

## Research Article

# Stratigraphic evidence for culturally variable Indigenous fire regimes in ponderosa pine forests of the Mogollon Rim area, east-central Arizona

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## Abstract

The impact of Indigenous populations on historical fire regimes has been controversial and beset by mismatches in the geographic scale of paleofire reconstructions and the scale of land-use behaviors. It is often assumed that anthropogenic burning is linearly related to population density and not different cultural practices. Here we take an off-site geoarchaeology strategy to reconstruct variability in historical fire regimes (<1000 years ago) at geographic scales that match the archaeological, ethnohistorical, and oral tradition evidence for variability in the intensity of Indigenous land use by two different cultural groups (Ancestral Pueblo and Western Apache). We use multiple, independent proxies from three localities in ponderosa pine (*Pinus ponderosa*) forests in east-Central Arizona to reconstruct fire regime variability during four phases of cultural use of different intensities. Elevated charcoal with domesticated pollen (*Zea* spp.) but otherwise unchanged forest pollen assemblages characterized intensive land use by Ancestral Pueblo people during an early phase, suggesting fire use to support agricultural activities. By contrast, a phase of intensive pre-reservation Western Apache land use corresponded to little change in charcoal, but had elevated ash-derived phosphorus and elevated grass and ruderal pollen suggestive of enhanced burning in fine fuels to promote economically important wild plants.

**Keywords:** Anthropogenic burning, Off-site geoarchaeology, Western Apache, Ancestral Pueblo, *Pinus ponderosa*, Fire history

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## INTRODUCTION

Human ancestors evolved in the most flammable biome on the planet—tropical savannas—and almost certainly have an evolutionary history shaped by fire (Parker et al., 2016). Anthropogenic burning was likely a significant factor in ecological changes associated with the arrival of *Homo sapiens* to new environments in the Late Quaternary (McWethy et al., 2010; Bowman et al., 2011). Despite this close connection between people and fire, the ecological significance of landscape burning by Indigenous people in North America has often been controversial (Vale, 2002; Roos et al., 2014). In many cases, this has hinged on the ambiguity of distinguishing an anthropogenic signal in paleofire records that are already rich with fire (Roos et al., 2019). In other cases, large-scale fire syntheses (regional to continental) often lack clear evidence of human impacts (Oswald et al., 2020), but the

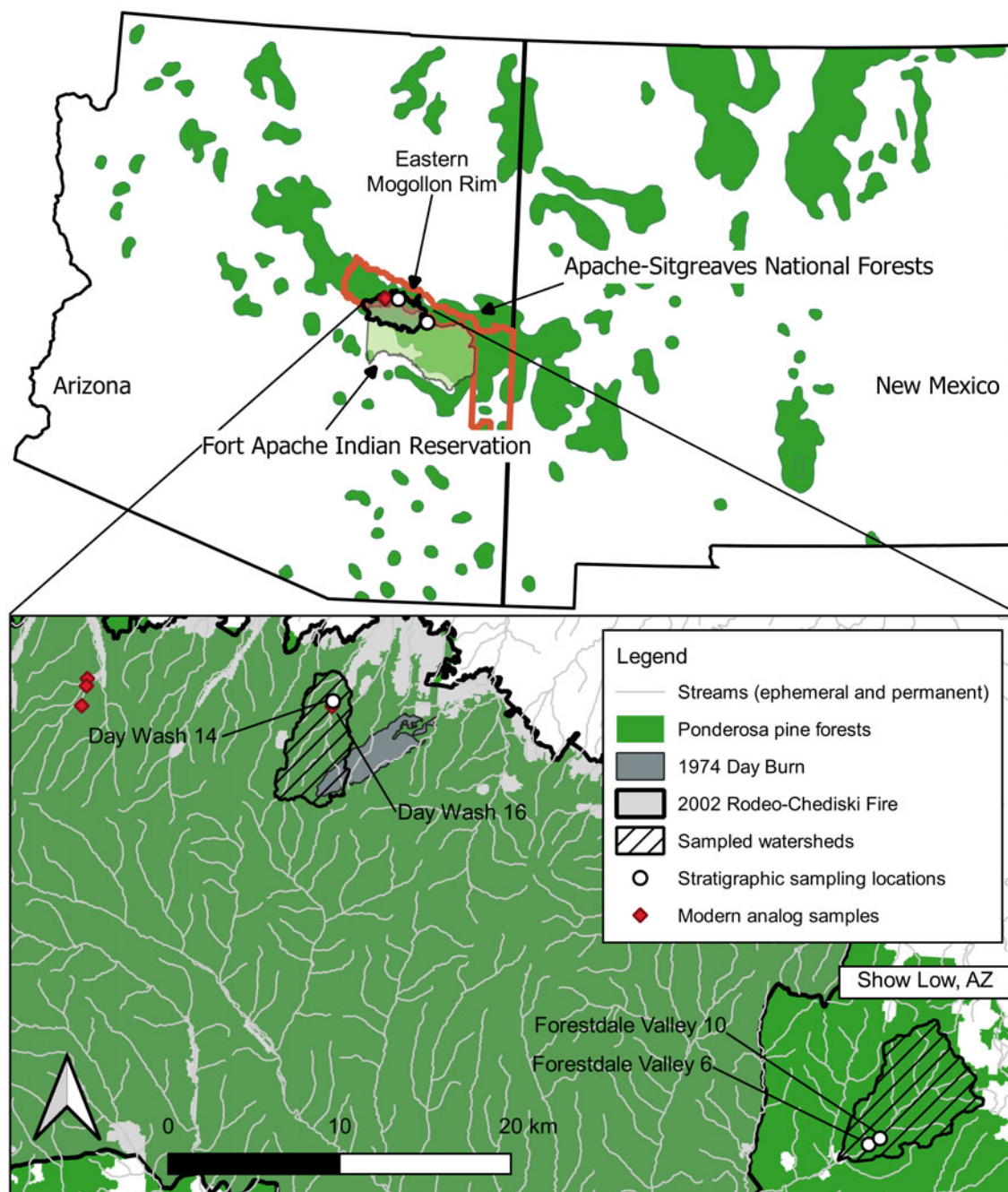
linkage between these syntheses and the scales at which land-use behavior operated has not been established (Roos, 2020).

Indigenous communities have lived in the fire-adapted forests of the North American Southwest (hereinafter “the Southwest”) for millennia, but their long-term legacies on Southwest fire histories is debated, because the climate is amenable to frequent fires and lightning is an abundant source of ignitions (Allen, 2002). But more than just the presence or absence of fires, the ecological significance of Indigenous burning in landscapes with abundant non-human fire is likely to be subtle in terms of changes in burned area, fuels, and patch size (McWethy et al., 2013). Here we leverage prior archaeology, history, ethnography, and Apache oral traditions in a landscape geoarchaeology approach to identify spatial and temporal variability in fire regimes in the ponderosa pine (*Pinus ponderosa*) forests of east-central Arizona (Fig. 1). We use stratigraphic charcoal, pollen, extractable phosphorus (soil P), sedimentology, and sedimentation rates to infer changes in biomass burning, vegetation, and ash-related nutrients while controlling for the impact of depositional variability on these fire proxies (Nichols et al., 2000; Scott et al., 2000). Bayesian calibration of accelerator mass spectrometry radiocarbon dates and age–depth modeling allow us to compare fire regime proxies from four different periods that document different intensities of occupation by Ancestral Pueblo and Apache people: AD 1000–1400; AD 1400–1550; AD 1550–1870; AD 1870 to present.

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**Figure 1.** The location of the Mogollon Rim study area, study watersheds, geoarchaeological localities, and modern analog sample sites relative to the distribution of ponderosa pine forests and the 2002 Rodeo-Chediski Fire and the 1974 Day Burn. Day Wash 16 (DaW 16) is a stratigraphic context that provides a “modern analog” for high-severity fire from the Day Burn.

### Environmental context

We concentrate on ponderosa pine forests along the eastern Mogollon Rim in east-central Arizona that were home to ancestors of Pueblo and Western Apache people (Fig. 1). These forests span elevations between 1700 and 2300 m above sea level along the southern margin of the Colorado Plateau (Kaldahl and Dean, 1999). Ponderosa pine forests are dominated by one canopy species, ponderosa pine, with rare contributions of various juniper (*Juniperus* spp.) and piñon (*Pinus* spp.) at lower elevations, and Douglas fir (*Pseudotsuga menziesii*) and Southwestern white pine (*Pinus strobiformis*) at higher elevations. Historically,

understory plant communities were dominated by bunchgrasses (especially *Festuca arizonica*), forbs (especially those in Asteraceae and Amaranthaceae), and some shrubs, including various species of oak (*Quercus* spp., which can also grow in tree form as occasional codominants), sumac (*Rhus trilobata*), and manzanita (*Arctostaphylos* spp.). These forests are dotted by rare, small meadows (<25 ha) with a similar composition of grasses and forbs as were present in the historical understory.

Landscapes “below” the Mogollon Rim (i.e., to the south) receive more rainfall than those above due to the effect of orography. Average annual precipitation at Show Low, AZ, just above the

Mogollon Rim, is 420 mm with strong bimodality of peak rainfall during the summer monsoon in July, August, and September and a second, smaller mode from cyclonic winter storms from the Pacific from October to March. April, May, and June are reliably dry, creating conditions each year when fires can ignite and spread. Average low temperatures are above freezing from April through October, the primary growing season for both wild plants and crops, although late (spring/summer) and early (summer/autumn) frosts are not uncommon (Kaldahl and Dean, 1999).

Frequent, low-severity surface fires were historically ubiquitous in ponderosa pine and dry mixed-conifer forests in the Southwest until livestock grazing, logging, and fire suppression led to a near total cessation of wildfires beginning in the late nineteenth century (Swetnam and Baisan, 2003; Swetnam et al., 2016). Fire-scarred ponderosa pines can be tree-ring dated to the year and often to the portion of the growing season when the surface fires occurred (Dieterich and Swetnam, 1984). Between ca. AD 1700 and AD 1900 (the period of greatest tree-ring sample depth), fires tended to occur in a stand once or twice per decade in surface fuels (grasses, needle litter, etc.) during the arid fore-summer (April–June) or at the onset of the monsoon with dry lightning storms (July) (Fulé et al., 1997; Moore et al., 1999). Unpublished tree-ring records from the greater Mogollon region indicate that the region experienced unusually high frequencies of surface fire (three or more per decade) for at least two centuries before early twentieth-century fire suppression (Kaib et al., 2000).

### Cultural context

As part of the larger movement to Indigenize the past, we embrace tribal knowledge that speaks to Indigenous presence in east-central Arizona since time immemorial. By underpinning our own research with goals that speak to tribal perceptions of their own cultural persistence in the Southwest, this is an acknowledgment of tribal sovereignty and self-determination necessary to understand and situate the past in the twenty-first century (Gonzalez et al., 2006). This is also an important recognition in the context of land-use and fire management histories, because Indigenous communities have developed and curated fire-keeping practices for generations and this knowledge is powerful, salient, and important today (Kimmerer and Lake, 2001; Lake et al., 2017). By prioritizing indigenous perspectives on cultural and land-use history, we organize our understanding of the archaeology and ethnohistory in a way that emphasizes persistence while subdividing time to recognize variability in the intensity of use by different cultural groups.

We concentrate on Ancestral Pueblo (for some, the term “Mogollon Pueblo” is preferred; Riggs, 2010) and Western Apache land use after AD 1000, when widely distributed small villages, hamlets, and farmsteads appeared (Mills and Herr, 1999; Mills et al., 1999a; Herr, 2001). Although the settlements were small, this was the period of greatest population size in the region (Newcomb, 1999). Grinding stones and paleoethnobotanical remains all indicate a dependence upon farming (Huckell, 1999). By the late AD 1200s, populations coalesced into a few large but widely separated pueblos (Kaldahl et al., 2004). One of these (the Bailey Ruin) was located in the Day Wash area above the Mogollon Rim (Mills et al., 1999b), and another (Tundastusa) in the Forestdale Valley below it (Haury, 1985b; Riggs, 2010). Ethnographically and archaeologically, we know that Pueblo people used fire for myriad purposes, including burning to establish and clean agricultural fields and irrigation ditches;

to promote wild plant resources for food, medicine, and craft materials; in game drives, to promote habitat for preferred game animals; and in religious pilgrimages and practices (Gifford, 1940; White, 1943; Bohrer, 1983; Sullivan and Mink, 2018; Roos et al., 2021). Although populations moved their perennial homes away from the area by AD 1400, Pueblo people have continued to maintain relationships with the Mogollon Rim region (Ferguson and Hart, 1985).

The area is also home to Western Apaches, who were historically seasonally mobile forager-gardeners who lived in ponderosa pine forests and adjacent woodlands from spring through autumn as part of seasonal mobility patterns (Graves, 1982). Apache Elders describe traditions of their presence in eastern Arizona since time immemorial (Welch and Riley, 2001). Incorporating Apache oral tradition in reference to Apache presence in the Southwest since time immemorial not only sets a baseline for understanding Apache presence but also helps to foreground Apache interpretations of their own culture and histories that have often been constructed and interpreted by non-Apache researchers. While current interpretations based on archaeology (Herr, 2013) and ethnohistory (Forbes, 1960) document intensive Western Apache use of the Mogollon Rim region by AD 1550, here we recognize oral traditions that Apaches were in the area at the same time as Ancestral Pueblo peoples. Western Apaches used fire in many activities, including those described for Ancestral Pueblo peoples (Griffin et al., 1971; Buskirk, 1986). A large portion of the eastern Mogollon Rim region is within the Fort Apache Indian Reservation, which was established in 1870.

