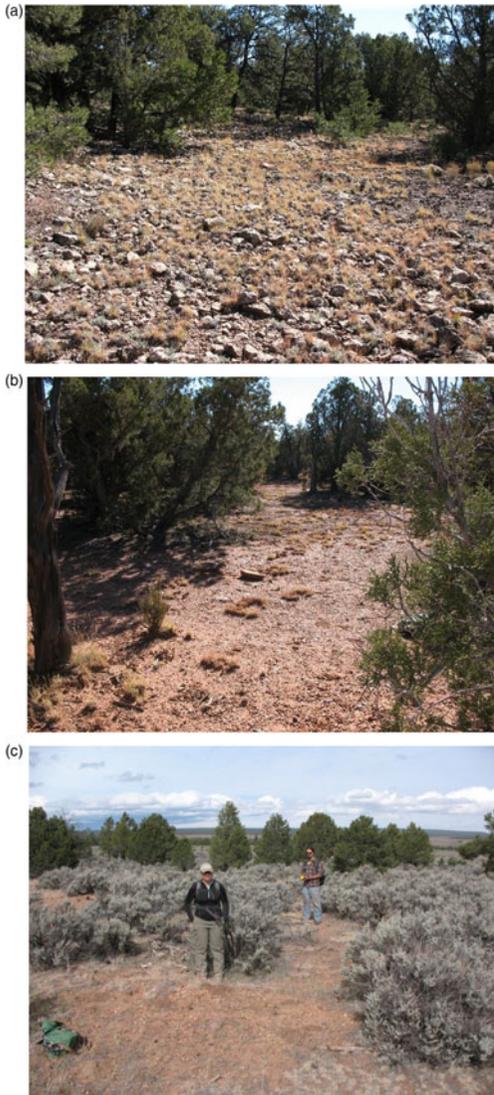
Figure 1. Location of the Upper Basin, northern Arizona, showing excavated sites and area burned by the Scott Fire.

to where it might be needed for maize production (Metzger 1961; cf. Benson 2011:40–41). Further, interannual variation in the Upper Basin’s paleoprecipitation patterns was so unpredictable (Sullivan and Ruter 2006:185–188)<sup>2</sup> that, given the sensitivity of maize to the timing and amount of rain it needs to germinate (Adams 2015:29–32), successful harvests were undoubtedly uncommon events (Schwartz et al. 1981:121; see also Bocinsky and Varien 2017:299). On the other hand, importantly, even the lowest values of tree ring–reconstructed annual precipitation for the Upper Basin, that is, 25.4 cm in AD 1067, are more than adequate to ensure the survival of ruderals, such as amaranth (Salt Spring Seeds 2014:3) or chenopodium (*Chenopodium quinoa* [Smith 2017:2]).

### Discussion

In terms of soil fertility and frost-free precipitation, the two principal factors stipulated in maize productivity modeling studies, the Upper Basin’s pinyon-juniper woodland is a “hostile”

environment that is ill-suited for maize production, even during the best of times (i.e., when annual precipitation equaled or exceeded the average of 36.6 cm). It is hardly surprising, therefore, to learn that no ethnographic, ethnohistoric, or historic accounts mention maize farming in the Upper Basin or on the eastern Coconino Plateau by Native Americans or Euro-Americans (Begay and Roberts 1996:199–202; Cleeland et al. 1990; Hough and Brennan 2008; Martin 1985). These factors explain, as well, why we have encountered negligible amounts of maize remains such as botanicals or pollen (for comparable results from Black Mesa, see Ford 1984:131; Ruppé 1985:521) in archaeological contexts that typically are associated with maize farming in the upland Southwest (Sullivan and Forste 2014). In fact, no matter which consumption or production contexts are examined—structures or processing areas (Supplemental Table 1)—the archaeo-economic assemblages from them are overwhelmingly and consistently dominated by ruderal seeds and pinyon nuts (Figure 3).



**Figure 2.** Agriculturally unproductive soils in the Upper Basin: (a) bedrock and very cobbly loam; (b) cobbly and very gravelly sandy loam; (c) very gravelly/sandy loam. (Color online)

### Suitability of the Upper Basin for Fire-Based Ruderal Foodways

#### *Estimating Amaranth Consumption and Production*

To illustrate the feasibility of the fire foodway provisioning strategy, we estimate how much amaranth would be required to support one person for a year. This estimate is based on the same

parameters featured in numerous maize-based productivity studies and, therefore, involves the following considerations (based on Kohler et al. 2000:160; Pool 2013:96; Van West and Lipe 1992:111):

- One person requires at least 2,000 kcal/day, which is roughly the midpoint in the published range for preindustrial populations (1,560 to 2,550 kcal/day).
- Sixty-nine percent of the annual diet was amaranth, which is roughly the midpoint of the published range for maize consumption (60% to 77%).
- One kilogram of amaranth yields 3.7 kcal (Putnam et al. 1989:4), which is comparable to maize (3.5 kcal/kg).

