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Tree rings reveal persistent Western Apache (Ndee) fire stewardship and niche construction in the American Southwest

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Identifying the influence of low-density Indigenous populations in paleofire records has been methodologically challenging. In the Southwest United States, well-replicated fire histories suggest that abundant lightning and suitable climate conditions drove frequent low-severity wildfires in dry pine forests independent of human activities even as ethnography provided hints that highly mobile indigenous populations used fire in myriad land use contexts. Here, we leverage published and unpublished tree-ring fire history records from pine forests in Western Apache (Ndee) traditional territory in central and eastern Arizona (N = 34 sites, N = 649 trees) to demonstrate that historical fire regimes were overwhelmingly influenced by Ndee cultural burning. Our tree-ring synthesis shows significantly more frequent fires in Ndee territory than elsewhere in the region for centuries before the establishment of reservations (1600–1870 CE). Despite the heightened fire activity, fires were largely small and asynchronous, occurred disproportionately in late April and May, when Ndee invested significant subsistence activities in these pine forests, and occurred independent of climate drivers. This suggests that Ndee fire stewardship created a patchwork of nearly annual small, spring fires that inhibited natural fire spread and limited the influence of drought on fire activity. Our work shows that even relatively small, highly mobile populations of forager-gardeners had significant influence on some pre-Euroamerican fire regimes despite abundant natural ignitions. Our study shows clearly that Indigenous fire management impacted fire-size distributions, fire frequencies, and fire seasonality in ways that cannot be explained by seasonal and annual lightning densities.

ponderosa pine forests | fire ecology | cultural burning | Western Apache

Significance

Indigenous fire stewardship—the practice of using controlled fire to achieve cultural goals—was well documented in contemporary communities and in the ethnographic record but has often been undetected in historical fire records. Here, we use well-replicated tree-ring records from Western Apache homelands in Arizona to show that fire regimes here were structured by Indigenous fire stewardship for centuries even as many fire regimes elsewhere in the region were driven primarily by lightning ignitions and climate over the last few millennia. Western Apache fire stewardship persisted on the San Carlos Reservation well into the 20th Century and provides an alternative model to current institutional prescribed burning for restoring cultural fire regimes and resilience to Southwestern dry forests.

Contemporary wildfires pose ecological, socioeconomic, and climatological challenges (1–4). In the Western United States, wildfires are burning in unprecedented ways, with substantial increases in canopy-killing high-severity burned areas that are transforming forests to nonforest conditions (5–8). Understanding the magnitude of these changes requires an understanding of historical fire regimes—regular patterns of fire frequency, size, seasonality, and severity (9–11). Although lightning ignitions are abundant in the Western United States (12), human ignitions remain a major contributor to modern fire regimes (13). Historically, many Indigenous populations in the Western United States used cultural burning as a deliberate land management tool (14) but identifying human influences in paleofire records of the region has been challenging (15), notably because of the widespread importance of lightning-started fires (16).

This has been a particularly thorny problem for the fire history of landscapes inhabited by mobile, low-density populations of foragers (17), who are thought to have dispersed their land-use activities so lightly and broadly across the landscape as to be difficult to observe in paleofire records (18). In areas with abundant lightning that burned once or twice per decade, such as the dry pine forests of the Southwest United States, identifying frequent burning by mobile foragers would be particularly challenging using conventional fire frequency metrics (19). Nevertheless, several studies indicate that while Indigenous fire stewardship might not be distinguishable from lightning fire regimes in terms of frequency, Indigenous burning might be evident in altered fire–climate associations (20, 21), burn patch size or synchroneity (22–25), and ecological impacts (26, 27). The ecological consequences of cultural burning by foragers may have generated reinforcing feedbacks for continued use of particular areas via niche construction (28) and Allee effects—increased fitness or niche productivity positively correlated with population density and intensity of use (29).

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Here we use 34 tree-ring fire history sites from within the traditional territory of Western Apaches (who refer to themselves as Ndee) in eastern and central Arizona (Fig. 1) to assess whether mobile, low-density populations of Ndee people influenced fire regimes in a landscape with abundant lightning ignitions. We compare the fire frequency, seasonality, size, and fire–climate associations for tree-ring sites within Ndee territory with 277 tree-ring sites from throughout Arizona and New Mexico [a subset of the sites from Roos et al. (21)] from the North American Fire-Scar Network (30).

Ndee traditional territory is unique in the Southwest for being an area with abundant pine forests that were continuously occupied by one culturally and linguistically related population throughout the period of greatest tree-ring sample depth (after 1600 CE) (27, 31) as well as for the depth of ethnographic and cultural knowledge about fire stewardship (32). Western Apaches used fire for myriad purposes in hunting, wild plant management, and horticultural enterprises but these were spatially and temporally heterogeneous in their distribution (Table 1) (32, 33). With the establishment of the White Mountain Reserve in 1870 (34), land use outside of the reservation was prohibited and traditional land stewardship within the reservation persisted but was heavily curtailed (31, 32, 35), although some off-reservation economic activities persisted for some time (36). This allows us to examine the unique signature of Western Apache fire management in the full multicentury record, as well as its persistence within the reservation after fire exclusion had interrupted fires outside of the reservation.

From the ethnographic and fire science literature, we hypothesize that Ndee people burned very frequently, perhaps even annually in some contexts (14, 18), but that fire sizes would have typically been small. In fact, overall fire sizes on Ndee landscapes, whether started by Apaches or lightning, would have been small due to the self-limiting effects of frequent burning even when climate was suitable for driving widespread fires (21, 32). Furthermore, Apache burning would have altered the seasonal occurrence of fires to timings that reflected Ndee land use (32).

We use these hypotheses to structure the following questions for our tree-ring analysis. Are fire return intervals in Ndee territory significantly shorter than fire intervals at sites across Arizona and New Mexico? Were fires in Ndee territory unusually small compared to the rest of the region? Did fires in Ndee territory burn with a different seasonal pattern than other sites? If so, could any of these patterns in fire size, frequency, or seasonality be explained by the lightning and precipitation climatology of the Ndee forests? Did fires in Ndee territory mute the influence of climate drivers of fire activity as seen elsewhere in the region (21)?

Western Apache Settlement, Land Use, and Fire Use. The term Western Apache has been applied by anthropologists and historians to Indigenous populations in the rugged country of eastern and central Arizona that share linguistic and cultural traits (31). Ndee traditional territory covered roughly 48,800 km^2 in 1850 (35) and mid-19th century populations were estimated to have been 4,000 to 5,000 people (31, 37) for an average population density of less than 0.1 person km^{-2}.