### MATERIALS AND METHODS

In June and August 2005, we surveyed and sampled off-site alluvial stratigraphic sequences in two first-order watersheds along the Mogollon Rim of east-central Arizona for proxies of fire-related sedimentation and vegetation (Fig. 1). To explore the variable legacies of Indigenous fire use, we used existing archaeological data to select two watersheds that were likely to have both Ancestral Pueblo and Apache land-use histories. The Forestdale Valley is located south of Show Low, AZ, on the Fort Apache Indian Reservation and has been the subject of intensive archaeological research since the 1930s (Haury, 1985c). The latest Ancestral Pueblo village in the Forestdale Valley, Tundastusa, was occupied until at least AD 1400, when Pueblo people migrated elsewhere (Haury, 1985b; Riggs, 2010). The Day Wash watershed in Apache-Sitgreaves National Forest includes the late-occupied Bailey Ruin (ca. AD 1275–AD 1325) (Mills et al., 1999b). Other archaeological evidence from near the Bailey Ruin and the Forestdale Valley indicate at least episodic, repeated settlement of these areas since ca. AD 200, with continuous, intensive occupation after AD 1000 (Haury, 1985a [1940]; Haury and Sayles, 1985 [1947]; Mills, 1999; Mills and Herr, 1999; Roos, 2005). Archaeological and ethnohistorical evidence documents intensive Western Apache use of the Mogollon Rim region, including the Forestdale and Day Wash areas, for at least the past 440 years (Basso, 1998; Herr et al., 2009).

Using our understanding of cultural persistence, we use archaeology, ethnohistory, and oral tradition to subdivide the past 1000 years into periods of varying land-use intensity. Period 1 (AD 1000–1400) represents a time of relatively intensive use by Ancestral Pueblo people as well as use by Apache groups. Period 2 (AD 1400–1550) represents a time of less intensive use of the area. Period 3 (AD 1550–1870) is a time of more intensive

Apache use of the landscape. Period 4 (AD 1870 to present) represents more intensive use by settler colonists and general suppression of traditional land-use practices by the U.S. military, although some traditional practices persisted through this period (Watt, 2015).

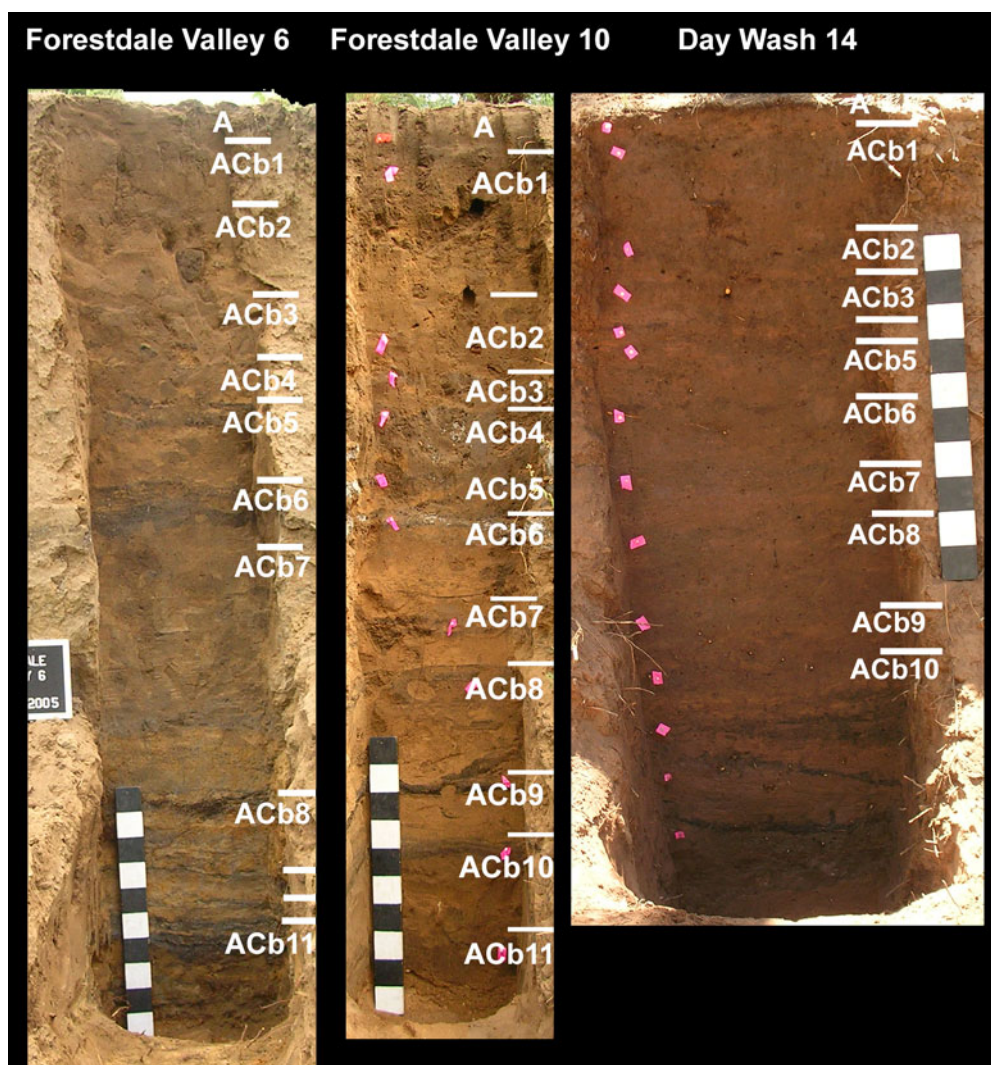
Day Wash and the Forestdale Valley are both small, first-order watersheds (the smallest stream category with no real tributary streams [Strahler, 1957]—less than 4000 ha in our case). Concentration on small, first-order discontinuous ephemeral streams means that most of the record is characterized by charcoal, pollen, and sediment accumulated from hillslope sources within the watershed rather than from storage in older alluvium, making these hyperlocal records of fire-derived sediments produced within these small basins (Bull, 1997; Hereford, 2002). Both watersheds are generally low gradient and have similar bedrock geology dominated by nutrient-poor Cretaceous and Permian sedimentary rocks with average slopes between 5.2% (Day Wash) and 8.6% (Forestdale).

Incised reaches of targeted watersheds were surveyed on foot for exposed alluvium and soils that indicated somewhat rapid and recent accumulation (fluvial soils: alluvial soils with weakly developed soil morphology) (Birkeland, 1999; Holliday, 2004).

Narrow (ca. 1- to 2-m-wide) trenches were manually excavated into selected localities within the two watersheds: two in Day Wash and four in the Forestdale Valley. Detailed analysis was done on one Day Wash locality (DaW 14), and two localities in Forestdale Valley (FDV 6 and 10; Fig. 2). Soil stratigraphic units were described in the field based on color, soil structure, bedding features, and boundary types using standard terminology (Schoeneberger *et al.*, 2012).

Surface sediments from a channel fan/bar context in Rocky Draw in Apache-Sitgreave and a shallow, recent channel fan in Day Wash (DaW 16) were both sampled as “modern analogs” of fine-grained (mostly <2 mm grain size) channel fan sediments produced in depositional settings analogous to our ancient ones after the 2002 Rodeo-Chediski Fire and the 1974 Day Burn, respectively (Fig. 1). At ancient localities and modern analog sites, ca. 7- to 9-cm-thick undisturbed blocks were collected from pedogenic or depositional stratigraphic units for micromorphological analysis to supplement in-field descriptions of soil stratigraphic units (Stoops, 2003; Goldberg and Berna, 2010).

At each intensively studied locality, bulk samples for the analysis of gravel content (>2 mm), grain-size distributions less than



**Figure 2.** Photographs of exposed profiles at the three geoarchaeological localities annotated with soil stratigraphic boundaries and assignments. ACb9 and ACb10 are unlabeled in Forestdale Valley 6 (FDV 6), and ACb4 is unlabeled in Day Wash 14 (DaW 14).

**Table 1.** Geoarchaeological locality measurements and samples.

| Locality                 | Thickness of exposure (m) | No. bulk samples | Sedimentary charcoal and soil P | Pollen | No. thin sections | <sup>14</sup> C dates |
|--------------------------|---------------------------|------------------|---------------------------------|--------|-------------------|-----------------------|
| Day Wash 14              | 2.55                      | 31               | 124                             | 15     | 14                | 10                    |
| Forestdale Valley 10     | 3.40                      | 23               | 161                             | 12     | 13                | 10                    |
| Forestdale Valley 6      | 3.83                      | 30               | 179                             | 15     | 13                | 9                     |
| Day Wash 16              | 0.68                      | 8                | 17                              | 4      | 3                 | NA                    |
| Rocky Draw modern analog | 0.02                      | 13               | 13                              | 1      | 1                 | NA                    |
| Total N =                |                           | 84               | 464                             | 42     | 40                | 29                    |

2 mm (Janitsky, 1986b), CaCO<sub>3</sub> content (Machette, 1986), and unburned soil organic matter content (SOM) (Janitsky, 1986a) were collected from each described soil stratigraphic and sedimentary unit (Table 1). To simplify grain-size presentations, these data are presented as the ratio of fines (silt + clay; <63 µm) to sand (63 µm–2 mm). Continuous or overlapping monoliths of soil/sediment were collected in the field and sampled continuously at 2 cm intervals for sedimentary charcoal analysis (Whitlock and Larsen, 2001). Five cubic centimeters of sample was disaggregated using 25 mL 10% Na-hexametaphosphate in 100 mL of deionized water, lightly oxidized using 25 mL of 3% H<sub>2</sub>O<sub>2</sub> (Rhodes, 1998), sieved with deionized water through a 250 µm steel sieve, and counted under a binocular microscope at 7–40× magnification. Raw counts of charcoal pieces >250 µm were converted to concentrations (counts/cm).

Both watersheds are situated on nutrient-poor sedimentary bedrock and derived soils that are naturally low in phosphorus and other nutrients. Biological phosphorus volatilizes when combusted at more than 770°C, but at lower temperatures it oxidizes to phosphate where it adsorbs to soil mineral surfaces or forms new calcium phosphate minerals in the alkaline ash (DeBano et al., 1998). Ash from low-intensity wildfires is an important source of phosphorus in low-P soil environments like those of the Mogollon Rim (Cowan et al., 2016). Mehlich II extractable soil P (a measure of ash-derived nutrient fluxes) was measured every 4 cm using a colorimetric method on the <125 µm fraction of monolith samples (Terry et al., 2000).

Samples of sediment from the monoliths were collected for extracting and quantifying pollen from soil horizons using standard methods (Traverse, 2007). Pollen and fungal spores were identified using in-house comparative collections for the Southwest (Davis, 2007). Pollen was generally well preserved but variably abundant. On average, deteriorated and indeterminate pollen grains made up 6.5% of individual samples (±6.6%). These grains (and any encountered wetland taxa) were not included in the terrestrial pollen sum. Pollen concentrations were generally low and variable, so we restrict our interpretations to the relative abundances of two major categories: undifferentiated *Pinus*, and grasses and ruderals (Amaranthaceae + Asteraceae + Poaceae). Samples with pollen grain counts below 50 are displayed in figures as gray dots but not included in our pollen interpretations. General vegetation interpretations are guided by pollen values for reference studies of modern ponderosa pine forests and meadows (Martin, 1963; Rankin, 1980; Hevly, 1988). These indicate that ponderosa pine forests have 40–80% pine pollen and 10–30% grass and ruderal pollen, while meadows typically have lower *Pinus* pollen (15–60%) and more abundant pollen of grasses and ruderals (50–80%). The dung fungus

*Sporormiella* is reported as a percentage of the terrestrial pollen sum and is interpreted as a proxy for herbivore biomass (Davis, 1987). Table 2 identifies potential interpretations of variability in these major proxy categories.

Individual pieces of charcoal for radiocarbon dating were collected from the disaggregated and sieved charcoal samples. When possible, non-wood xylem tissues were preferred for dating. Radiocarbon dates were calibrated using a Bayesian algorithm in BCal (Buck et al., 1991, 1999) that incorporated stratigraphic relationships between samples as prior information. Charcoal in alluvium generally provides *terminus post quem* ages (“date after which”) (Brown, 1997), so unusually old dates that did not fit the rest of the population were excluded from Bayesian calibrations. All standard and Bayesian calibrations were done using IntCal20 (Reimer et al., 2020) and are reported at 2σ and 95% highest probability density (hpd) for Bayesian date ranges (Table 3). Age–depth models were calculated in CLAM (Blauw, 2010) using the Bayesian 95% hpd ranges to assign soil stratigraphic units to land-use time periods and to generate estimated time series.

## RESULTS

Charcoal in modern analog samples showed a strong log-linear relationship with fines:sand ratios, suggesting that depositional energy had a strong impact on charcoal variability in modern samples (Fig. 3a), further supporting experimental observations of charcoal taphonomy by Nichols and Scott (Nichols et al., 2000; Scott et al., 2000). In aggregate, the ancient charcoal samples from FDV 6, FDV 10, and DaW 14 do not show such a strong relationship with grain size (Fig. 3b), indicating that there was variability in ancient charcoal accumulations related to fire activity and not just depositional energy. At DaW 16, soil P and unburned organic matter also demonstrate a strong correlation to either depositional energy or charcoal concentration (Fig. 3d). In thin section at DaW 16 and the Rocky Draw modern analog sites, unburned plant tissues are roughly as common as charcoal in modern postfire erosion deposits, and these unburned plant tissues may be the origin for their curious palynological properties. Pine pollen from four pollen samples at DaW 16 and one at the Rocky Draw range from 82% to 93.4%, higher in the earliest deposits and higher even than twentieth-century pine forest samples despite having a portion of the tree canopy killed by fire (see Table 4). This is probably due to enhanced postfire scouring of surfaces bringing unburned organic matter with adhering pine pollen as well as charcoal and phosphate-rich ash to the depositional sites.