With these understandings, one person would require 0.37 kg of amaranth per day, or 136 kg per year.

Although estimates for amaranth (and, for comparison, chenopodium) productivity vary widely, ranging from 340.25 to 4,310 kg/ha (Supplemental Table 2), we chose the lowest yield value (Amaranth 2) because it is from modern hand-cultivated amaranth farming, which we think more closely approximates prehistoric cultivation practices. Adoption of this value means that 0.40 ha (ca. 1 ac) of land would be needed to produce enough amaranth to satisfy one person's needs per year.

#### *Estimating Population*

To estimate the number of people that amaranth could have supported between AD 875 and 1200 in the Upper Basin, we projected the number of room spaces ( $n = 886$ ) that surveys have recorded (Foust 2015) and “time-corrected” it to yield the number of architectural spaces per 25-year period (Downum and Sullivan 1990), or roughly one human generation (cf. Roberts 2011:13). These “corrections” allow us to maximize population in the face of Grand Canyon’s complicated and incompletely understood population history, which involves several groups (Cohonina, Virgin Anasazi [sensu Euler 1992], and Grand Canyon Anasazi [sensu Schwartz 1990]) whose perennial settlements were occupied no longer than 10–15 years (Mink 2015;

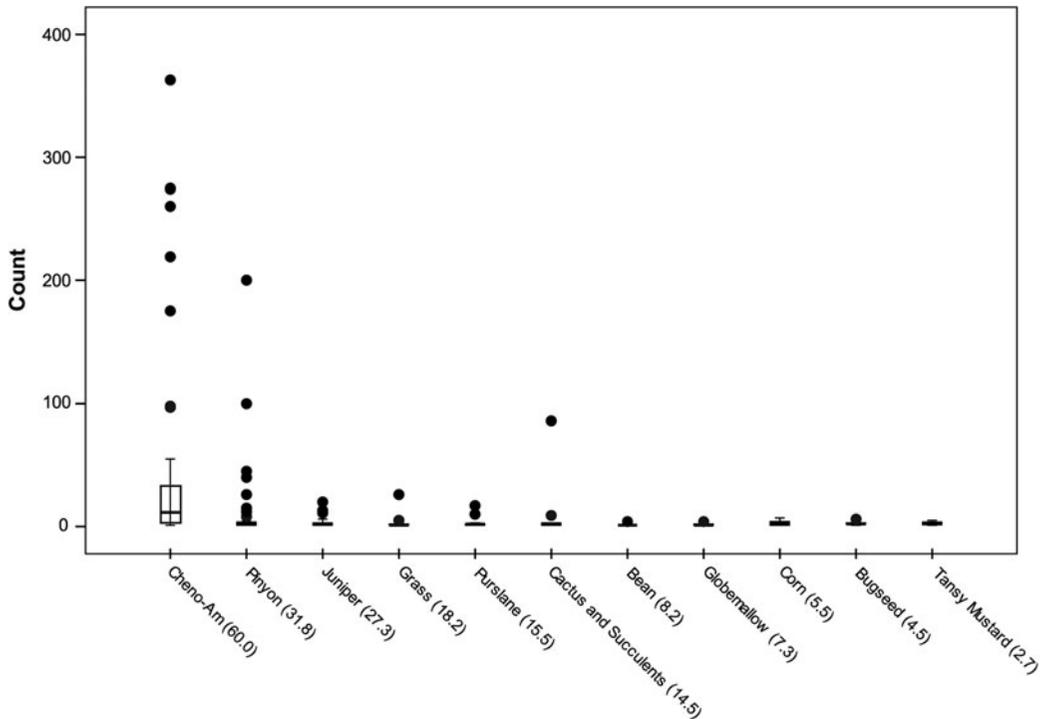


Figure 3. Variation in the abundance and ubiquity of seeds and nuts ( $n = 3,485$ ) identified in 110 samples recovered from features (postholes, thermal features, fire-cracked rock piles), artifacts (vessels, grinding stones), and occupation surfaces at 10 archaeological sites in the Upper Basin and Grand Canyon National Park (see Supplemental Table 1 for details). Each dot represents the frequency of nuts or seeds in a single sample, broken down by taxon (seeds classified by different archaeobotanists as cheno-am seeds, amaranth seeds, or chenopodium seeds are aggregated as “Cheno-am”). The data do not include counts of indirect indicators of plant use, such as cone scales, seed coats, nutshell, bark, needles, stems, leaves, wood, or cupules. This method was selected because it tightly constrains frequencies of edible plant parts—seeds or nuts—that in all likelihood were the objects of wild plant cultivation, wild plant gathering, or domesticated plant cultivation (Sullivan et al. 2015:44). Ubiquity values are given in parentheses.

cf. Matson et al. 1988:253–254; Ortman et al. 2016:235).