Ndee people in Western Apache territory were primarily organized in matrilocal local groups, which were made up of extended family households called *gota* and defined largely on the location of farm sites and their associated longer-term camp sites. Linguistic

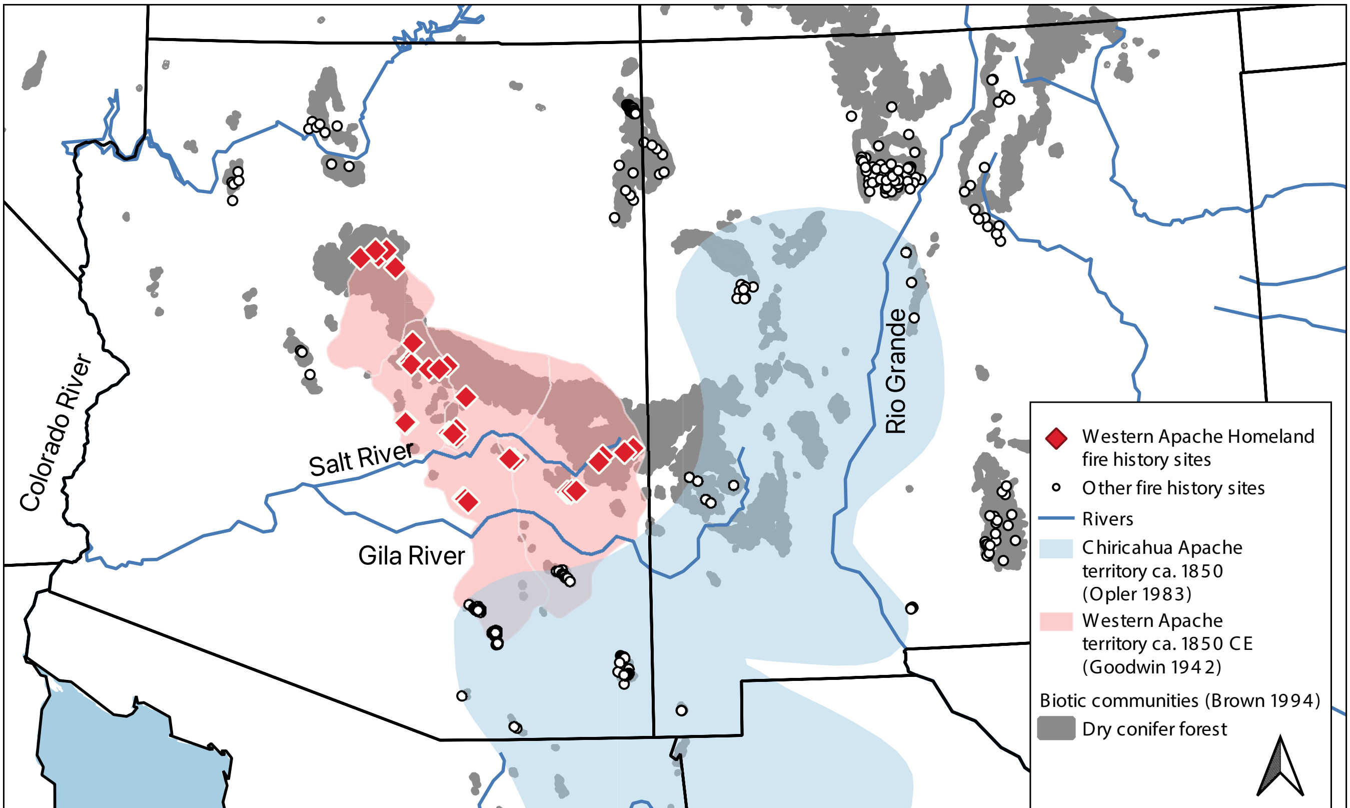

Fig. 1. The location of tree-ring fire history sites used in this study (red diamonds; N = 34 sites) within Western Apache traditional territory (pink area). Regional fire history sites from the International Multiproxy Paleofire Database (IMPD; white dots; N = 277 sites) used in regional comparisons (21), the traditional territory of Chiricahua Apaches (blue area), and the distribution of dry conifer forests dominated by ponderosa pine (*Pinus ponderosa*; gray areas) are also indicated.

Table 1. Summary of Western Apache fire uses in myriad land-use contexts from Buskirk (32)

Category	Fire use	Ecological context	Seasonality	Pages
Horticulture	Field clearance	Farm sites (Upper Sonoran and pine forest)	April/May	61
Horticulture	Burning for grassy surface fuels for ash bed effect/nutrients	Farm sites (Upper Sonoran and pine forest)	April/May	25
Horticulture	Clean irrigation ditches	Farm sites (Upper Sonoran and pine forest)	April/May	43
Horticulture	Increase productivity of cultivated tobacco	Farm sites (Upper Sonoran and pine forest)	April/May	97
Horticulture	Clean up harvest detritus	Farm sites (Upper Sonoran and pine forest)	August–November	72
Hunting	Fire surround/drive of rabbits	"Suitable terrain"	Summer	135 to 136
Hunting	Fire surround/drive of deer	"Timbered high country" (pine and fir forests)	Summer	127, 131
Gathering	Increase productivity of wild seed collecting areas	?	?	165 to 166
Gathering	Promote wild tobacco	Farm sites (Upper Sonoran and pine forest)	April/May?	166
Gathering	Promote shrubs for basketry materials	Upper Sonoran and pine forest	?	166

and cultural similarities connected local groups into bands and bands into subtribal groups (Northern Tonto, Southern Tonto, Cibecue, San Carlos, and White Mountain groups). Despite the cultural importance of farm sites to Ndee local group identity, horticultural products made up a relatively small portion of the diet (<25%) (31, 32, 35). Buskirk and Goodwin both estimate that gathering and hunting made up the bulk of both the diet and economic pursuits. Subtribal groups varied in their emphasis on horticulture. For example, among the Northern Tonto, horticulture was almost never practiced (32) while it was most heavily practiced among Cibecue and White Mountain groups (35). However, even within subtribal groups, particular *gota* varied in their emphasis on horticulture.