FDV 6 and FDV 10 were cut into alluvial terraces in the upper reaches of the valley bottom alluvium in the Forestdale Valley

**Table 2.** Paleoeological proxies and possible interpretations.

| Value            | Charcoal<br>(count/cm <sup>3</sup> )    | Soil P<br>(mg/kg)                                      | <i>Pinus</i> pollen (%)             | Grass and ruderal<br>pollen (%)     | <i>Sporormiella</i> spores<br>(%)   |
|------------------|-----------------------------------------|--------------------------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| Anomalously low  | Little or no fire                       | Little or no fire                                      | Forest clearance                    | Canopy closure                      | Low density of herbivores           |
|                  | Or much faster sedimentation            | Or much faster sedimentation                           | Or anomalously high % of other taxa | Or anomalously high % of other taxa | Or much faster sedimentation        |
|                  | Or leaching                             |                                                        |                                     |                                     |                                     |
| Low              | Less fire                               | Less fire                                              | Open pine forest                    | Dense forest                        | Moderate density of wild herbivores |
|                  | Or increase in proportion of fine fuels | Or leaching                                            | Or high % of other taxa             | Or high % of other taxa             |                                     |
| High             | High fire                               | High rates of low-severity fire                        | Pine forest                         | Meadow                              | Domesticated herbivores present     |
| Anomalously high | High-severity fire?                     | High rates of low-severity fire and/or livestock dung? | Deposition after high-severity fire | Forest clearance?                   | Domesticated livestock herds        |

**Table 3.** Radiocarbon data for Forestdale Valley 6 and 10 and Day Wash 14.

| Locality/sample no.  | Depth (cm) | $\delta^{13}\text{C}$ (‰) | Material <sup>a</sup>           | Radiocarbon age ( <sup>14</sup> C yr BP) | 2 $\sigma$ Calibrated age AD                     | 95% hpd Bayesian-calibrated age AD <sup>b</sup> |
|----------------------|------------|---------------------------|---------------------------------|------------------------------------------|--------------------------------------------------|-------------------------------------------------|
| Forestdale Valley 6  |            |                           |                                 |                                          |                                                  |                                                 |
| AA-71712             | 46–48      | –21.8                     | Unidentified non-xylem charcoal | 212 ± 54                                 | 1831–1909<br>1719–1826<br>1633–1711<br>1527–1555 | 1726–1909                                       |
| AA-68652             | 72–79      | –24.3                     | Charred conifer twig            | 390 ± 33                                 | 1538–1634<br>1441–1524                           | 1553–1637                                       |
| AA-71711             | 86–88      | –24.4                     | <i>Pinus</i> needle             | 723 ± 84                                 | 1158–1405                                        | N/A                                             |
| AA-68653             | 140–145    | –22.6                     | Conifer xylem                   | 355 ± 38                                 | 1538–1634<br>1456–1530                           | 1458–1589                                       |
| AA-71710             | 174–176    | –24.9                     | <i>Pinus</i> needle             | 629 ± 95                                 | 1251–1442<br>1223–1249                           | 1394–1510                                       |
| AA-71709             | 236–238    | –24.6                     | Charred stem                    | 477 ± 69                                 | 1573–1623<br>1386–1524<br>1304–1364              | 1379–1459<br>1339–1355                          |
| AA-71708             | 298–300    | –24.7                     | Charred stem                    | 777 ± 65                                 | 1363–1386<br>1155–1310<br>1051–1079              | 1342–1396<br>1311–1324                          |
| AA-68654             | 340–342    | –24.2                     | Conifer xylem                   | 535 ± 57                                 | 1380–1452<br>1302–1368                           | 1290–1357                                       |
| AA-68655             | 365–373    | –22.5                     | Conifer xylem                   | 973 ± 59                                 | 990–1212                                         | 975–1178<br>898–916                             |
| Forestdale Valley 10 |            |                           |                                 |                                          |                                                  |                                                 |
| AA-74344             | 32–34      | –23.8                     | Charred stem                    | 371 ± 34                                 | 1551–1632<br>1448–1527                           | 1549–1640<br>1490–1525                          |
| AA-68647             | 56–62      | –20.6                     | Conifer xylem                   | 755 ± 36                                 | 1221–1292                                        | N/A                                             |
| AA-68648             | 114–122    | –24.5                     | <i>Pinus</i> needle             | 615 ± 34                                 | 1297–1402                                        | N/A                                             |
| AA-71707             | 124–126    | –12.8                     | Unidentified non-xylem charcoal | 518 ± 64                                 | 1377–1476<br>1299–1372                           | 1574–1584<br>1555–1566<br>1428–1527             |
| AA-68649             | 156–162    | –23.7                     | Charred conifer twig            | 439 ± 34                                 | 1419–1500                                        | 1412–1470                                       |

(Continued)

Table 3. (Continued.)

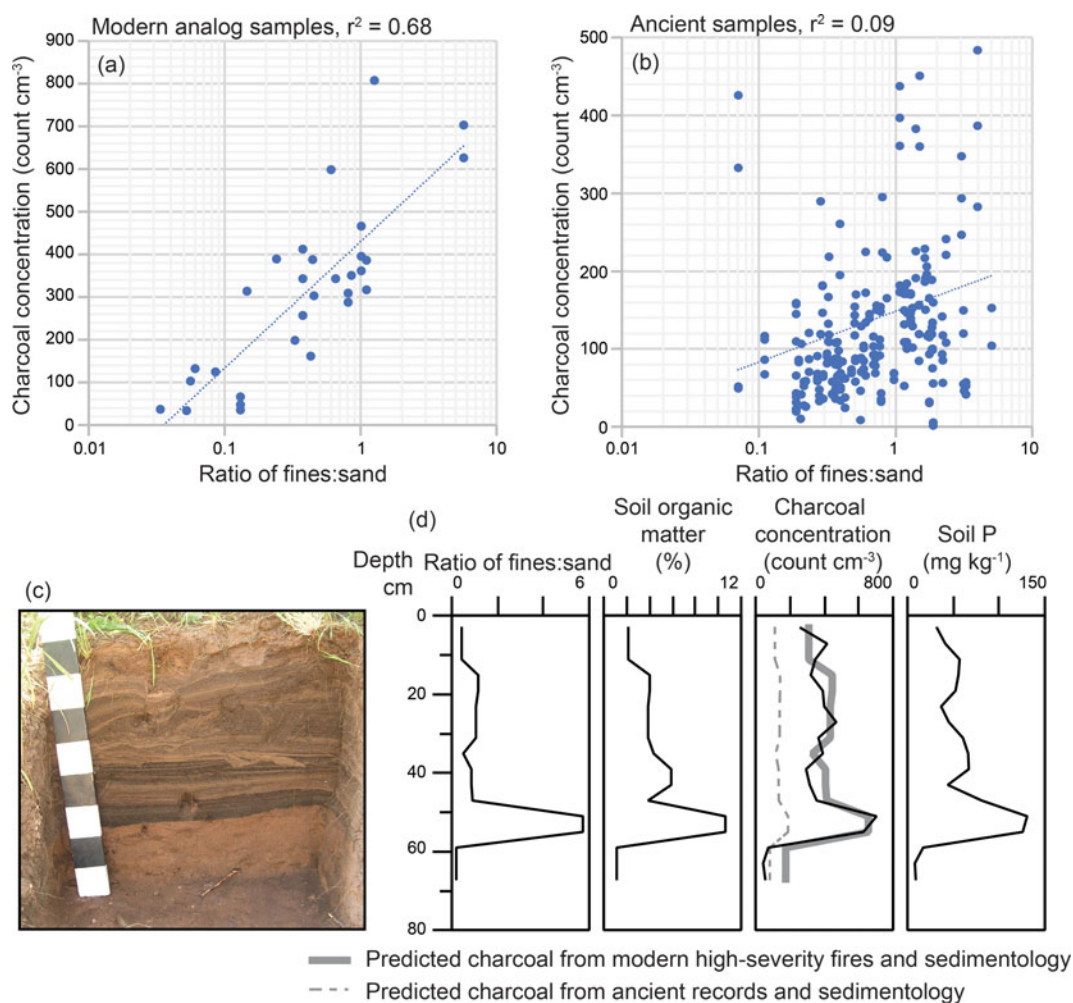
| Locality/sample no. | Depth (cm) | $\delta^{13}\text{C}$ (‰) | Material <sup>a</sup>           | Radiocarbon age ( $^{14}\text{C}$ yr BP) | 2 $\sigma$ Calibrated age AD       | 95% hpd Bayesian-calibrated age AD <sup>b</sup> |
|---------------------|------------|---------------------------|---------------------------------|------------------------------------------|------------------------------------|-------------------------------------------------|
| AA-71706            | 182–184    | –12.3                     | Unidentified non-xylem charcoal | 619 $\pm$ 38                             | 1294–1402                          | 1313–1405                                       |
| AA-68650            | 208–210    | –21.8                     | Conifer xylem                   | 1,580 $\pm$ 140                          | 207–673                            | N/A                                             |
| AA-68651            | 246–250    | –23.8                     | Unidentified non-xylem charcoal | 672 $\pm$ 35                             | 1355–1393<br>1276–1324             | 1360–1374<br>1272–1324                          |
| AA-71705            | 274–276    | –24.7                     | <i>Pinus</i> needle             | 1,120 $\pm$ 120                          | 1136–1151<br>1078–1134<br>666–1047 | 1056–1263                                       |
| AA-71704            | 302–304    | –26.5                     | <i>Pinus</i> needle             | 800 $\pm$ 97                             | 1360–1387<br>1030–1315             | 1153–1172<br>976–1151<br>890–928                |
| Day Wash 14         |            |                           |                                 |                                          |                                    |                                                 |
| AA-74348            | 44–46      | –23.7                     | Unidentified non-xylem charcoal | 364 $\pm$ 59                             | 1444–1639                          | 1918–1949<br>1731–1809<br>1600–1670             |
| AA-77079            | 46–48      | –23.3                     | <i>Pinus</i> needle             | 262 $\pm$ 75                             | 1723–1811<br>1451–1697             | 1567–1797                                       |
| AA-71718            | 62–64      | –24.6                     | Unidentified non-xylem charcoal | 370 $\pm$ 33                             | 1552–1633<br>1449–1527             | 1552–1641                                       |
| AA-71717            | 104–106    | –25.7                     | <i>Pinus</i> needle             | 580 $\pm$ 110                            | 1600–1610<br>1220–1505             | 1494–1618                                       |
| AA-77080            | 142–144    | –26.2                     | Charred stem                    | 540 $\pm$ 35                             | 1390–1440<br>1320–1358             | N/A                                             |
| AA-71716            | 150–152    | –23.1                     | <i>Pinus</i> needle             | 605 $\pm$ 89                             | 1262–1451                          | 1467–1590                                       |
| AA-71715            | 180–182    | –24.2                     | Charred stem                    | 397 $\pm$ 70                             | 1420–1639                          | 1405–1520                                       |
| AA-77081            | 210–212    | –24.2                     | <i>Pinus</i> needle             | 599 $\pm$ 88                             | 1265–1453                          | 1273–1450                                       |
| AA-71714            | 216–218    | –24.5                     | Charred stem                    | 342 $\pm$ 51                             | 1456–1641                          | 1436–1525                                       |
| AA-71713            | 226–228    | –24.5                     | Charred stem                    | 397 $\pm$ 39                             | 1568–1628<br>1435–1525             | 1434–1508                                       |

<sup>a</sup>All dates on charcoal measured at the University of Arizona Mass Spectrometry lab.<sup>b</sup>Calibrated ages from Bayesian modeling are in italics. hpd, highest probability density.

(Fig. 1). FDV 6 is a 3.83 m exposure near the northeastern limit of the large valley bottom meadow today. FDV 10 is a 3.4 m alluvial exposure surrounded by forest (hence consistently higher *Pinus* pollen values at FDV 10 than at FDV 6; see Figs. 4 and 5). Both Forestdale localities shared a similar sequence of 12 weakly separated alluvial soils within three sequential lithostratigraphic units (Fig. 2). The bottom unit (Unit I; soil units ACb7 to ACb11) is composed of well-bedded upward-fining sets of sandy to silty alluvium with high concentrations of charcoal in the finer-grained facies (Figs. 4–6). Fine-grain facies were enriched in SOM and displayed evidence for incipient soil formation (diffuse boundaries, lack of preserved bedding features) but low carbonate concentrations. Unit I soils at FDV 6 also displayed evidence for fluctuating water tables in the form of field-observed and micromorphological redoximorphic features (e.g., diffuse Fe-oxyhydroxide nodules and mottling; see Fig. 6). Unit II conformably overlies Unit I and consists of organic-rich, massive, fine-grained sandy silts and clays (soils ACb3 to ACb6). Unit II displayed weakly separated or welded fluvents with abundant SOM and pedogenic carbonate filaments overprinted from soil formation in the overlying Unit III soils. Unit III is composed of predominantly sandy sheetwash with

very weakly separated alluvial soils within it (soils A to ACb2). The lithostratigraphic and soil stratigraphic similarity across these two localities and their overlapping radiocarbon dates indicate that each of these three stratigraphic units is roughly contemporaneous with the others. FDV 6 and 10 both probably began accumulating in the AD 1000s or AD 1100s (presumably after major downcutting immediately prior; Hereford, 2002; Karlstrom, 2005; Table 2). Sedimentation slowed with the overbank deposition of Unit II in the AD 1400s, which probably corresponded to shallow entrenchment downstream that eroded part of the Tla Kii ruin great kiva (Haury, 1985c). Unit III saw a further change in sediment delivery from predominantly fine-grained overbank deposits to sandy sheetwash sometime in the AD 1500s. Entrenchment of the channel of Forestdale Creek to current levels did not happen until after AD 1910 (Haury, 1985c), thereby abandoning FDV 6 and 10 as contexts for further deposition.