Next, we calibrated the time-corrected room counts by a perennial occupancy rate. This calculation involved dividing the number of structures ( $n = 324$ ) whose artifact density exceeded seven artifacts/m<sup>2</sup> (based on an excavated perennial settlement [Sullivan 2008]) by the number of room spaces ( $n = 604$ ) for which we have controlled, standardized artifact inventories (Uphus 2003). To convert time-corrected and perennially occupied room counts into numbers of people, we multiplied those values by 2.5 (which is the average interior floor area of 226 single-room structures [13.8 m<sup>2</sup>] divided by 5.6 m<sup>2</sup>/person [Liebmann et al. 2016]). These estimates over-represent the maximum number of people to be fed during any year (Supplemental Text 5).

Finally, these figures were multiplied by 0.40 ha to yield the maximum number of hectares to be cultivated per year to sustain the estimated population on amaranth alone (Figure 4).

### Managing Fire-Foodway Ecological Impacts on the Landscape

In modeling the ecological impact of fire-based amaranth production, our assumption is that the Upper Basin’s occupants ignited many small fires rather than a few large conflagrations (Adams 2011:125; Scherjon et al. 2015:309). To constrain these estimates further, we rely on Mellars’s (1976) classic article in which he posits that, for pinyon-juniper woodlands in northern Arizona, a burn plot no larger than 400 m in diameter (12.6 ha) maximizes ruderal

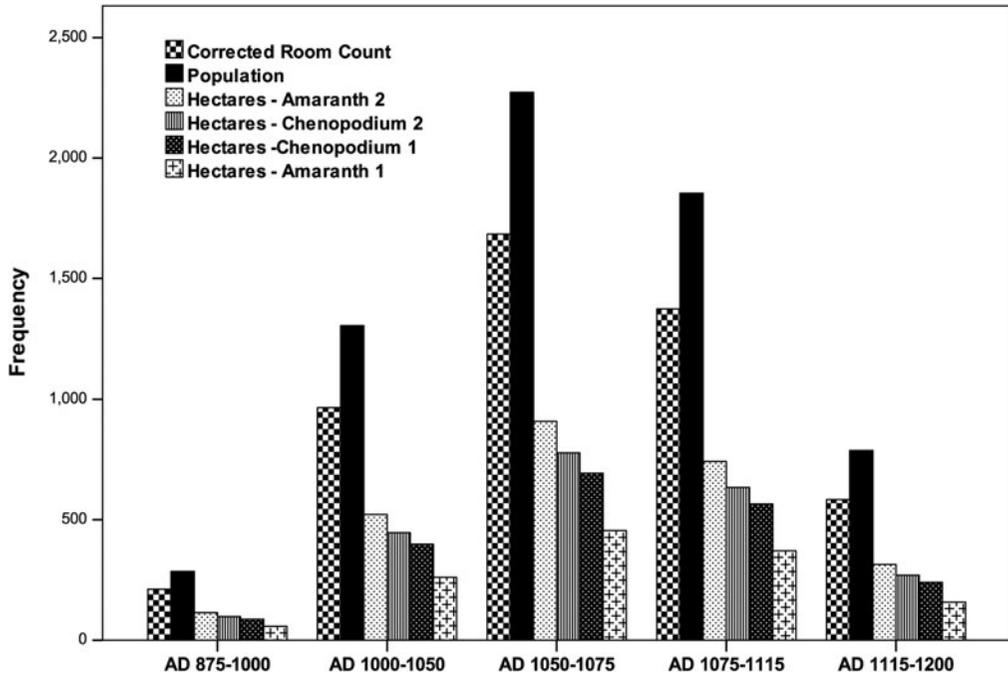


Figure 4. Estimated time-corrected room counts, annual population, and hectares to be cultivated under different yields (kg/ha) of amaranth and chenopodium (based on data in Supplemental Table 2).

production. Applying this figure to the quantities of amaranth needed to support varying numbers of people, based on differing productivity estimates, means that between five and 72 400 m diameter fires would have to be ignited per year (Table 2), burning at most no more than 4.2% of the Upper Basin (218.73 km<sup>2</sup>, excluding unburnable locations, such as bedrock and rock-filled drainages).