The diverse geography of Western Apache territory had a major influence on Ndee resource availability and subsistence patterns. Western Apache hunted and gathered widely across biotic zones from the Sonoran Desert at the lowest elevations (below ca. 1,500 m), to semidesert grasslands and conifer woodlands with pinyon (*Pinus edulis*), juniper (Juniperus spp.), and various oaks (Quercus spp.) (1,350 to 2,450 m), to dry conifer forest dominated by ponderosa pine (*Pinus ponderosa*) and dry mixed conifer forests (ponderosa with *Pseudotsuga menziesii*, *Pinus strobiformis*) and oaks (2,100 to 2,900 m), to the highest elevation subalpine conifer forests with spruce (Picea spp.) and fir (Abies spp.) (2,700 to 3,700 m) (38).

Ndee *gota* moved among these life zones in an annual hunting and gathering pattern based primarily on the seasonality of wild plant and animal resources centered around their spring farm sites (areas with long-term camps nearby and small <0.4 ha plots of corn, beans, and squash) (35). Although some Apaches spent the winter months at or near their farm sites, many spent the cold months between November and March in lower elevations, moving every 10 to 14 d primarily to hunt and harvest mescal (Agave spp.) and visit friends. In late March, April, or May, local groups moved to farm sites in the woodland and dry conifer forest zones to clear, establish, and plant fields of corn, beans, and squash. Fire was used in preparing, cleaning up debris, and recycling nutrients in horticultural fields as well as for cleaning up irrigation ditches (32).

After planting, most of the *gota* and local groups often migrated to hunting and foraging areas. Elderly and young often remained to maintain the farm sites. Summer hunting and foraging for food, fiber, and medicinal resources were found throughout the biotic zones included woodland (mescal, cactus), grassland, and dry conifer forest resources (acorns, grass seeds, greens, pine nuts) as well as the lower Sonoran Desert (saguaro fruits, mescal, mesquite [Prosopis spp.] pods). Some bands of Northern and Southern Tonto exclusively summered in the timbered high country (35), a practice that likely favored hunting (39).

Ndee fire uses were reported in numerous farming and hunting practices, to prepare wild tobacco plots, and in pine-nut gathering (Table 1) (32, 35). Fire was used to burn out pack-rat nests and to hunt turkey in roosts at night. Although most hunting was done by individual males, during the summer months groups of Ndee hunters might use fire drives or surrounds to harvest mule deer (*Odocoileus hemionus*) or jackrabbits (*Lepus californicus*) (32). In the fall, Ndee families returned to farm sites to harvest important wild resources (Chenopodioideae and Compositae seeds, acorns, pinyon nuts) and crops and store them at strategic locations for winter. Fall was also the best time for hunting game in the higher elevations before returning to lower elevations for winter camps.

Buskirk reports on myriad fire uses by Ndee people across their seasonal rounds (Table 1). All of these uses apply to contexts in the woodland or pine forest biotic zones tethered to foraging, hunting, and land-use activities within 5 to 10 km of the farm sites because these were bases for logistical foraging activities (40), even if not all of this fire stewardship is associated with horticulture. Further sources of anthropogenic ignitions would have included accidental and escaped fires from campsites. Western Apache myths and legends further connect Ndee fire stewardship and knowledge to dry pine forests. In traditional stories, before Ndee people possessed fire, the original fire keeper was Abert's squirrel (*Sciurus aberti*)—an animal endemic to ponderosa pine forests. When Ndee people acquired fire from Abert's squirrel their first act was to burn understory vegetation in the pine forest (41).

There is some evidence for Apache influences on fire regimes in local and landscape records across the Southwest. In alluvial stratigraphic records of the Forestdale Valley in the Carrizo Band territory of the Cibecue group on the White Mountain Apache Reservation, Roos et al. identified evidence for Ndee burning that enhanced the abundance of sunflower family plants and grasses for centuries (27) that persisted until the establishment of the reservation in 1870 CE. In the Chiricahua Mountains, Kaib identified changes in fire frequency associated with periods of warfare between Apaches and their neighbors (42). In Mescalero Apache territory in New Mexico, Kaye, and Swetnam identified subtle changes in fire frequency and seasonality during periods of local Apache use (43). At a larger landscape scale, Roos and others inferred that Apache fire management muted the impacts of climate across the Chiricahua and Pinaleño Mountains (21) and in other "sky island" mountain ranges in southern Arizona (44).

In this paper, we focus on the Ndee landscape north of the Gila River (hereinafter just Ndee or Western Apache territory) because the area south of the Gila overlaps with Chiricahua Apache territory (Fig. 1) and is close enough to the presidio and community of Tucson (est. 1775 CE) that traditional fire stewardship may have been regularly impacted by conflict with people of European descent and Indigenous Pima residents (21, 42). We further limit ourselves to the dry conifer forest biotic zone, particularly ponderosa pine and dry mixed conifer forests, because these are the areas from which most tree-ring fire history sites are located and the context for many ethnographic Ndee fire uses.

Fire Ecology of Southwestern United States Dry Conifer Forests. Southwestern dry conifer forests have one of the best-known historical fire regimes in the world, largely due to an extensive and well replicated tree-ring record of fire activity (20, 30). With more than 4,000 individual tree records and more than 400 site records published for the region (21), there is a robust pattern of frequent (once or twice per decade) surface fires that largely left mature trees alive but occasionally killed patches of trees up to 100 ha (9). Across the region fires predominantly occurred in the arid foresummer period up to the start of the summer monsoon (April–early July) (45). Climate played a significant role in synchronizing widespread fire activity across local to regional scales (46), although this was muted by Indigenous fire management at local and landscape scales in particular places during particular periods of time (21).

Years prior to fire events were generally significantly wet to produce abundant fine fuels and fire years were significantly dry to allow those fuels to dry and burn widely—what we call the "canonical" fire–climate association in the Southwest (45, 47, 48). Because lightning is abundant in the region and fires were already frequent, it has generally been challenging to unambiguously identify Indigenous contributions to fire regimes using conventional fire frequency metrics (16, 19).