Soils within lithostratigraphic Unit I roughly correspond to the period of most intensive land use by Ancestral Pueblo people (Period 1). Charcoal concentrations were at their highest levels during Period 1 at both FDV 6 and FDV 10 (Table 4), although



**Figure 3.** (a) Scatter plot and regression line for modern analog charcoal samples by grain size; (b) scatter plot of ancient charcoal and grain size; (c) photograph of the profile exposed at modern analog site Day Wash 16 (DaW 16); and (d) stratigraphic plot of grain size, organic matter, charcoal, and phosphorus from DaW 16. Predicted charcoal abundance was calculated using a linear regression of charcoal concentration predicted by the  $\log_{10}$  of silts and clays to sands. The relationship between charcoal and grain size for all modern analog samples was used to calculate the predicted high-severity fire curve. The relationship between charcoal and grain size for all paleoecological samples was used to calculate the predicted charcoal concentration for ancient fires.

they varied significantly due to varying depositional energy (Figs. 4 and 5). Pine pollen at both localities was generally within the range of historical ponderosa pine forests at the time. Grass and ruderal pollen increased over time within Unit I at FDV 6 (from 21% to 49.3%) and fluctuated at FDV 10 (from 6.9% to 29.2%). *Zea* pollen was recovered from the ACb11 soil at FDV 10. Phosphorus was generally low at both Forestdale Valley localities but was lower at FDV 6 than at FDV 10, which may be due to the fluctuating water table putting phosphate into solution and leaching it from the locality. *Sporormiella* spores were absent entirely from FDV 10, and only found in traces from two pollen samples from FDV 6 for this period.

Soils ACb3 through ACb6 at FDV 6 and ACb2 through ACb6 at FDV 10 are roughly assigned to land-use Period 2, with the lowest-intensity use of the areas. In these strata, charcoal declined and became less variable at both Forestdale Valley localities, although the fine-grained overbank deposits would have been suitable for higher charcoal concentrations, hence our higher predicted than actual charcoal concentrations. Pine pollen was essentially unchanged from the Unit I ranges until ACb4, when it declined at both localities for the rest of the record, corresponding

to an increase in the abundance of grass and ruderal pollen. Phosphorus declined slightly in the unoccupied period at FDV 10, but without the impact of leaching at FDV 6 it increased slightly. *Sporormiella* spores were more common at FDV 6 and at very high levels (6.9%) from a pollen sample in ACb6 (immediately after Pueblo depopulation) that otherwise had very low pollen abundance. The only measurable *Sporormiella* spores in the entire record at FDV 10 were also from the ACb6 soil immediately after Pueblo depopulation.

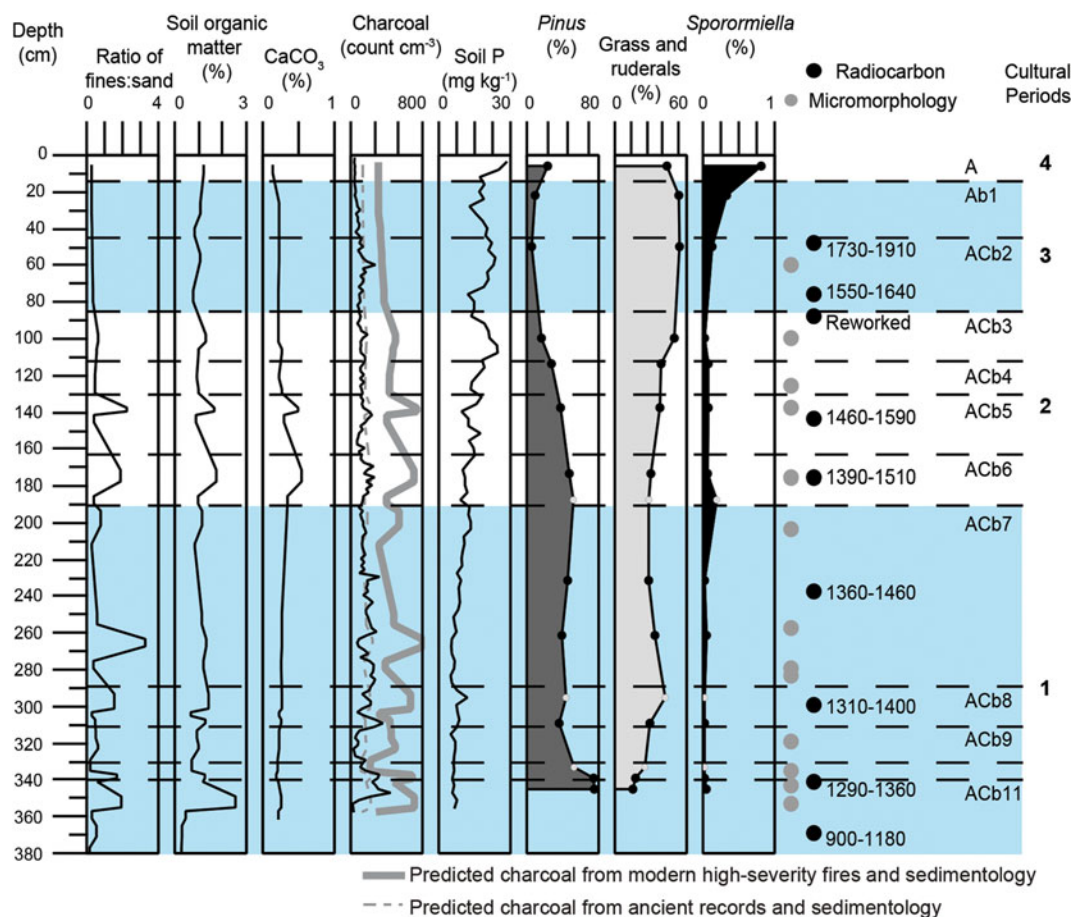
Soils ACb1 and ACb2 belong to the period of intensive Apache land use (Period 3), wherein charcoal remained essentially the same or declined from the Period 2 at FDV 6 and FDV 10, even when accounting for grain-size differences that would predict lower charcoal concentrations. Phosphorus was variable but increased in both Forestdale localities. Pine pollen and grass and ruderal pollen continued the pattern established by the formation of ACb4 with lower pine pollen and elevated grass and ruderal pollen. While *Sporormiella* was absent from Apache-era deposits at FDV 10, concentrations at FDV 6 increased at that time.

DaW 14 was a 2.55-m-deep trench cut into an alluvial channel fan within a meander bend of Day Wash (Figs. 1 and 2). The

**Table 4.** Paleoeological proxies across cultural periods.<sup>a</sup>

| Locality and period <sup>b</sup>           | Charcoal<br>(count/cm <sup>3</sup> ) | Soil P<br>(mg/kg)          | <i>Pinus</i> pollen (%)     | Grass and ruderal pollen (%) | <i>Sporormiella</i> spores (%) |
|--------------------------------------------|--------------------------------------|----------------------------|-----------------------------|------------------------------|--------------------------------|
| FDV 6—Period 1                             |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 115.8 ± 62.9                         | 4.9 ± 1.5                  | 46.7 ± 17.3                 | 35.8 ± 12.4                  | 0.4 ± 0.6                      |
| Range                                      | 2–326.8                              | 2.9–8.6                    | 30.6–65.7                   | 21–49.3                      | 0–1.1                          |
| FDV 6—Period 2<br>(without ACb3–ACb4)      |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 92.0 ± 34.3<br>(101.5 ± 40.2)        | 10.0 ± 3.0<br>(8.3 ± 1.9)  | 27.1 ± 11.9<br>(36.4 ± 6.2) | 57.8 ± 12.4<br>(49.9 ± 8.2)  | 1.5 ± 1.0<br>(1.9 ± 0.3)       |
| Range                                      | 40.2–189<br>(40.2–189)               | 5.7–16.3<br>(5.7–11.7)     | 12.9–40.7<br>(32–40.7)      | 44.1–74.2<br>(44.1–55.7)     | 0–2.1<br>(1.7–2.1)             |
| FDV 6—Periods 3 and 4<br>(with ACb3–ACb4)  |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 56.5 ± 35.6<br>(64.6 ± 32.6)         | 12.6 ± 2.7<br>(12.5 ± 2.7) | 9.6 ± 8.4<br>(12.9 ± 8.2)   | 75.2 ± 9.1<br>(71.4 ± 10.2)  | 16.4 ± 14.4<br>(10.3 ± 13.2)   |
| Range                                      | 15.2–196<br>(15.2–196)               | 7.8–18.7<br>(7.8–18.7)     | 3.2–19.1<br>(3.2–22.9)      | 64.7–80.9<br>(57.2–80.9)     | 4.3–32.3<br>(0–32.3)           |
| FDV 10—Period 1                            |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 118.0 ± 97.5                         | 10.9 ± 3.6                 | 67.8 ± 7.4                  | 21.0 ± 8.8                   | 0 ± 0                          |
| Range                                      | 20–483.4                             | 3.4–20.7                   | 59.3–79.2                   | 6.9–29.2                     | 0–0                            |
| FDV 10—Period 2<br>(without ACb2–ACb4)     |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 80.4 ± 33.2<br>(79.64 ± 40.0)        | 11.4 ± 2.9<br>(9.9 ± 3.2)  | 54.6 ± 12.6<br>(68.2 ± 2.1) | 38.6 ± 12.0<br>(26.0 ± 1.5)  | 0.32 ± 0.7<br>(0.8 ± 1.1)      |
| Range                                      | 26.0–149.4<br>(26.0–149.4)           | 7.3–18.3<br>(7.3–18.3)     | 42.4–69.7<br>(66.7–69.7)    | 24.9–51.8<br>(24.9–27.0)     | 0–1.6<br>(0–1.6)               |
| FDV 10—Periods 3 and 4<br>(with ACb2–ACb4) |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 94.1 ± 40.4<br>(87.9 ± 35.9)         | 16.0 ± 4.8<br>(14.2 ± 4.2) | 43.2<br>(44.9 ± 2.5)        | 48.6<br>(47.4 ± 4.0)         | 0.0<br>(0 ± 0)                 |
| Range                                      | 25.2–196.0<br>(25.2–196.0)           | 11.6–26.6<br>(8.2–26.6)    | NA<br>(42.4–47.5)           | NA<br>(42.3–51.8)            | NA<br>(0–0)                    |
| DaW 14—Unit I, Period 2                    |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 210 ± 155                            | 7.0 ± 4.1                  | 71.9 ± 15.0                 | 20.5 ± 9.3                   | 0.6 ± 1.2                      |
| Range                                      | 11.8–608.2                           | 3.3–20.1                   | 54.8–91.3                   | 6.9–27.4                     | 0–2.4                          |
| DaW 14—Unit II, Period 2                   |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 155.2 ± 34.0                         | 12.0 ± 5.5                 | 64.4 ± 3.1                  | 26.0 ± 4.8                   | 0.1 ± 0.1                      |
| Range                                      | 74.6–224.4                           | 5.9–27.2                   | 63.6 ± 70.7                 | 19.0–31.3                    | 0–0.3                          |
| DaW 14—Periods 3 and 4                     |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 101.6 ± 39.6                         | 25.7 ± 16.1                | 65.0 ± 22.6                 | 26.9 ± 15.5                  | 0.2 ± 0.3                      |
| Range                                      | 41.6–190.8                           | 8.2–62.8                   | 27.9–89.0                   | 8.0–50.5                     | 0–0.8                          |
| DaW 16—high-severity fire                  |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 338.5 ± 177.9                        | 53.7 ± 34.6                | 85.9 ± 3.5                  | 8.7 ± 2.4                    | 0.4 ± 0.3                      |
| Range                                      | 36–702.8                             | 6.5–130.4                  | 82.1–90                     | 5.6–11.3                     | 0–0.7                          |
| Rocky Draw—high-severity fire              |                                      |                            |                             |                              |                                |
| Mean ± SD                                  | 272.9 ± 226.3                        | NA                         | 93.4                        | 5.0                          | 0                              |
| Range                                      | 34.0–807.2                           | NA                         | NA                          | NA                           | NA                             |

<sup>a</sup>Values for modern analog samples after high-severity fire are included for comparison.<sup>b</sup>DaW, Day Wash; FDV, Forestdale Valley.



**Figure 4.** Stratigraphic plot for Forestdale Valley 6 (FDV 6) showing grain size, organic matter, carbonate, charcoal, phosphorus, *Pinus* pollen, *Sporormiella*, the location of radiocarbon and micromorphology samples, and rounded Bayesian-calibrated age ranges. Blue areas indicate rough assignments of soil strata to cultural periods based on an age-depth model of Bayesian-calibrated radiocarbon ages. Samples with pollen grain counts below 50 are displayed in figure as gray dots but not included in our pollen interpretations.