Combining the facultative ecological orientation of niche construction theory with the methodological robustness of applied historical ecology, we propose that anthropogenic niches 1.1 km in diameter (0.95 km<sup>2</sup>) were established to enable the ignition of 400 m diameter burn plots within which ruderal production occurred (Figure 5; this configuration is comparable conceptually to the 200 m<sup>2</sup> [4 ha] cells that have been used for maize production modeling in southwest Colorado [e.g., Kohler and Van West 1996:179]). Furthermore, we suggest that to ensure sufficient fuel accumulation to carry low-intensity surface fires, to avoid nutrient depletion that would arise from overuse, and to prevent the establishment of shrubs in the burn plots (which

would decrease yields and reduce species diversity; Huffman et al. 2013), each burn plot would have been used only once every three years, which is a rotational pattern that aligns with pinyon-juniper ecological succession patterns (Wagner et al. 1984:617) and ethnographic accounts (Myers and Doolittle 2014:13; Roos 2017:689–690).

As a measure of the sustainability and low ecological impact of the fire foodway model, we predict that through time, burn plots within anthropogenic niches were deactivated and anthropogenic niches were abandoned altogether as population declined (Figure 6). For instance, if we focus on the yields for Amaranth 2 (Table 2), nine burn plots would have been established initially in nine anthropogenic niches between AD 875 and 1000. Thereafter, as population increased, the original nine anthropogenic niches would have been supplemented by 33 new ones during AD 1000–1050 and with 30 new ones during AD 1050–1075. After AD 1075, our figures indicate that no new anthropogenic niches needed to be established and, importantly, burning in previously established niches and their associated burn plots would have declined at an accelerating rate, thereby conserving the woodlands

Table 2. Estimated Number of Fires Needed per Year Based on Different Productivity Estimates for Amaranth and Chenopodium.

| Period <sup>a</sup> | Population | Amaranth 1<br>(0.20) <sup>b</sup> |       | Chenopodium 1<br>(0.305) <sup>b</sup> |       | Chenopodium 2<br>(0.342) <sup>b</sup> |       | Amaranth 2<br>(0.40) <sup>b</sup> |       |
|---------------------|------------|-----------------------------------|-------|---------------------------------------|-------|---------------------------------------|-------|-----------------------------------|-------|
|                     |            | Ha                                | Fires | Ha                                    | Fires | Ha                                    | Fires | Ha                                | Fires |
| 1                   | 285        | 57.0                              | 5     | 86.9                                  | 7     | 97.5                                  | 8     | 114.0                             | 9     |
| 2                   | 1,304      | 261.0                             | 21    | 398.0                                 | 32    | 446.0                                 | 36    | 522.0                             | 42    |
| 3                   | 2,273      | 455.0                             | 36    | 693.3                                 | 53    | 777.4                                 | 62    | 909.0                             | 72    |
| 4                   | 1,854      | 371.0                             | 30    | 565.5                                 | 45    | 634.1                                 | 51    | 742.0                             | 59    |
| 5                   | 788        | 158.0                             | 13    | 240.3                                 | 20    | 69.5                                  | 22    | 315.0                             | 25    |

Note: Estimated fires are 400 m in diameter. See Supplemental Table 2 for background data.

<sup>a</sup>Period 1 = AD 875–1000; Period 2 = AD 1000–1050; Period 3 = AD 1050–1075; Period 4 = AD 1075–1115; Period 5 = AD 1115–1200.

<sup>b</sup>Value in parentheses indicates productivity estimate in hectares per person per year (ha/person/year).