Results

Fire Frequency. We analyzed individual tree records from 34 tree-ring fire history sites (N = 649 trees) from ponderosa pine dominated woodlands and mixed conifer forests in Ndee traditional territory north of the Gila River (*SI Appendix*, Table S1) and compare them to 277 fire history sites across Arizona and New Mexico (N = 3,880 trees; a subset of the 451 sites used by Roos et al. (21) that met the criteria for the current analysis; see *Materials and Methods*) for the 271-y period prior to the establishment of the Fort Apache Indian Reservation, 1600 to 1870 CE (Fig. 1). Fires occurred somewhere in Ndee traditional territory nearly every year (93.7% of all years). At least 10% of Ndee sites burned in 78% of all years and at least 25% of Ndee sites burned in 47.3% of all years (*SI Appendix*, Fig. S1). With the exception of sites in the nonagricultural Northern Tonto territory, virtually all fire history sites are in landscapes associated with Ndee farm sites or preferred longer-term camp sites (32, 35) (*SI Appendix*, Table S1).

Mean fire intervals for all Ndee homeland fires (MFI_{all}) were typically very short (mean = 3.9 y). Across both Ndee and regional sites, only 35 of 311 total sites (11.3%) had MFI_{all} less than 4 y. Twenty-one of these (60%) are from Ndee traditional territory north of the Gila River. Another five of these sites are from the Chiricahua Apache traditional territory, meaning that 74.3% of all Southwest fire history sites with MFI_{all} < 4 y are from Apache traditional homelands (*SI Appendix*, Fig. S2). There are only four sites in the entire region that had similarly frequent fires persist after 1920 (MFI_{all} < 4 y), all of which occur on the San Carlos Indian Reservation (*SI Appendix*, Fig. S1 and Table S2).

Fire frequency metrics at Ndee sites are not influenced by sample depth. Larger fire scar collections including more trees and larger sample areas tend to reduce fire intervals by capturing more fire events (49), so we specifically tested whether sample size (N trees) influenced the fire return intervals we found at Ndee sites. There were significant log–linear relationships between sample size and MFI_{all} for both regional sites (adjusted r^2 = 0.2176, P < 0.0001, slope = −0.35204) and Ndee sites (adjusted r^2 = 0.1783, P = 0.0075, slope = −0.2365) but with different intercept points. Ndee sites had significantly shorter MFI_{all} compared to the rest of the region, and this was clearly independent of sample size (Fig. 2 and Table 2). Regional mean MFI_{all} (11.0 y) was 2.8 times longer than the mean for Ndee sites (MFI_{all} = 3.9). The same was true when restricting the set of fire years to those that scarred at least 2 trees (MFI_2) or ≥25% of trees at each site scarred ($MFI_{25\%}$). Regional mean MFI_2 (15.1) and $MFI_{25\%}$ (16.8) were roughly twice that of Ndee MFI_2 (7.6) and $MFI_{25\%}$ (9.7), differences that are statistically significant (Table 2). The same was true if you replaced mean fire intervals with median fire intervals (Table 2).

Fires were so frequent at Ndee sites that consecutive fire years were remarkably common at individual sites and 1- and 2-y intervals were relatively common *on individual trees*. Of 6,572 precisely dated fire scars across Ndee sites, 10.1% were part of 1-y or 2-y fire interval sets on individual trees (Fig. 2*A*). Every-other-year scar intervals within trees are occasionally but less frequently observed in non-Ndee sites, and consecutive-year scars on the same trees are very rare (see examples from *SI Appendix*).

Nearly all (93.5%) of these 1- and 2-y interval sets of scars on the same tree date to the period before the establishment of the White Mountain Reserve in 1870. Of the 6.5% of these scar sets that postdate 1870, the samples largely fall into two categories: 1) they are located on the San Carlos Reservation, where frequent fires persisted beyond 1920; or 2) they are from the Sierra Anchas or other areas adjacent to the White Mountain Reserve dating prior 1891 when the Fort Apache Reservation was reshaped. More than half (N = 18) of all Ndee sites had at least one specimen with single-year fire intervals on the same tree.

In the past, differences in the environment, climate, or lightning abundance have been used to explain the unusually short fire-return intervals of Western Apache homeland tree-ring sites (51, 52). On average, Ndee sites are warmer, wetter, and lower in elevation than regional sites, although the ranges of values overlap substantially (Table 2). This suggests that, on average, Ndee sites may have been more productive in terms of biomass than regional sites, perhaps facilitating shorter fire return intervals by faster regrowth of herbaceous fuels. However, lightning strike densities are generally the same between Ndee and regional sites (for annual and fire season lightning) and Ndee lightning densities are significantly lower than regional sites during the dry period from April–June (Table 2). Lightning abundance and seasonal precipitation had very little relationship to MFI_{all} at both Ndee and regional