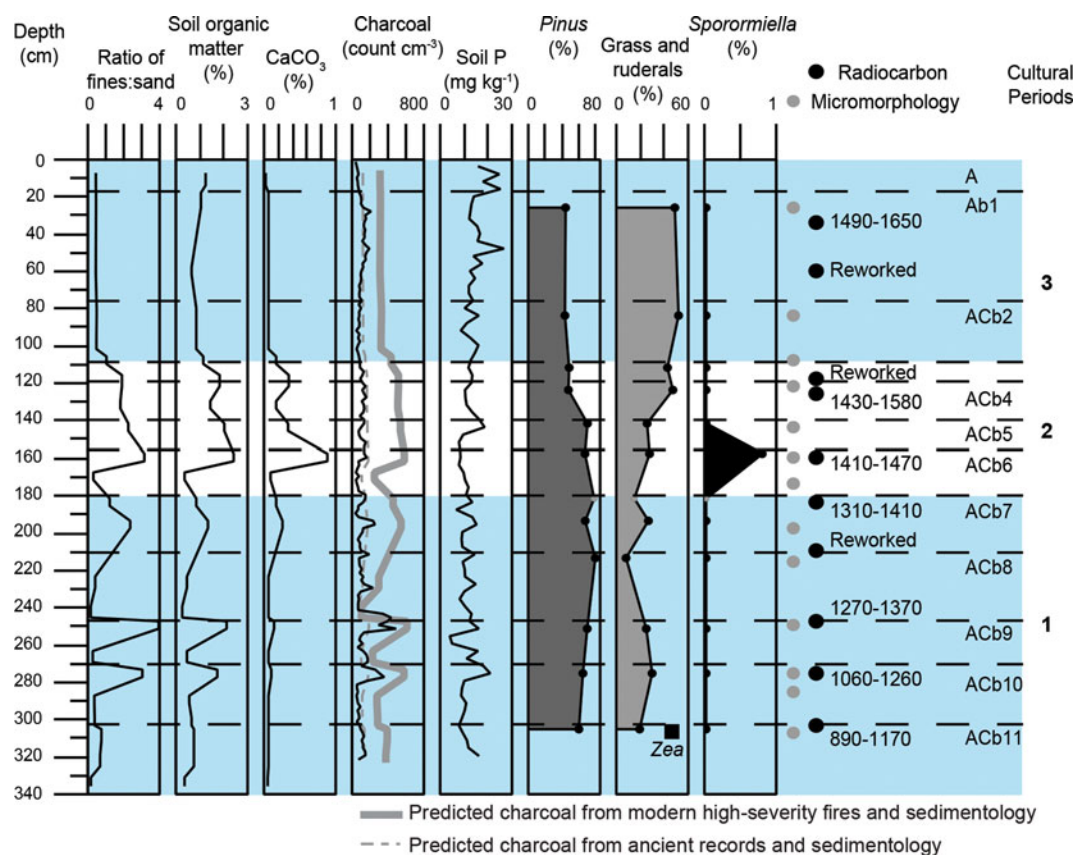
exposed strata contain two lithostratigraphic units that include massive weakly sorted upward-fining sets with intercalated charcoal beds (Unit I; soil ACb10) underlying upward-coarsening sets of weakly separated sandy alluvial soils indicated by diffuse, irregular boundaries between units; micromorphological observations of homogenization and biological activity; and SOM measurements (Unit II; A to ACb9). Micromorphological observations indicate that Unit I accumulated very rapidly and included the preservation of unweathered ashes visible in thin section (Roos, 2008; Fig. 7). Radiocarbon dates point to the deposition of Unit I in the mid- to late AD 1400s (Period 2). These dates were assumed to be contemporaneous in the Bayesian calibrations. Unit II accumulated more slowly than Unit I but still relatively rapidly, with both depositional and pedogenic features present in soil thin sections. Radiocarbon dates suggest that Unit II formed between AD 1500 and AD 1910, assuming modern down-cutting occurred here contemporaneous with its occurrence in Forestdale.

Because deposition at DaW 14 began in the AD 1400s, there is no stratigraphic evidence for intensive Ancestral Pueblo land use, which would have ended there by AD 1325 (Mills et al., 1999b). Unit I deposits formed during Period 2, when the area was less intensively used (Fig. 8). Unit I had the highest charcoal concentrations of any of the records, although this varied with

depositional energy. Even accounting for grain-size variability, these charcoal concentrations were comparable to the modern high-severity fire deposits (see Table 4). *Pinus* pollen was also at the highest levels in any record in association with the first organic-rich charcoal bed within this unit, at levels comparable to modern high-severity fire deposits (>90%). By contrast, soil P concentrations were relatively low, although this could have been impacted by postdepositional leaching, as at FDV 6. A spike in *Sporormiella* coincides with the uppermost charcoal bed near the top of this deposit.

Charcoal concentrations were lower in the Unit II–Period 2 strata, although they were higher than comparable strata at Forestdale and track grain-size predicted concentrations very closely. Soil P increased slightly, while pollen assemblages remained essentially unchanged from the top of the ACb10 soil at values consistent with a pine forest. Charcoal continued to decline in the Western Apache period, although this largely tracked changes in grain size. The most notable changes in the intensive Western Apache period (Period 3) were spikes in soil P and grass and ruderal pollen. *Sporormiella* spores, while low in concentration, show up in two pollen samples largely coincident with these spikes in soil P and ruderal pollen during the Western Apache period.

The surface soils at FDV 6, 10, and DaW 14 correspond to the period after the establishment of the Fort Apache Indian



**Figure 5.** Stratigraphic plot for Forestdale Valley 10 (FDV 10) showing grain size, organic matter, carbonate, charcoal, phosphorus, *Pinus* pollen, *Amaranthaceae* + *Asteraceae* + *Graminae* pollen, *Sporormiella*, the location of radiocarbon and micromorphology samples, and rounded age Bayesian-calibrated age ranges. Blue areas indicate rough assignments of soil strata to cultural periods based on an age–depth model of Bayesian-calibrated radiocarbon ages. Samples with pollen grain counts below 50 are displayed in figure as gray dots but not included in our pollen interpretations.

Reservation in 1870 (Period 4). These deposits have increased *Pinus* pollen, high levels of *Sporormiella* spores, and the lowest levels of charcoal concentrations, while FDV 6 and 10 have high levels of soil P.

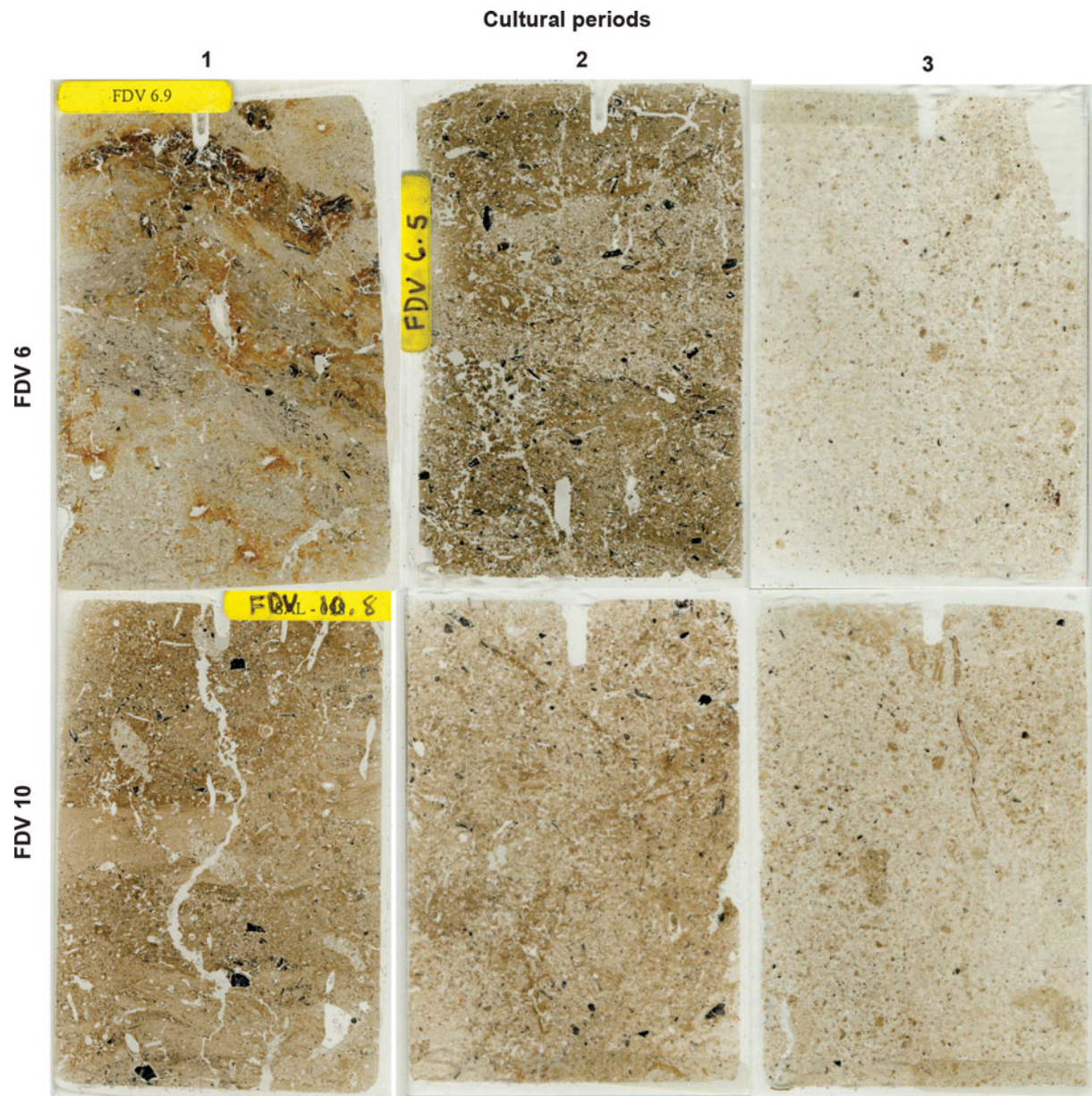
## DISCUSSION

Compared with the other periods, Period 1 at Forestdale had abundant charcoal, slightly higher phosphorus, and stable forest vegetation and domesticated pollen, which suggests that Pueblo and Apache residents of the area before AD 1400 used fire to manage their local landscape by adding extra burned area but not significantly impacting vegetation composition (Fig. 9; Table 5). This latter feature makes sense if the primary uses of fire were agricultural, perhaps something akin to the burn-plot farming hypothesized by Sullivan (Sullivan, 1982; Roos et al., 2010). In this area of low-nutrient soils, low-intensity burning of surface biomass would have recycled nutrients critical for agriculture (DeBano et al., 1998; Giardina et al., 2000). Moderate phosphorus concentrations in the alluvial sediments coincident with high levels of charcoal may indicate that much of the phosphorus generated by these low-intensity fires was taken up by cultigens and not remobilized to alluvial deposits (Giardina et al., 2000). At Forestdale, the biggest change when Ancestral Pueblo people migrated away from the area was a decline in charcoal and probably phosphorus (Tables 4 and 5). In other words, even in the absence of Pueblo burning, fires persisted, as

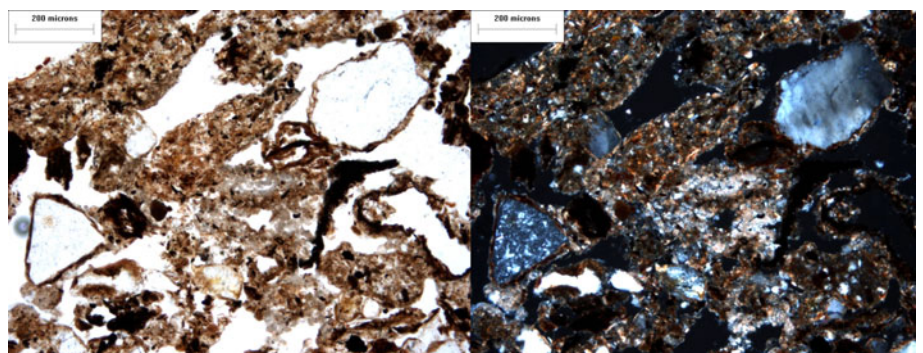
corroborated by Mogollon Rim-wide and local Forestdale fire-scar chronologies (Weaver, 1951; Kaib et al., 2000). A spike in *Sporormiella* immediately after Pueblo depopulation in Period 2 indicates that there may have been a recovery in local herbivores once hunting pressure was removed (Schollmeyer and Driver, 2013; Jones, 2015).

At Day Wash, however, the earliest deposits look very much like more recent high-severity fire deposits both in morphology and in the paleofire proxies. Rapid sedimentation with anomalously high charcoal concentrations and extraordinarily high unburned organic matter and *Pinus* pollen are all consistent with high-severity fire deposits (compare Unit I in Fig. 8 with Fig. 3c). There is a spike in *Sporormiella* within these deposits as well that could either be a reflection of the herbivore rebound from fifteenth-century Pueblo depopulation or a local postfire benefit to deer (*Odocoileus hemionus*) or elk (*Cervus canadensis*) populations from the mid-1400s high-severity fire (Lewis et al., 2022). Like at Forestdale, charcoal was abundant in Unit II deposits in association with normal forest pollen assemblages, probably indicative of a lightning-driven surface fire regime after the mid-1400s high-severity fire, suggesting that the AD 1400s fire was not large enough to remove the entire canopy, much like the 1974 Day Burn, which only burned a portion of the watershed and was followed by ponderosa pine regeneration.

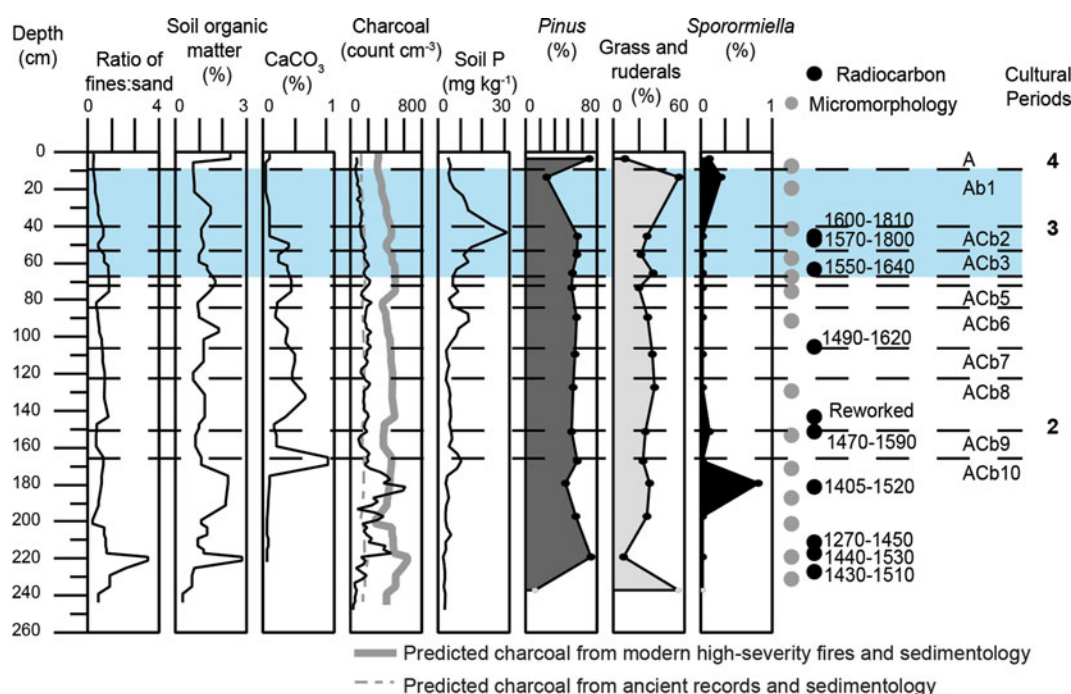
Western Apache economic and subsistence strategies focused on broad-spectrum hunting and gathering over large areas and included a wide variety of fire uses to promote hunting and



**Figure 6.** Macroscans of soil thin sections representative of each cultural period in the Forestdale Valley localities. Note the evidence of redox activity in FDV 6 in Period 1 soils and the decrease in both size and abundance of charcoal (black punctuations) in Period 3 soils at both localities. Notches mark the top of the sample. Each sample is ~50 mm wide.