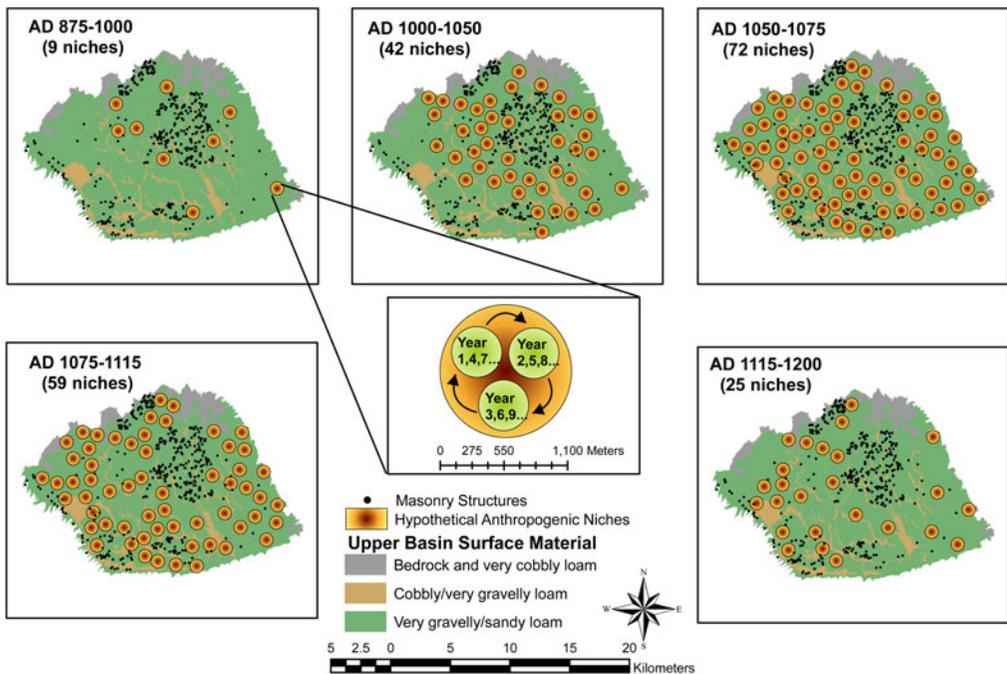


Figure 5. Randomly placed, spatially scaled anthropogenic niches (1.1 km in diameter), with insert showing embedded burn plots (400 m in diameter) by time period in the Upper Basin.

and their economic resources (cf. Peeples et al. 2006).

**The Archaeological Significance of the 2016 Scott Fire**

Sometime shortly after midnight on June 28, 2016, a lightning strike ignited the Scott Fire in the western reaches of the Upper Basin (Figure 1).

By the time the fire was suppressed on July 18, 2016, a total of 1,076.5 ha had burned, much of it so severely that the woodland was destroyed (Figure 7), a consequence of high fuel loads attributable to fire exclusion and suppression, among other factors (Fulé 2010:376; Vankat 2013:278–281).

The Scott Fire is significant for the fire foodway model in several respects. First, to provide a

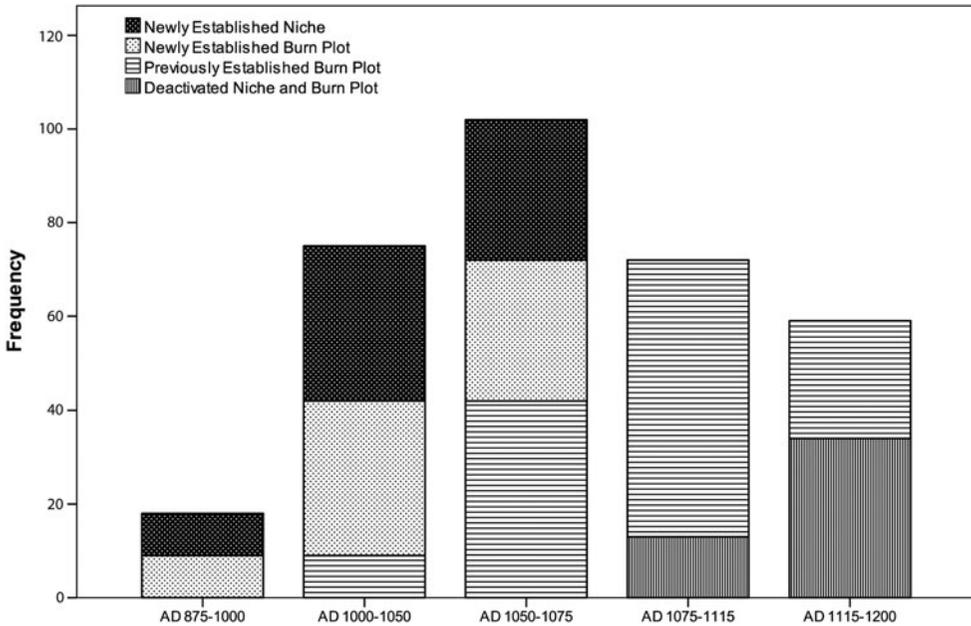


Figure 6. Dynamics of anthropogenic niche and burn plot establishment and abandonment in the Upper Basin through time.



Figure 7. Upper Basin pinyon-juniper woodland (a) before (2008) and (b) after (2017) the lightning-caused Scott Fire (2016). (Color online)

sense of scale in considering the effects of food fires on landscapes, the area burned by the Scott Fire is larger than the highest estimated number of hectares burned based on Amaranth 2 yields, 909 ha (Table 2). Second, as Figure 8 shows, by spring 2017, significant portions of the burned area were covered by “fetid goose-foot” (*Dysphania graveolens*), which historically has been an economically important plant to Pueblo peoples (Springer et al. 2009:324–325).