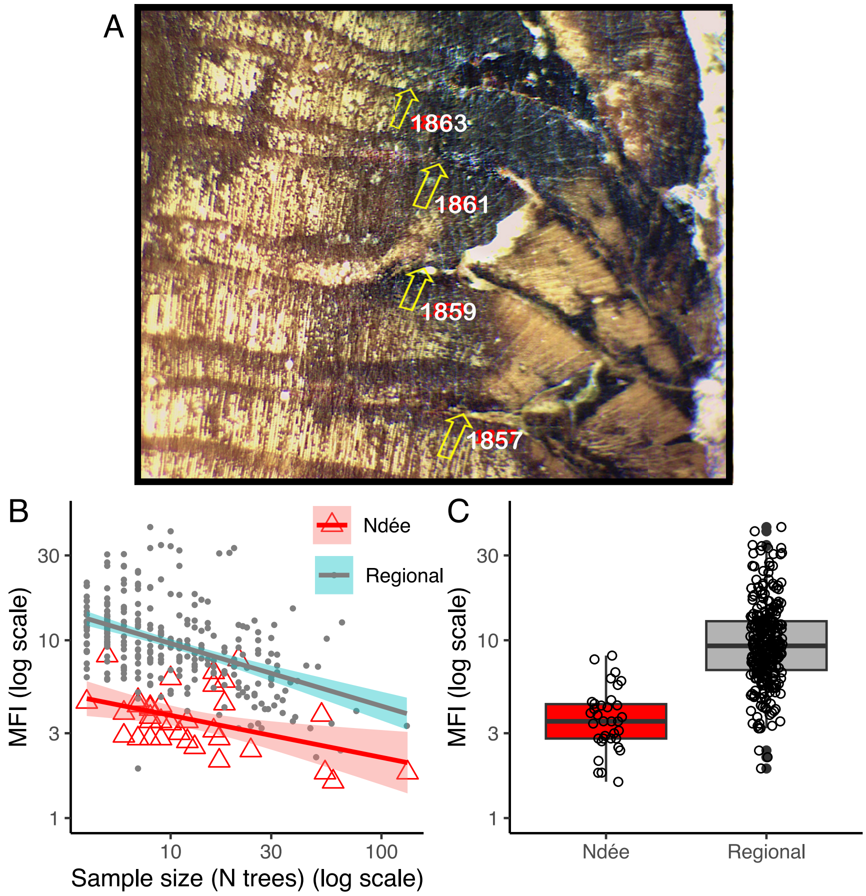

Fig. 2. Photomicrograph (*A*) of multiple every-other-year fire scars from sample LMF3 from Limestone Flat within the Western Apache (Ndee) homelands (50), and a scatterplot (*B*) and boxplot (*C*) of mean fire return intervals (MFI_{all}) for Ndee and all other (regional) sites. In (*B*), there are significant, negative log–linear relationships between sample size and MFI_{all} for regional sites and Ndee sites. Ndee sites have significantly shorter fire return intervals compared to the rest of the region (Table 2).

sites (Fig. 3) suggesting that neither lightning abundance nor seasonal precipitation explain variability in fire return intervals.

Fire–Climate Associations. Using all fire years at the local scale, very few Ndee sites (20.6%) had statistically significant fire–climate associations during 1600–1870 (Fig. 4*A*), whereas 41.9% of regional sites had significant fire–climate associations for the same period of time (Fig. 4*B*). Most Ndee sites had only slightly wet prior years [mean maximum prior year Palmer Drought Severity Index (PDSI) = 0.435 vs. 0.899 for regional sites] and slightly dry fire years (mean fire year PDSI = −0.39 vs. −0.968 for regional sites) while regional values were more than double for both measurements. Even when limiting the analysis to only fire years that burned at least 10% of Ndee sites, Superposed Epoch Analysis (SEA) indicates that there were no statistically significant fire–climate associations (Fig. 4*C*). Only when using the most widespread fire years that burned at least 25% of Ndee sites (i.e., highly synchronous fire events across sites) were statistically significant associations between fires and climate evident (Fig. 4 *A* and *D*). However, the actual deviations for prior year PDSI (0.806) and fire year PDSI (−0.698) for years with at least 25% sites burned were both lower magnitude than the mean values for all regional non-Apache sites, suggesting a relatively modest influence of climate on even the most widespread fire years (Fig. 4 *B* and *D*). By contrast, SEA on regional sites showed fires that burned at both 10% and 25% of all non-Apache sites had significant and high magnitude fire–climate associations with both fire-year drought and prior moisture for fuel production, i.e., the canonical fire–climate pattern (Fig. 4*D*) (21).

Fire Size. The ratio of MFI for highly synchronous or widespread fires (e.g., those that scarred at least 25% of all recording trees; $MFI_{25\%}$) to MFI_{all} can be used as a rough proxy for the relative importance of small fires in the fire regime of a particular stand or landscape. We follow Huffman and others (53) and Fulé and others (54) in using the $MFI_{25\%}$:MFI_{all} ratio with higher values to indicate a greater importance for small or nonsynchronous fire years. The $MFI_{25\%}$:MFI_{all} ratios for Ndee sites had a mean of 2.74. Twelve of the 34 Ndee sites (35.3%) had ratios greater than 2.5, indicating that at those sites, small fires were at least 2.5 times more common than highly synchronous fires. By contrast the $MFI_{25\%}$:MFI_{all} ratios for all regional sites had a mean of 1.86. Only 11.1% of regional sites for which this ratio could be calculated had ratios greater than 2.5. Western Apache sites have significantly higher $MFI_{25\%}$:MFI_{all} ratios (Table 2) indicating that small fires were significantly more frequent in Western Apache forests than elsewhere in the region (Fig. 5).

Fire Seasonality. We limit our seasonality comparisons of the Ndee sites to the seasonality of lightning strikes at these sites and to other Arizona sites outside of Chiricahua Apache territory, given the similar economies and mobility patterns between Western and Chiricahua Apaches (55). Compared to non-Apache Arizona sites, Western Apache sites have much greater representation of early earlywood scars (generally formed in late

Table 2. Descriptive statistics and statistical comparisons of fire history, elevation, and climate for Western Apache homeland tree-ring sites and all other regional tree-ring sites

	Western Apache homeland tree-ring sites (N = 34) Mean ± SD	Regional tree-ring sites (N = 277) Mean ± SD	Wilcoxon rank sum statistics
Elevation (m)	**2,028 ± 340**	**2,365 ± 315**	**W = 2,098, $P < 0.0001$**
Mean annual temperature (C)	**11.0 ± 2.1**	**9.4 ± 2.6**	**W = 6,324.5, $P = 0.0011$**
Mean annual precipitation (mm)	**651 ± 99**	**607 ± 143**	**W = 5,708, $P = 0.0436$**
April–June precipitation (mm)	**52 ± 8**	**70 ± 22**	**W = 2,794, $P = 0.0001$**
April–September precipitation (mm)	**268 ± 39**	**335 ± 84**	**W = 2,250, $P < 0.0001$**
Annual lightning count/100 km^2	338 ± 63.6	316 ± 95.3	W = 5,504, $P = 0.1598$
April–June lightning count/100 km^2	**24.3 ± 7.4**	**34.6 ± 18.3**	**W = 3,642, $P = 0.0311$**
April–September lighting count/100 km^2	323 ± 63.5	303 ± 93.6	W = 5,354, $P = 0.1927$
MFI_{all}	**3.9 ± 1.6**	**11 ± 6.8**	**W = 673, $P < 0.0001$**
Median FRI_{all}	**2.9 ± 1.5**	**9 ± 5.9**	**W = 665, $P < 0.0001$**
MFI_2	**7.6 ± 7.7**	**15.1 ± 8.8**	**W = 1,261.5, $P < 0.0001$**
Median FRI_2	**5.6 ± 5.7**	**12.9 ± 9.1**	**W = 1,086, $P < 0.0001$**
$MFI_{25\%}$	**9.8 ± 7.4**	**16.8 ± 8.9**	**W = 1,492.5, $P < 0.0001$**
Median $FRI_{25\%}$	**7.3 ± 5.4**	**14.4 ± 8.9**	**W = 1,113, $P < 0.0001$**
$MFI_{25\%:all}$	**2.7 ± 1.7**	**1.9 ± 1.0**	**W = 5,855, $P = 0.0001$**

Bold indicates statistically significant differences.