**Figure 7.** Photomicrographs of unweathered ashes (gray rhombs in plane-polarized light; left) and with high order interference colors in cross-polarized light; right)) from Unit I at Day Wash 14 (DaW 14). These are indicative of very rapid deposition in the postfire environment to preserve these features.



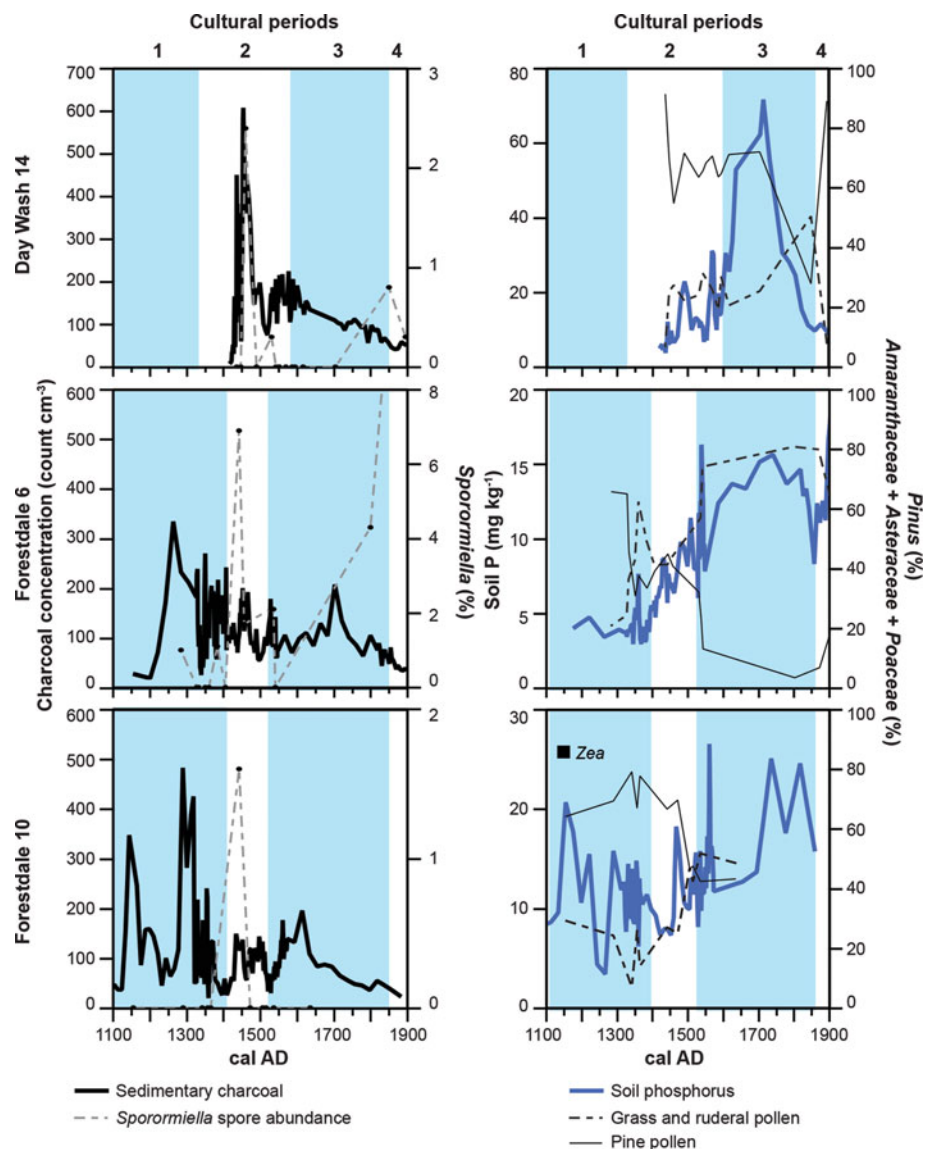
**Figure 8.** Stratigraphic plot for Day Wash 14 (DaW 14) showing grain size, organic matter, carbonate, charcoal, phosphorus, *Pinus* pollen, *Amaranthaceae* + *Asteraceae* + *Graminae* pollen, *Sporormiella*, the location of radiocarbon and micromorphology samples, and rounded Bayesian-calibrated age ranges. Blue areas indicate rough assignments of soil strata to cultural periods based on an age–depth model of Bayesian-calibrated radiocarbon ages. Samples with pollen grain counts below 50 are displayed in figure as gray dots but not included in our pollen interpretations.

gathering resources as well as to support gardening (Buskirk, 1986; Roos, 2015). We expected the most intensive Western Apache land use during Period 3, wherein charcoal declined but soil P and grass and ruderal pollen increased substantially at both Forestdale localities and at Day Wash. The elevated phosphorus and ruderal pollen would suggest increased fire activity that promoted these disturbance-loving taxa in the understory, but the charcoal is ambiguous (Fig. 9). Charcoal is sensitive to both changes in burned area but also to changes in fuel type (Marlon et al., 2006). Grass and herbaceous fine fuels combust more completely and produce less macroscopic charcoal (as measured here,  $>250\ \mu\text{m}$ ), so it is possible that increased burning in these fuel types may not have increased macroscopic charcoal production even as it did increase ash-related nutrients and favored disturbance-loving plants. Coincident with these increases in fire proxies are increases in *Sporormiella* at DaW 14 and FDV 6, which may indicate either large game benefiting from Apache cultural burning or, more likely, the keeping of domesticated livestock by Apaches (Basso, 1998). Apaches used fire for many purposes, including to promote economically important plants represented by the ruderal pollen (Buskirk, 1986; Roos, 2015). The increases in *Sporormiella* may mean that some of this burning was to improve pasture for livestock. The establishment of these patterns for Period 3 clearly began when ACb4 was formed at both FDV 6 and FDV 10, earlier than what is marked by the conservative age–depth estimates for Period 3 on Figures 4, 5, and 9, consistent with Antonio de Espejo's observations of intensive Apache land use before AD 1583 (Forbes, 1960, p. 59).

The contrasts between the fire proxies during different cultural periods suggest that the eastern Mogollon Rim area experienced four different fire regimes over the last 1000 years. During Pueblo and Apache occupation (Period 1), lightning and horticultural burning may have provided the greatest amounts of area

burned in surface fires over that time. When Pueblo people migrated away after AD 1400 and Apache use was light, fires persisted, but the substantial reduction of human ignitions reduced burned area or fire frequency. When Apache land use increased in intensity by the mid-sixteenth century, frequent surface fires in increasingly fine fuels promoted more grass, forb, and ruderal understory plants. Regional tree-ring records suggest that the Apache period had higher fire frequencies than much of the Southwest (Kaib et al., 2000). The fourth fire regime of the last millennium is the most contrastive with the other three. Beginning as early as the AD 1870s with settler colonialism and the suppression of traditional land use, fire has been largely excluded from Mogollon Rim forests until recent decades. The long fire-free intervals have increased stand density and made forests more vulnerable to high-severity, tree-killing fires. Two of the largest fires in Arizona's recorded history have been in the eastern Mogollon Rim region and the adjacent White Mountains. The 2002 Rodeo-Chediski and 2011 Wallow fires burned 380,000 ha of forest, much of this at high severity, including part of our study area. Before these megafires, the 1974 Day Burn burned at high severity, killing most trees in 1000 ha of our study area after at least six decades without fire. The basal deposits at Day Wash indicate that a high-severity fire event analogous to the 1974 Day Burn happened in the middle to late AD 1400s. Day Wash had been unoccupied by Ancestral Pueblo people for more than a century at that point, perhaps hinting that the absence of intensive Indigenous burning may have left some forests vulnerable to high-severity fire.

Paleoclimate patterns pertinent to ancient fire activity support these interpretations that the fire regimes described here are anthropogenic rather than driven by climate. In pine forests across the western United States, drought is a potent driver of burned area (Abatzoglou and Williams, 2016); the 10-year average



**Figure 9.** Plots of charcoal and *Sporormiella* (left), and phosphorus and grass and ruderal pollen (right) for Day Wash 14 (DaW 14; top), Forestdale Valley 6 (FDV 6; middle), and Forestdale Valley 10 (FDV 10; bottom) between AD 1100 and AD 1900 using age-depth models of Bayesian-calibrated radiocarbon ages. Blue areas indicate cultural periods.

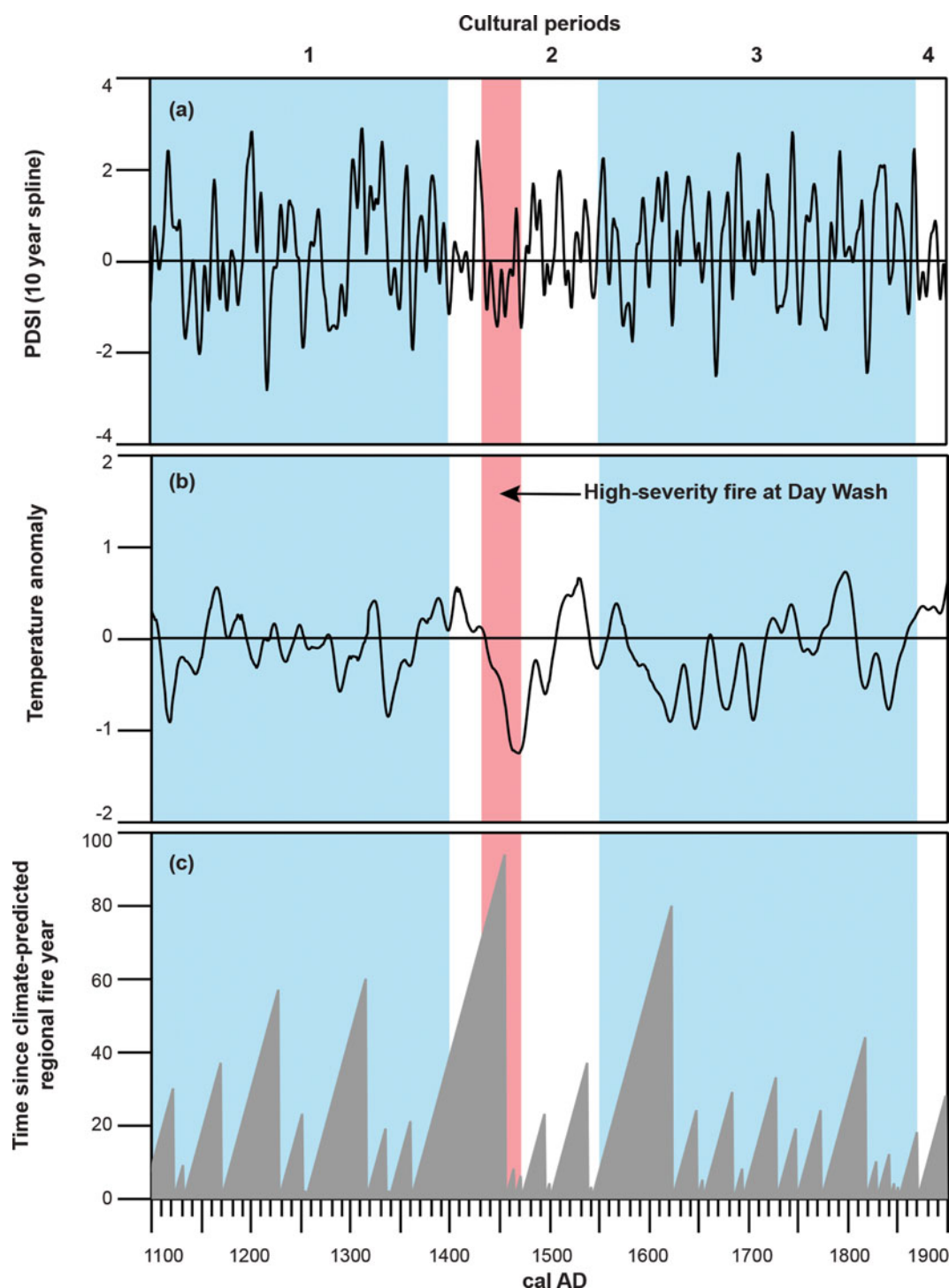
**Table 5.** General patterns of paleoecological proxies for each locality over time. All periods/proxies with high or anomalously high values are in bold.