The fact that this ruderal was particularly dense in and around abandoned masonry structures suggests not only that it is fire-responsive but that its seedbed has endured for centuries (Yarnell 1965). Third, that the effects of the Scott Fire on the appearance of ruderals are not anomalous can be appreciated by considering the data in Table 3, which show a uniform ruderal response despite differences in fire size, ignition type, or severity.



**Figure 8.** Aftermath of the Scott Fire, which burned 1,076.5 ha in the Upper Basin between June 28 and July 18, 2016, showing dead trees and prehistoric masonry structure surrounded by fetid goosefoot in April 2017 (image used with permission of Neil Weintraub, Kaibab National Forest, US Department of Agriculture Forest Service).

In addition to providing evidence for Yarnell's (1965) "Camp Follower" hypothesis, which is intended to explain abnormally high densities of wild economic plants in and around archaeological sites, the results of our study lend support for Henry Dobyns's (1972) "Altitude Sorting" hypothesis. Based on ethnohistoric accounts that describe the ubiquity of amaranth and chenopodium production in New World economies, widespread archaeological occurrences of cheno-ams in the American Southwest, and the environmental constraints on maize farming, particularly for densely occupied upland locales after AD 1000, Dobyns proposed that upland groups "depended upon amaranth and perhaps chenopodium cultivation," in contrast to populations living in lower elevations that "grow more corns, beans, squash, and cotton, and less chenopodium and amaranth" (1972:45; see Bohrer 1991:232–233 on the use of fire for ruderal production in the Sonoran Desert). The results of our and other modern archaeological investigations broadly align with the Camp Follower

and Altitude Sorting hypotheses (e.g., Merrill et al. 2009) and indicate that maize dependency was localized and uneven across the prehispanic American Southwest (Bayman and Sullivan 2008; Rocek 1995; cf. Spielmann et al. 2011).

### **Fire-Based Ruderal Production and the Economic Prehistory of the American Southwest**

From southwestern Arizona (Bayman et al. 2004:132) to northeastern New Mexico (Kirkpatrick and Ford 1977) and from southeastern Nevada (McGuire et al. 2014) to southeastern New Mexico (Jelinek 1966), archaeological evidence indicates that chenopodium and amaranth have been economic keystone species for centuries in the Southwest (Fritz et al. 2017) and elsewhere in the New World (Carmody et al. 2017). The method of their cultivation, however, is poorly understood (Ford 1981:22) because considerations of the economic effects of burning

Table 3. Forest Fires in the Upland American Southwest that Produced Amaranth or Chenopodium.

| Location  | Date | Name            | Fire Type    | Forest Type                                   | Area Burned (Ha) | Ruderal Species Observed <sup>a</sup> | Reference  |
|---|------|-----------------|--------------|---|------------------|---------------------------------------|--|
| Upper Basin, Kaibab National Forest, northern Arizona   | 2016 | Scott           | Wildfire     | Pinyon-juniper                                | 1076.5           | Chenopodium, amaranth                 | Judith D. Springer (personal communication 2017) |
| Kaibab National Forest, Tusayan, Arizona                | 2004 | Topeka          | Experimental | Pinyon-juniper                                | –                | Chenopodium, amaranth                 | Huffman et al. (2013)                            |
| White Mountain Apache Reservation, East-central Arizona | 2002 | Rodeo-Chediski  | Wildfire     | Ponderosa pine, pinyon-juniper, mixed conifer | 189,650          | Chenopodium, amaranth                 | Kuenzi et al. (2008)                             |
| Grand Canyon National Park, northern Arizona            | 1999 | Fire Point      | Wildfire     | Ponderosa pine                                | 156              | Chenopodium                           | Laughlin et al. (2004)                           |
| Grand Canyon National Park, northern Arizona            | 1993 | Northwest III   | Prescribed   | Mixed conifer                                 | 490              | Chenopodium                           | Huisinga et al. (2005)                           |
| Mesa Verde National Park, Colorado                      | 1989 | Long Mesa       | Wildfire     | Pinyon-juniper                                | –                | Chenopodium                           | Adams and Dockter (2013)                         |
| Bandelier National Monument, New Mexico                 | 1977 | La Mesa         | Wildfire     | Ponderosa pine                                | 6070.5           | Chenopodium                           | Foxx (1996)                                      |
| Mesa Verde National Park, Colorado                      | 1959 | Morfield Canyon | Wildfire     | Pinyon-juniper                                | 826.8            | Chenopodium                           | Erdman (1970)                                    |