April and May) than would be expected (Fig. 6), a pattern that is statistically significant (Fisher's exact test $P < 0.001$). However, the significant increase in early earlywood scars is not present at all sites. Notably, it is absent from all (nonhorticultural) Northern Tonto group sites.

On average, early and middle earlywood scars make up 61.8% of all scars that can be assigned to season at Ndee sites. These scars likely correspond to fires in late April, May, and June. Lightning is significantly less abundant at Ndee sites from April to June (Fig. 3*C*) compared to regional sites, making lightning a less likely ignition source for the abundance of fires recorded during this time, particularly those from the early earlywood (April and May).

Discussion

Western Apache fire history sites have the shortest fire return intervals anywhere in the Southwest United States—a pattern that is statistically significant. While on average, these areas also have high annual and fire-season lightning densities, this pattern is not statistically different from the rest of the region and does not explain the short MFI at Ndee sites. The exclusive occurrence of this very high frequency fire regime before the establishment of the White Mountain Reserve in 1870 (except for on the Reserve where frequent fires persisted after the establishment of the Reserve) provides strong support that Ndee cultural burning (in addition to lightning fires) was responsible for the short fire return intervals.

This inference is further corroborated by the seasonality of much of the frequent burning. With the exception of Northern Tonto territories, Ndee fire history sites exhibit a surplus of fire scars in the early earlywood, which is generally assigned to late April and May (56, 57). This corresponds to the period when Ndee *gota* and local groups were returning to their farm sites, preparing for horticultural activities and engaging in intensive hunting (31, 32, 35) but lightning was relatively uncommon (Fig. 3*C*). Although not all Ndee *gota* farmed, farm sites and the migration to woodland and pine forest biotic zones in the spring were major features of annual settlement patterns. The Northern Tonto groups were least reliant upon horticulture (32, 35), so the difference between the seasonality of fire scars in the

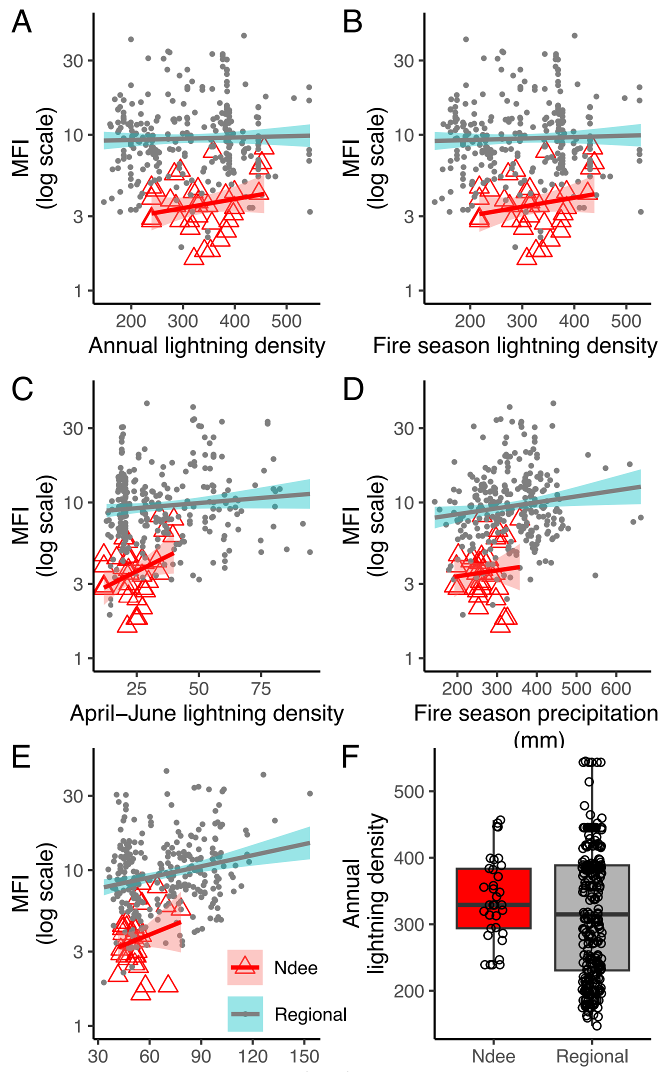

Fig. 3. Scatterplots of mean fire return interval (MFI_{all}) and annual (*A*), April–September/fire-season (*B*), and April–June seasonal drought (*C*) lighting densities, as well as MFI_{all} and fire-season (*D*) and April–June (*E*) precipitation for Ndee and regional sites along with a boxplot of annual lightning density (*F*).