| Locality and period                                                                  | Charcoal<br>(count/cm <sup>3</sup> ) | Soil P<br>(mg/kg) | <i>Pinus</i> pollen (%) | Grass and ruderal<br>pollen (%) | <i>Sporormiella</i><br>spores (%) |
|--------------------------------------------------------------------------------------|--------------------------------------|-------------------|-------------------------|---------------------------------|-----------------------------------|
| Period 1 (AD 1100–AD 1400)                                                           |                                      |                   |                         |                                 |                                   |
| Agricultural burning enhancing lightning fire regime                                 |                                      |                   |                         |                                 |                                   |
| FDV 6                                                                                | High                                 | Low               | Moderate                | High                            | Low                               |
| FDV 10                                                                               | High                                 | High              | High                    | Moderate                        | Anomalously low                   |
| Period 2 (AD 1400–AD 1600)                                                           |                                      |                   |                         |                                 |                                   |
| Lightning dominated fire regimes + AD 1400s local high-severity fire                 |                                      |                   |                         |                                 |                                   |
| FDV 6                                                                                | Moderate                             | Moderate          | Moderate                | High                            | High                              |
| FDV 10                                                                               | Moderate                             | Moderate          | High                    | Moderate                        | Moderate                          |
| DaW 14—Unit I                                                                        | Anomalously high                     | Low               | Anomalously high        | Low                             | Moderate                          |
| DaW 14—Unit II                                                                       | High                                 | High              | High                    | Moderate                        | Low                               |
| Period 3 (AD 1550–AD 1870)                                                           |                                      |                   |                         |                                 |                                   |
| Western Apache burning in fine fuels to enhance wild plants and forage for livestock |                                      |                   |                         |                                 |                                   |
| FDV 6                                                                                | Low                                  | High              | Low                     | Anomalously high                | Anomalously high                  |
| FDV 10                                                                               | Moderate                             | High              | Moderate                | High                            | Anomalously low                   |
| DaW 14                                                                               | Moderate                             | Anomalously high  | High                    | Moderate to high                | Low                               |

of the Palmer Drought Severity Index (PDSI; Cook et al., 2010; Gille et al., 2017) was dynamic across the Mogollon Rim region, but there are no clear long-term differences between the cultural periods (Fig. 10a). By contrast, long-term trends in temperature indicate clear differences between Period 1, which largely includes the warmer Medieval Climate Anomaly (MCA) and Periods 2 and 3, which include the Little Ice Age (LIA; Salzer et al., 2014; Fig. 10b). Paired two-sample *t*-tests identified no

significant differences in PDSI across the periods, but Periods 2 and 3 were significantly cooler than Period 1 at  $P \leq 0.05$ . Cooler temperatures during Period 3 may have enhanced fuel accumulation (Marlon et al., 2006), but this is actually in contrast to the evidence for lower charcoal deposition.

Fire activity in the Southwest has been influenced by more than just fire-year drought. Significantly wet years before the fire year were important to build sufficient and continuous



**Figure 10.** (a) Plots of Palmer Drought Severity Index (PDSI; Cook et al., 2010), (b) regional temperature (Salzer et al., 2014), and (c) intervals between regional fire years in a model of climate-driven surface fire activity (Roos and Swetnam, 2012) with the cultural periods used in this study and the possible evidence for high-severity fire in Day Wash in the mid-1400s. Blue areas indicate cultural periods, and pink bars indicate probable high-severity fire in Day Wash.

fuelbeds. Roos and Swetnam (2012) used dendroclimatic methods to calibrate a regression model of fire activity (percentage of regional tree-ring sites recording a fire) using up to three prior years and fire-year moisture. This reconstruction showed that conditions suitable for widely spreading fires were frequent during both the MCA and LIA but that the transition between the two may have seen unusually long fire-free intervals (Fig. 10c). These modeled climate drivers were equally common across the two most intensive land-use periods (Periods 1 and 3), indicating that the differences in fire proxies in the intensive-use periods cannot be explained by changes in climate drivers. However, longer fire return intervals may have been important in Period 2, when there is evidence for an increase in fire severity at DaW 14.

## CONCLUSIONS

Ethnographic, paleoecological, and tree-ring evidence indicates that Ancestral Pueblo and Apache people managed fire on their more intensively used cultural landscapes, albeit in culturally variable ways (Buskirk, 1986; Roos et al., 2021). Anthropologists and ecologists increasingly recognize that Indigenous people serve keystone roles in ecosystems (Bliege Bird and Nimmo, 2018; Ellis et al., 2021). Indigenous burning, fuelwood harvesting, seed dispersal, and predation all have impacts on ecosystem composition, structure, and diversity across scales. In detailed ecological and ethnographic studies, Indigenous burning had important positive benefits on between-patch biodiversity and prey abundance (Bliege Bird et al., 2018). The legacies of Indigenous land use may still be discernible in global biodiversity hot spots today (Ellis et al., 2021), especially when research goals are foregrounded in reference to Indigenous presence and knowledge systems.

Small-patch burning by Indigenous people produces pyrodiversity that can have important ecological consequences. Differences in the spatial pattern of fire can allow fire-sensitive taxa to coexist with flammable ones (Trauernicht et al., 2015). Even when fire frequencies are roughly similar between Indigenous and lightning-dominated fire regimes, cultural burning can modulate fire–climate relationships (Bliege Bird et al., 2012; Swetnam et al., 2016; Taylor et al., 2016; Carter et al., 2021).

The seeming redundancy of Indigenous burning with existing lightning fire regimes has sometimes been used to dismiss Native American burning as ecologically unimportant (Vale, 2002). As demonstrated here, ancient landscapes that were subject to Native American fire management produced different fire regimes than lightning-only regimes but were also culturally variable. Different cultural applications of landscape burning had variable impacts on more than just burned area, including the types of fuels burned and the ecological consequences of that burning.

This study highlights important temporal and spatial diversity in the pyrogeography of the Southwest and elsewhere. Across the Mogollon Rim and elsewhere in the Southwest (Roos et al., 2021), there were different fire regimes at different places and times across scales related to lightning density, topography, and prior disturbance as well as the intensity of human use, population density, and cultural practices of the local residents (Taylor et al., 2016; Roos et al., 2021). Particular local patterns should not be overgeneralized or projected across scales, because human behavior is spatially heterogeneous and scale dependent (Roos, 2020). Rather, scientists, managers, and policy makers need to recognize and appreciate this cross-scalar form of geographic pyrodiversity in research design and for place-based management.

**Data availability statement.** All pollen and geoarchaeological data are available via Neotoma (<https://www.neotomadb.org>). Dataset ID nos.: 54690 (FDV 10), 54686 (FDV 6), and 27241 (DaW 14).

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## REFERENCES

- Abatzoglou, J.T., Williams, A.P., 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences USA* **113**, 11770–11775.
- Allen, C.D., 2002. Lots of lightning and plenty of people: an ecological history of fire in the upland Southwest. In: Vale, T.R. (Ed.), *Fire, Native Peoples, and the Natural Landscape*. Island Press, Washington, DC, pp. 143–193.
- Basso, K.H., 1998. *Western Apache Raiding and Warfare: From the Notes of Grenville Goodwin*. University of Arizona Press, Tucson, AZ.
- Birkeland, P.W., 1999. *Soils and Geomorphology*. 3rd ed. Oxford University Press, New York.
- Blaauw, M., 2010. Methods and code for “classical” age-modelling of radiocarbon sequences. *Quaternary Geochronology* **5**, 512–518.
- Bliege Bird, R., Bird, D.W., Fernandez, L.E., Taylor, N., Taylor, W., Nimmo, D., 2018. Aboriginal burning promotes fine-scale pyrodiversity and native predators in Australia’s Western Desert. *Biological Conservation* **219**, 110–118.
- Bliege Bird, R., Coddling, B.F., Kauhanen, P.G., Bird, D.W., 2012. Aboriginal hunting buffers climate-driven fire-size variability in Australia’s spinifex grasslands. *Proceedings of the National Academy of Sciences USA* **109**, 10287–10292.
- Bliege Bird, R., Nimmo, D., 2018. Restore the lost ecological functions of people. *Nature Ecology & Evolution* **2**, 1050–1052.
- Bohrer, V.L., 1983. New life from ashes: the tale of the burnt bush (*Rhus trilobata*). *Desert Plants* **5**, 122–125.
- Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Cochrane, M.A., D’Antonio, C.M., DeFries, R.S., et al., 2011. The human dimension of fire regimes on Earth. *Journal of Biogeography* **38**, 2223–2236.
- Brown, A.G., 1997. *Alluvial Geoarchaeology: Floodplain Archaeology and Environmental Change*. Oxford University Press, Oxford, UK.
- Buck, C.E., Christen, J.A., James, G.N., 1999. BCal: on line Bayesian radiocarbon calibration tool. *Internet Archaeology* **7**. <https://doi.org/10.11141/ia.7.1>.
- Buck, C.E., Kenworthy, J.B., Litton, C.D., Smith, A.F.M., 1991. Combining archaeological and radiocarbon information: a Bayesian approach to calibration. *Antiquity* **65**, 808–821.
- Bull, W.B., 1997. Discontinuous ephemeral streams. *Geomorphology* **19**, 227–276.
- Buskirk, W., 1986. *The Western Apache: Living with the Land before 1950*. University of Oklahoma Press, Norman.
- Carter, V.A., Brunelle, A., Power, M.J., DeRose, R.J., Bekker, M.F., Hart, I., Brewer, S., et al., 2021. Legacies of Indigenous land use shaped past wildfire regimes in the Basin-Plateau Region, USA. *Communications Earth & Environment* **2**, 72.
- Cook, E.R., Seager, R., Heim, R.R., Vose, R.S., Herweijer, C., Woodhouse, C., 2010. Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context. *Journal of Quaternary Science* **25**, 48–61.