<sup>a</sup>One to two years post-burn.

have not been coupled with the understanding that these plants are fire-responsive and that fire was an essential food-producing technology of prehistoric Southwestern societies. The plausibility of the fire-foodway model can be appreciated, we suggest, by embracing the idea that the effects of low-intensity burning on understory vegetation align with forest ecology, fire ecology, and the contents of the archaeobotanical record in ways that maize agriculture does not. Moreover, with human-controlled landscape fire, people actively manage the structure and composition of vegetation communities by disrupting ecological succession patterns, manipulating understory fuel loads, and rotating burn plots to encourage species diversity without soil nutrient loss (Bird 2015). In short, the evidence indicates that sustainable fire-based ruderal agriculture was practiced extensively and in areas where maize agriculture was a risky and insecure endeavor (Dean 1996).

We realize that some aspects of this model are ideal, if not mechanistic, constructs, for example,

the size of burn plots, number of annual fires, and duration of fallow periods, but they serve to illustrate that, even when considering the lowest yields of just one plant and the caloric needs of the highest levels of population, fire foodways could easily provision the occupants of pinyon-juniper woodlands in areas that are environmentally hostile to maize farming. In addition, in view of the low impact of ruderal cultivation on pinyon-juniper woodlands, food fires could be ignited virtually continuously wherever sufficient fuels accumulate without jeopardizing the integrity of the ecosystem and its other economic resources, such as pinyon nuts and cactus (cf. Innes et al. 2013:88). In this regard, Lanner's observation that "the food potential of piñon forests in the Southwest has never been reliably estimated, but it is enormous" (1981:105) is supported by our rough estimates of fire-responsive ruderal yields. Importantly, significant quantities of economic resources can be produced without much labor, without destroying the woodlands themselves, and by increasing edible biomass enormously,

particularly if more than one ruderal was cultivated (Bye 1981; Ford 1984:135–137).

By incorporating aspects of the forest ecology and fire ecology of the Southwest's pinyon-juniper woodlands, our study illustrates the synergistic potential of applied historical ecology and niche construction theory in revealing the effects of anthropogenic fire in transforming the carrying capacity of these once heavily occupied ecosystems. Hence, it seems unlikely that the livelihoods of the prehistoric occupants of the Southwest's pinyon-juniper woodlands were challenged by slowly regenerating resources, by low carrying capacity, by scarce wild resources, and by the uncertain effectiveness of slash-and-burn maize cultivation (Wilcox 1978). It is more ecologically realistic to view these woodlands as having been structured by the historic dynamics of anthropogenic fire regimes—systematic understory burning during periods of occupation, dramatic reduction of understory burning during periods of abandonment, and exclusion or suppression of fire during the twentieth century (Margolis 2014).<sup>3</sup>

### Conclusion

In archaeological contexts across the prehistoric American Southwest, the widespread ubiquity and high frequencies of ruderal plant remains—especially seeds and pollen from amaranth and chenopodium—support the proposition that the cultivation practices for these plants involved deliberately set understory fires (Sullivan and Forste 2014). Furthermore, we think that anthropogenic fires, which triggered the disturbances that enabled ruderal production whenever and wherever sufficient understory fuels had accumulated, represent a form of sustainable agriculture whose yields were independent of the problematic rainfall and soil conditions that bedevil maize productivity and made it such a risky venture (Bocinsky and Varien 2017). The systematic management of understory fuel loads with low-intensity burning not only provided a dependable food supply, whose productive capacity was controlled by the ecosystem's inhabitants, but insulated the forests from catastrophic crown fires by eliminating the ladder-fuel problem that makes our overgrown woodlands so vulnerable to wildfires

today (Huffman et al. 2013), as the Scott Fire dramatically demonstrates.

Ruderal-producing fire foodways were sustainable because they required minimal fuel loads and efforts to ignite them, could be prosecuted on the most agriculturally unproductive soils, and, in the case of amaranth specifically, did well with less than 25 cm of precipitation and did not deplete soil of nitrogen to the same degree as maize. Intercropped with other drought-resistant, fire-responsive ruderals, such as chenopodium and various grasses, low-intensity understory “food fires” created a foodway that was largely inoculated against long-term climatic change and short-term environmental variability (Fulé et al. 2002a:44). Moreover, fire foodways take advantage of highly predictable successional pathways (Barney and Frischknecht 1974) that virtually guaranteed, with fire rotation (i.e., resting formerly burned areas for a year or two to promote fuel regeneration; Lightfoot and Cuthrell 2015:1585), interannual continuity in food provisioning (Bates and Davies 2016:127). Hence, this sustainable strategy contributed to a degree of food security that was rarely enjoyed by maize-based foodways in view of their vulnerability to capricious and largely uncontrollable environmental factors. The fire-foodway model illustrates that, by integrating archaeobotanical, fire-ecological, and surface archaeological data, we can enrich our narratives about how groups of economically autonomous people, with the judicious application of fire, engineered landscapes and secured livelihoods by unleashing the productivity capacity of ancient pinyon-juniper woodlands—upland ecosystems whose fire regimes, structure, and appearance have few counterparts in the twenty-first century.