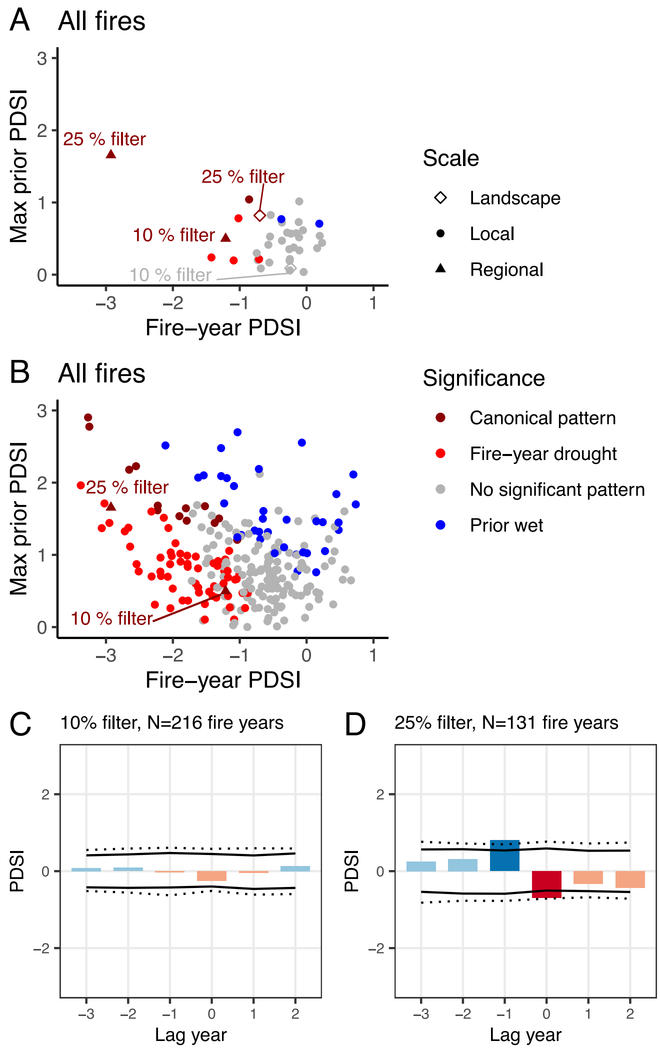

Fig. 4. SEA of fire–climate relationships at the local (fire history site, solid dots), cultural landscape (all of Ndee traditional territory north of the Gila River; open diamonds), and regional scales (all of Arizona and New Mexico, solid triangles). (*A* and *B*) plot fire-year PDSI (an index of summer moisture or drought) and the maximum PDSI in the 3 y prior to fire years for Ndee (*A*) and regional (*B*) sites. At the landscape scale, years that saw fire at least 10% or 25% of all Ndee sites lack a strong climate pattern (diamonds in *A*). At the 10% filter (at least 10% of sites recording a fire), there is no apparent fire–climate association (*C*), especially compared to regional 10% fire years (*A* and *B*). The largest fire years (scarring at least 25% of all sites) presented a statistically significant "canonical" pattern of wet prior conditions and dry fire conditions that were only trivially wet and dry (*A* and *D*), particularly when compared to the region (*B* and *D*).

Northern Tonto area vs. all other sites further supports our interpretation that fire was commonly used during the return to farm sites.

These fires seem to have been asynchronous and probably small, even as fires were a nearly annual feature of the Ndee landscape. Individual horticultural fields were usually less than 0.4 ha and a *gota* might only cultivate two or three fields a year. Fires recorded in fire scars are more likely to be associated with other land use activities related to foraging and hunting on the landscapes tethered to farm sites (<5 to 10 km away) rather than exclusively related to horticultural fire use since the tree-ring sites were not deliberately situated adjacent to ancient horticultural plots. Fires that scarred few trees are more common than those that scarred at least 25% of trees in a given year, although it is noteworthy that even these synchronous fire years occurred more frequently in Western Apache territory than elsewhere in the Southwest, something that does not rule out synchronous fire years simply having more small fires rather than larger individual fires (19).

Climate variability was not an important factor in the frequency of historical fires at most Ndee sites. Across the Southwest (48) and even much of the western United States (20, 58), climate has been a major driver of widespread fire activity but this was not evident during Ndee fire stewardship prior to the establishment of reservations. Rather Ndee fire management muted the influence of climate drivers in a way similar to Chiricahua Apache, Navajo, and Jemez fire stewardship (21). This is evident at the landscape scale too (i.e., all of the Western Apache sites), in which years when at least 10% of sites burned had no significant climate associations. In years when at least 25% of sites had fire, statistical associations were present but climate deviations were less than the average for the entire region. In sum, regional climate patterns still influenced regional fire synchrony (extent), but local human fire uses muted the influence of climate on fire activity in the Ndee homelands.

Even as Western Apache people were restricted from much of their territory with the imposition of reservations beginning in 1870 CE, and military occupation limited many traditional practices (32), there is evidence in the fire-scar record that Ndee fire stewardship persisted decades into the 20th century. Only four of our 311 sites have evidence for very frequent fires (MFI_{all} < 4 y) beyond 1920 (*SI Appendix*, Table S2). All of these fire history sites are on the San Carlos Apache Indian Reservation, suggesting a continuity of Ndee fire stewardship practices on the reservation even after the establishment of reservations. Beginning in the 1950s, pioneering work on early prescribed burning efforts by Harold Weaver and Ndee crews on the Fort Apache and San Carlos Apache Reservations helped to set the stage for a move away from the policy of total fire suppression in the Southwest (59).

The persistent revisitation of particular farm sites for Ndee *gota* and local groups highlights the role of ecological feedbacks of both horticultural and wild resource productivity in these places that were most shaped by cultural burning and niche construction. Burning that promoted wild resources and forage for preferred game allowed these persistent places to remain productive in spite of moderate levels of resource use (60), likely due to Allee effects created by cultural burning (29). It is probably not a coincidence that the Ndee origin story for fire knowledge is associated with ponderosa pine fire ecology. Rather, this association likely belies the deep roots of Ndee fire knowledge and fire use in dry pine

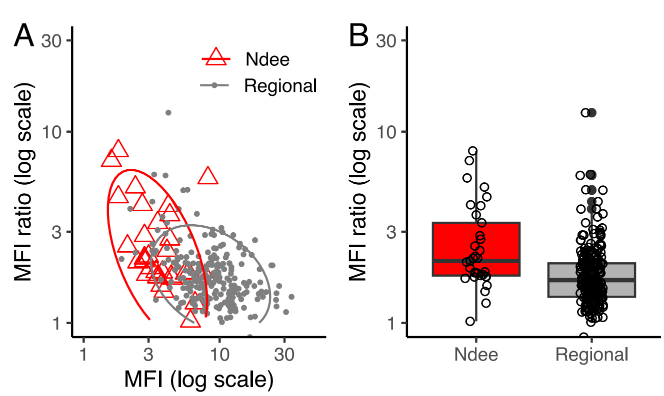

Fig. 5. Scatterplot (*A*) and boxplot (*B*) of mean fire intervals (MFI_{all}) and $MFI_{25\%}$:MFI_{all} ratios for Ndee and regional fire history sites. This ratio is a measure of the importance of relatively small fires (low levels of fire-year synchrony) when $MFI_{25\%}$:MFI_{all} ratios are higher. $MFI_{25\%}$:MFI_{all} ratios are significantly higher at Ndee sites (Table 2) indicating a greater prevalence for fires that scarred few trees, which we interpret as qualitatively smaller fires.