- Cowan, A.D., Smith, J.E., Fitzgerald, S.A., 2016. Recovering lost ground: effects of soil burn intensity on nutrients and ectomycorrhiza communities of ponderosa pine seedlings. *Forest Ecology and Management* **378**, 160–172.
- Davis, O.K., 1987. Spores of the dung fungus *Sporormiella*: increased abundance in historic sediments and before Pleistocene megafaunal extinction. *Quaternary Research* **28**, 290–294.
- Davis, O.K., 2007. *Palynology of Mogollon Rim Morphologic Features, Final Report on 13 Sites (Unpublished Report)*. University of Arizona, Tucson.
- DeBano, L.F., Neary, D.G., Ffolliott, P.F., 1998. *Fire's Effects on Ecosystems*. Wiley, New York.
- Dieterich, J.H., Swetnam, T.W., 1984. Dendrochronology of a fire scarred ponderosa pine. *Forest Science* **30**, 238–247.
- Ellis, E.C., Gauthier, N., Klein Goldewijk, K., Bliege Bird, R., Boivin, N., Díaz, S., Fuller, D.Q., et al., 2021. People have shaped most of terrestrial nature for at least 12,000 years. *Proceedings of the National Academy of Sciences USA* **118**, e2023483118.
- Ferguson, T.J., Hart, E.R., 1985. *A Zuni Atlas*. University of Oklahoma Press, Norman.
- Forbes, J.D., 1960. *Apache, Navaho, and Spaniard*. University of Oklahoma Press, Norman.
- Fulé, P.Z., Covington, W.W., Moore, M.M., 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. *Ecological Applications* **7**, 895–908.
- Giardina, C.P., Sanford, R.L., Dockersmith, I.C., 2000. Changes in soil phosphorus and nitrogen during slash-and-burn clearing of a dry tropical forest. *Soil Science Society of America Journal* **64**, 399–405.
- Gifford, E.W., 1940. *Apache-Pueblo*. University of California Press, Berkeley.
- Gille, E.P., Wahl, E.R., Vose, R.S., Cook, E.R., 2017. NOAA/WDS Paleoclimatology — Living Blended Drought Atlas (LBDA) Version 2—Recalibrated Reconstruction of United States Summer PMDI over the Last 2000 Years. NOAA National Centers for Environmental Information. <https://doi.org/10.25921/7xm8-jn36>.
- Goldberg, P., Berna, F., 2010. Micromorphology and context. *Quaternary International* **214**, 56–62.
- Gonzalez, S.L., Modzelewski, D., Panich, L.M., Schneider, T.D., 2006. Archaeology for the Seventh Generation. *American Indian Quarterly* **30**, 388–415.
- Graves, M.W., 1982. Apache adaptation to the mountains. In: Reid, J.J. (Ed.), *Cholla Project Archaeology*. Arizona State Museum Archaeological Series No. 161. Arizona State Museum, Tucson, pp. 193–215.
- Griffin, P.B., Leone, M.P., Basso, K.H., 1971. Western Apache ecology: from horticulture to agriculture. In: Basso, K.H., Opler, M.E. (Eds.), *Apachean Culture History and Ethnology*. University of Arizona Press, Tucson, pp. 69–73.
- Haury, E.W., 1985a [1940]. *Excavations in the Forestdale Valley, East-Central Arizona, Mogollon Culture in the Forestdale Valley, East-Central Arizona*. University of Arizona Press, Tucson, pp. 135–279.
- Haury, E.W., 1985b. *The Forestdale Valley Cultural Sequence, Mogollon Culture in the Forestdale Valley, East-Central Arizona*. University of Arizona Press, Tucson, pp. 375–407.
- Haury, E.W., 1985c. *Mogollon Culture in the Forestdale Valley, East-Central Arizona*. University of Arizona Press, Tucson.
- Haury, E.W., Sayles, E.B., 1985 [1947]. *An Early Pit House Village of the Mogollon Culture, Forestdale Valley, Arizona, Mogollon Culture in the Forestdale Valley, East-Central Arizona*. University of Arizona Press, Tucson, pp. 220–371.
- Hereford, R., 2002. Valley-fill alluviation during the Little Ice Age (ca. A.D. 1400–1880), Paria River Basin and Southern Colorado Plateau, United States. *Geological Society of America Bulletin* **114**, 1550–1563.
- Herr, S., North, C., Wood, J.S., 2009. Scouting for Apache archaeology in the sub-Mogollon Rim region. *Kiva* **75**, 37–62.
- Herr, S.A., 2001. *Beyond Chaco: Great Kiva Communities on the Mogollon Rim Frontier*. University of Arizona Press, Tucson.
- Herr, S.A., 2013. In search of lost landscapes: the Pre-reservation Western Apache archaeology of central Arizona. *American Antiquity* **78**, 679–701.
- Hevly, R.H., 1988. Prehistoric Vegetation and Paleoclimates on the Colorado Plateaus. In: Gummerman, G.J. (Ed.), *The Anasazi in a Changing Environment*. Cambridge University Press, Cambridge, pp. 92–118.
- Holliday, V.T., 2004. *Soils in Archaeological Research*. Oxford University Press, New York.
- Huckell, L.W., 1999. Paleoethnobotany. In: Mills, B.J., Herr, S.A., Van Keuren, S. (Eds.), *Living on the Edge of the Rim: Excavations and Analysis of the Silver Creek Archaeological Research Project 1993–1998*. Arizona State Museum, Tucson, pp. 459–504.
- Janitsky, P., 1986a. Organic carbon (Walkley-Black method). In: Singer, M.J., Janitsky, P. (Eds.), *Field and Laboratory Procedures Used in a Soil Chronosequence Study*. U.S. Government Printing Office, Washington, DC, pp. 34–36.
- Janitsky, P., 1986b. Particle-size analysis. In: Singer, M., Janitsky, P. (Eds.), *Field and Laboratory Procedures Used in a Soil Chronosequence Study*. U.S. Government Printing Office, Washington, DC, pp. 11–16.
- Jones, E.L., 2015. The “Columbian exchange” and landscapes of the Middle Rio Grande Valley, USA, AD 1300–1900. *The Holocene* **25**, 1698–1706.
- Kaib, M.J., Swetnam, T.W., Morino, K.A., 2000. *Fire history reconstructions in the Mogollon Province ponderosa pine forests of central Arizona*. International Multiproxy Paleofire Database. NOAA/NCDC Paleoclimatology Program, Boulder, CO.
- Kaldahl, E.J., Dean, J.S., 1999. Climate, vegetation, and dendrochronology. In: Mills, B.J., Herr, S.A., Van Keuren, S. (Eds.), *Living on the Edge of the Rim: Excavations and Analysis of the Silver Creek Archaeological Research Project 1993–1998*. Arizona State Museum, Tucson.
- Kaldahl, E.J., Van Keuren, S., Mills, B.J., 2004. Migration, factionalism, and the trajectories of Pueblo IV period clusters in the Mogollon Rim region. In: Adams, E.C., Duff, A.I. (Eds.), *The Protohistoric Pueblo World, A.D. 1275–1600*. University of Arizona Press, Tucson.
- Karlstrom, E.T., 2005. Late quaternary landscape history and geoarchaeology of two drainages on Black Mesa, northeastern Arizona. *Geoarchaeology* **20**, 1–28.
- Kimmerer, R.W., Lake, F.K., 2001. The role of Indigenous burning in land management. *Journal of Forestry* **99**, 36–41.
- Lake, F.K., Wright, V., Morgan, P., McFadzen, M., McWethy, D., Stevens-Rumann, C., 2017. Returning fire to the land: celebrating traditional knowledge and fire. *Journal of Forestry* **115**, 343–353.
- Lewis, J.S., LeSueur, L., Oakleaf, J., Rubin, E.S., 2022. Mixed-severity wildfire shapes habitat use of large herbivores and carnivores. *Forest Ecology and Management* **506**, 119933.
- Machette, M., 1986. Calcium and magnesium carbonates. In: Singer, M.J., Janitsky, P. (Eds.), *Field and Laboratory Procedures Used in a Soil Chronosequence Study*. U.S. Government Printing Office, Washington, DC, pp. 30–33.
- Marlon, J., Bartlein, P.J., Whitlock, C., 2006. Fire-fuel-climate linkages in the northwestern USA during the Holocene. *The Holocene* **16**, 1059–1071.
- Martin, P.S., 1963. *The Last 10,000 Years*. University of Arizona Press, Tucson.
- McWethy, D.B., Higuera, P.E., Whitlock, C., Veblen, T.T., Bowman, D.M.J.S., Cary, G.J., Haberle, S.G., et al., 2013. A conceptual framework for predicting temperate ecosystem sensitivity to human impacts on fire regimes. *Global Ecology and Biogeography* **22**, 900–912.
- McWethy, D.B., Whitlock, C., Wilmshurst, J.M., McGlone, M.S., Fromont, M., Li, X., Diffenbacher-Krall, A., Hobbs, W.O., Fritz, S.C., Cook, E.R., 2010. Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. *Proceedings of the National Academy of Sciences USA* **107**, 21343–21348.
- Mills, B.J., 1999. The reorganization of Silver Creek communities from the 11th to 14th centuries. In: Mills, B.J., Herr, S.A., Van Keuren, S. (Eds.), *Living on the Edge of the Rim: Excavations and Analysis of the Silver Creek Archaeological Research Project 1993–1998*. Arizona State Museum, Tucson, AZ, pp. 505–511.
- Mills, B.J., Herr, S.A., 1999. Chronology of the Mogollon Rim region. In: Mills, B.J., Herr, S.A., Van Keuren, S. (Eds.), *Living on the Edge of the Rim: Excavations and Analysis of the Silver Creek Archaeological Research Project 1993–1998*. Arizona State Museum, Tucson, pp. 269–293.
- Mills, B.J., Herr, S.A., Kaldahl, E.J., Newcomb, J.M., Riggs, C.R., Van Dyke, R.M., 1999a. Excavations at Pottery Hill. In: Mills, B.J., Herr, S.A., Van Keuren, S. (Eds.), *Living on the Edge of the Rim: Excavations and Analysis of the Silver Creek Archaeological Research Project 1993–1998*. Arizona State Museum, Tucson, pp. 117–148.

- Mills, B.J., Van Keuren, S., Stinson, S.L., Graves, W.M., III, Kaldahl, E.J., Newcomb, J.M., 1999b. Excavations at Bailey Ruin. In: Mills, B.J., Herr, S.A., Van Keuren, S. (Eds.), *Living on the Edge of the Rim: Excavations and Analysis of the Silver Creek Archaeological Research Project 1993–1998*. Arizona State Museum, Tucson, AZ, pp. 149–242.
- Moore, M.M., Covington, W.W., Fulé, P.Z., 1999. Reference conditions and ecological restoration: a southwestern ponderosa pine perspective. *Ecological Applications* **9**, 1266–1277.
- Newcomb, J.M., 1999. Silver Creek settlement patterns and paleodemography. In: Mills, B.J., Herr, S.A., Van Keuren, S. (Eds.), *Living on the Edge of the Rim: Excavations and Analysis of the Silver Creek Archaeological Research Project 1993–1998*. Arizona State Museum, Tucson, pp. 31–52.
- Nichols, G.J., Cripps, J.A., Collinson, M.E., Scott, A.C., 2000. Experiments in waterlogging and sedimentology of charcoal: results and implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* **164**, 43–56.
- Oswald, W.W., Foster, D.R., Shuman, B.N., Chilton, E.S., Doucette, D.L., Duranleau, D.L., 2020. Conservation implications of limited Native American impacts in pre-contact New England. *Nature Sustainability* **3**, 241–246.
- Parker, C.H., Keefe, E.R., Herzog, N.M., O'Connell, J.F., Hawkes, K., 2016. The pyrophilic primate hypothesis. *Evolutionary Anthropology: Issues, News, and Reviews* **25**, 54–63.
- Rankin, A.G., 1980. Pollen analytical studies in Corduroy Creek. In: Stafford, C.R., Rice, G.E. (Eds.), *Studies in the Prehistory of the Forestdale Region, Arizona*. Office of Cultural Resource Management, Department of Anthropology, Arizona State University, Tempe, pp. 333–373.
- Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin, M., et al., 2020. The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 Cal KBP). *Radiocarbon* **62**, 725–757.
- Rhodes, A.N., 1998. A method for the preparation and quantification of microscopic charcoal from terrestrial and lacustrine sediment cores. *The Holocene* **8**, 113–117.
- Riggs, C.R., 2010. Late Ancestral Pueblo or Mogollon Pueblo? An architectural perspective on identity. *Kiva* **76**, 245–270.
- Roos, C.I., 2005. Mobile farmers? Placing the Hall Point site in local context. paper presented at the 70th Annual Meeting of the Society for American Archaeology, Salt Lake City, UT, March 30 to April 3, 2005.
- Roos, C.I., 2008. *Fire, Climate, and Social-Ecological Systems in the Ancient Southwest: Alluvial Geoarchaeology and Applied Historical Ecology, Anthropology*. University of Arizona, Tucson.
- Roos, C.I., 2015. Western Apache pyrogenic placemaking in the mountains of eastern Arizona. In: Scheiber, L.L., Zedeño, M.N. (Eds.), *Engineering Mountain Landscapes: An Anthropology of Social Investment*. University of Utah Press, Salt Lake City, pp. 116–125.
- Roos, C.I., 2020. Scale in the study of Indigenous burning. *Nature Sustainability* **3**, 898–899.
- Roos, C.I., Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Cochrane, M., D'Antonio, C.M., et al., 2014. Pyrogeography, historical ecology, and the human dimensions of fire regimes. *Journal of Biogeography* **41**, 833–836.
- Roos, C.I., Sullivan, A.P., III, McNamee, C., 2010. Paleoecological evidence for Indigenous burning in the upland Southwest. In: Dean, R.M. (Ed.), *The Archaeology of Anthropogenic Environments*. Center for Archaeological Investigations, Southern Illinois University, Carbondale, pp. 142–171.
- Roos, C.I., Swetnam, T.W., 2012. A 1416-year reconstruction of annual, multi-decadal, and centennial variability in area burned for ponderosa pine forests of the southern Colorado Plateau region, Southwest US. *The Holocene* **22**, 281–290.
- Roos, C.I., Swetnam, T.W., Ferguson, T.J., Liebmann, M.J., Loehman, R.A., Welch, J.R., Margolis, E.Q., et al., 2021. Native American fire management at an ancient wildland-urban interface in the Southwest United States. *Proceedings of the National Academy of Sciences USA* **118**, e2018733118.
- Roos, C.I., Williamson, G.J., Bowman, D.M.J.S., 2019. Is anthropogenic pyrodiversity invisible in paleofire records? *Fire* **2**, 42.
- Salzer, M.W., Bunn, A.G., Graham, N.E., Hughes, M.K., 2014. Five millennia of paleotemperature from tree-rings in the Great Basin, USA. *Climate Dynamics* **42**, 1517–1526.
- Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Soil Survey Staff, 2012. *Field Book for Describing and Sampling Soils*. Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.
- Schollmeyer, K.G., Driver, J.C., 2013. Settlement patterns, source-sink dynamics, and artiodactyl hunting in the prehistoric U.S. Southwest. *Journal of Archaeological Method and Theory* **20**, 448–478.
- Scott, A.C., Cripps, J.A., Collinson, M.E., Nichols, G.J., 2000. The taphonomy of charcoal following a recent heathland fire and some implications for the interpretation of fossil charcoal deposits. *Palaeogeography, Palaeoclimatology, Palaeoecology* **164**, 1–31.
- Stoops, G., 2003. *Guidelines for Analysis and Description of Soil and Regolith Thin Sections*. Soil Science Society of America, Madison, WI.
- Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. *Eos, Transactions American Geophysical Union* **38**, 913–920.
- Sullivan, A.P., III, 1982. Mogollon agrarian ecology. *The Kiva* **48**, 1–15.
- Sullivan, A.P., Mink, P.B., 2018. Theoretical and socioecological consequences of fire foodways. *American Antiquity* **83**, 619–638.
- Swetnam, T.W., Baisan, C.H., 2003. Tree-ring reconstructions of fire and climate history of the Sierra Nevada and Southwestern United States. In: Veblen, T.T., Baker, C.M., Montenegro, G., Swetnam, T.W. (Eds.), *Fire and Climate Change in Temperate Ecosystems of the Western Americas*. Springer, New York, pp. 158–195.
- Swetnam, T.W., Farella, J., Roos, C.I., Liebmann, M.J., Falk, D.A., Allen, C.D., 2016. Multiscale perspectives of fire, climate and humans in western North America and the Jemez Mountains, USA. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**, 20150168.
- Taylor, A.H., Trouet, V., Skinner, C.N., Stephens, S., 2016. Socioecological transitions trigger fire regime shifts and modulate fire-climate interactions in the Sierra Nevada, USA, 1600–2015 CE. *Proceedings of the National Academy of Sciences USA* **113**, 13684–13689.
- Terry, R.E., Hardin, P.J., Houston, S.D., Nelson, S.D., Jackson, M.W., Carr, J., Parnell, J., 2000. Quantitative phosphorus measurement: a field test procedure for archaeological site analysis at Piedras Negras, Guatemala. *Geoarchaeology* **15**, 151–166.
- Trauernicht, C., Brook, B.W., Murphy, B.P., Williamson, G.J., Bowman, D.M.J.S., 2015. Local and global pyrogeographic evidence that indigenous fire management creates pyrodiversity. *Ecology and Evolution* **5**, 1908–1918.
- Traverse, A., 2007. *Paleopalynology*. Springer Science & Business Media, New York.
- Vale, T.R., 2002. *Fire, Native Peoples, and the Natural Landscape*. Island Press, Washington, DC.
- Watt, E.T., 2015. *Don't Let the Sun Step Over You: A White Mountain Apache Family Life, 1860–1975*. University of Arizona Press, Tucson.
- Weaver, H., 1951. Fire as an ecological factor in the Southwestern ponderosa pine forests. *Journal of Forestry* **49**, 93–98.
- Welch, J.R., Riley, R., 2001. Reclaiming land and spirit in the Western Apache homeland. *American Indian Quarterly* **25**, 5–12.
- White, L.A., 1943. *New Material from Acoma*. Smithsonian Institution, Washington, DC.
- Whitlock, C., Larsen, C.P.S., 2001. Charcoal as a fire proxy. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), *Tracking Environmental Change Using Lake Sediments*. Kluwer Academic, Dordrecht, Netherlands, pp. 75–97.