### Notes

1. Estimates range from 47,133 km<sup>2</sup> in Arizona alone (Miller and Tausch 2001:16) to 153,100 km<sup>2</sup> (Vankat 2013:268) to 291,374 km<sup>2</sup> (West 1999:288) for the greater Southwest.

2. Given the extensive interannual variability in paleoprecipitation patterns, there is no correlation between the precipitation values for a given year and its prior year ( $r = 0.025$ ,  $p = 0.663$ ,  $n = 301$ ). Also, the results of a nonparametric Runs test (number of runs = 164) indicate that annual precipitation values ( $n = 301$ ) are randomly distributed using either the mean ( $\bar{x} = 36.6$  cm,  $Z = 1.46$ ,  $p = 0.144$ ) or median ( $Md = 36.2$  cm,  $Z = 1.44$ ,  $p = 0.149$ ; Thomas 1986:339–340). (Data provided courtesy of Jeffrey S. Dean, Laboratory of Tree-Ring

Research, University of Arizona, Tucson, personal communication 2001.)

3. The results of grain size, soil phosphorous (P), charcoal concentration, and carbon isotope ratio analyses of axial alluvial fan deposits (McNamee 2003; Roos et al. 2010) and from botanical and pollen analyses of samples recovered from a wide variety of archaeological contexts (Sullivan and Ruter 2006; Sullivan et al. 2015) support the argument that the prehistoric fire regime in the Upper Basin between circa AD 875 and 1200 consisted of frequent, low-intensity, surface, understory anthropogenic fires (West 1984:1310). Mixed-severity or high-severity (lethal) fires (where 20% to more than 70% of the overstory is killed by fire [Williams and Baker 2013:301]) were rare until the area was abandoned (i.e., perennial occupation ceased ca. AD 1200). In contrast, the fire regime between AD 1700 and 2000, based on fire scar records (Fulé et al. 2003) and analysis of historic forest structure (Fulé et al. 2002b; Williams and Baker 2013), is characterized by infrequent, low- to medium-intensity, surface, nonanthropogenic fires punctuated by periodic severe (stand-replacing) canopy fires (Fulé 2010; cf. Liebmann et al. 2016). The character of the fire regime between AD 1200 and 1700 is unknown save for the presumption that fuel loads and ignitions were unmanaged by humans (cf. Herring et al. 2014:860).

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*Data Availability Statement.* Specialist reports of macrobotanical and pollen analyses, data files of archaeological survey records (including differentially corrected GPS data), and GIS shapefiles of Upper Basin environmental and archaeological characteristics used in the preparation of this article are available by contacting the corresponding author. In addition, primary archaeobotanical data referred to in this essay, including sample collection and analysis procedures, context types, sample numbers, identified taxa, nomenclature protocols, plant part, specimen condition, the presence or absence of charring, and miscellaneous comments, may be found by consulting the following sources: Berkebile (2014); Brandt (1991); Cummings and Puseman (1995, 1997, 2010); Huckell (1992); Scott (1986).

*Supplemental Materials.* For supplemental material accompanying this article, visit <https://doi.org/10.1017/aaq.2018.32>.

Supplemental Table 1. Archaeological Characteristics of 10 Excavated Sites in Grand Canyon National Park and the

Upper Basin, Northern Arizona, that Produced Macrobotanical Samples.

Supplemental Table 2. Productivity Estimates of Amaranth and Chenopodium.

Supplemental Text 1. Key References Consulted about the Relation between Anthropogenic Fire and Human Prehistory.

Supplemental Text 2. Key References Consulted about the Relation between Anthropogenic Landscape Fire Ecology and Subsistence Economies.

Supplemental Text 3. Key Ethnographic, Ethnohistoric, and Cross-Cultural Studies Consulted about Anthropogenic Landscape Burning.

Supplemental Text 4. Key References Consulted about Maize and Amaranth Evolution and Cultivation in the New World.

Supplemental Text 5. Population and Amaranth Productivity Estimates for the Upper Basin, AD 875–1200.

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