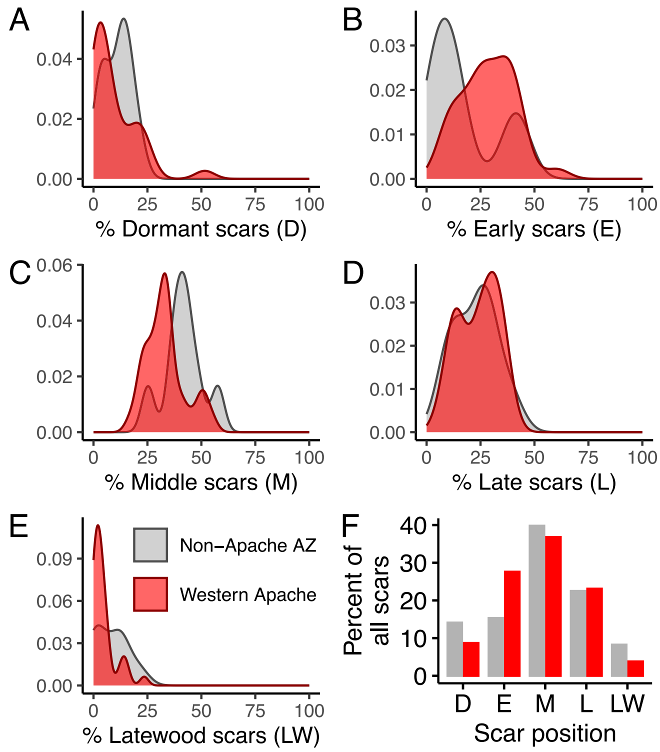

Fig. 6. Seasonality for Western Apache sites (red) compared to non-Apache Arizona sites (gray). Density plots show the frequencies with which particular percentages of scar placements occur across sites in each category (*A*–*E*). Across all trees aggregated for each category, early earlywood dates are unusually well represented at Western Apache sites (*F*). Individual sites in the Western Apache homeland have unusually high occurrences of early earlywood scars (late April or May) (*B*) but lower representation of middle earlywood (June) (*C* and *F*) scars compared to non-Apache Arizona sites.

forests to create and sustain productive environments on these ponderosa pine landscapes for foraging via niche construction (61).

For the Ndee, research done to benefit Ndee communities to better preserve and protect their culture, heritage, and identity on Ndee terms is an exertion of tribal sovereignty (62) in addition to supporting restoration of cultural keystone species (63). Other tribes are actively returning fire stewardship to their cultural landscapes for this purpose (64, 65). For Ndee specifically, the research described in this paper supports current initiatives to restore historical fire regimes for cultural keystone species such as Emory oak (*Quercus emoryi* Torr), a vital material to almost every Apache social and ceremonial function (63).

As we learn more about the ecological and historical importance of Indigenous fire stewardship across the Western United States, it is imperative to avoid research harm by striving to involve Indigenous Peoples in the process (66). While this study continues to reinforce the perspective that dry pine forests in the Western United States require frequent, low-severity surface fires for their ecological integrity (9), it highlights the important role of Indigenous populations in sustaining resilient forests and wildlife populations for centuries (26). However, it is not enough to acknowledge and imitate these practices within a modern institutional framework. Institutional burning, even when intended to mimic Indigenous fire regimes, can produce unintended and undesirable outcomes (67). Furthermore, the generalization that happens when conflating institutional burning with Indigenous fire stewardship often leads to erasure of Indigenous knowledge and worldview (68–71). When and where it is possible, Indigenous communities should be supported to restore their own cultural burning practices, as is true in parts of the United States (65, 72–74) and elsewhere in the world (75–77). When this is not feasible, Indigenous communities should be part of the decision-making and ecological monitoring processes to restore cultural burns by appropriate agencies (65, 78, 79).

The conceptual approach used here to document the influence of traditional burning by a small and mobile population has broad relevance to other areas where traditional burning was historically significant but often overlooked, including other Indigenous contexts (80) but also traditional burning practices in Europe (81) and Africa (82). Bringing archaeology, anthropology, and paleofire science together can generate novel approaches to longstanding problems in a wide variety of regional and historical contexts, such as the identification of the ecological significance, dynamics, and climate relationships of traditional burning over centuries to millennia (83). A better understanding of traditional fire practices, their ecological consequences, and their influence on climate vulnerability can contribute to a fire science and pyrogeography reimagined for modern fire challenges (84).

Materials and Methods

Study sites were located based on coordinates provided in the North American Fire Scar Network (30, 85). Fifteen of the 34 Ndee fire history sites have been published elsewhere (Table 1) (50, 52, 53, 86–92). The remaining 19 Ndee fire history sites mostly come from unpublished field research by Kaib in the Tonto National Forest and San Carlos Apache Reservation documented in technical reports and datasets (93, 94). Fire history data from the San Carlos Apache Tribe were used with permission of the tribe recognized by San Carlos Apache Tribal Council Resolution DC-23-219.

The unpublished research followed standard fire history methods, wherein saws were used to obtain partial or complete cross-sections of fire scarred conifer logs, stumps, or standing trees (50). Samples were located using Global Positioning System (GPS) for each site, along with general descriptions of stand composition and condition. Cross-sections were resectioned to obtain smooth, flat surfaces at the Laboratory of Tree-Ring Research in Tucson, Arizona. The cross sections were then sanded with progressively fine sandpaper to create a surface suitable for cross-dating all rings (95). Fire scars were assigned a date and positionality based on their occurrence within cross-dated rings (57). Specimens from the Kaib collection with 1-y and 2-y fire intervals were audited to ensure dating accuracy for the final analysis.

We limited the overall analysis to only sites with at least four recording trees and at least 100 y worth of record during the study period (1600 to 1870). This resulted in 34 Ndee fire history sites and 277 regional fire history sites for the analysis (see *SI Appendix*, Table S1 in ref. 21).

All analysis for this paper was done using the burnr package (96) in the R programming environment in R 4.3.0 (97). We used burnr to calculate mean fire return intervals (MFI) for all fires (i.e., unfiltered) in a composite record at each site since very small fires, including single-tree fires, are important for identifying cultural patch burning (19, 20). This MFI_{all} was compared to MFI from composites created using different filters that isolate more widespread fires [i.e., a liberal filter of fire years with a minimum of two trees recording fire for MFI_2; a conservative filter of fire years with at least 25% of all trees (and a minimum of two scarred trees)]. All composites were restricted to the prereservation period (i.e., 1600 to 1870 CE). Although there are several different metrics that have been used to identify the central tendency of fire interval distributions (98) we have chosen to use the MFI_{all} because it is the easiest to interpret and has been shown to provide the closest estimates to real fire return intervals in a landscape of highly patchy, small fires (19). The median is less sensitive to extreme values that could be due to scar misidentification (too short) or the early edge of the filter period when few trees may have been recording fires (too long). However, there are only very minor differences in these different metrics (mean vs. median) and we have simultaneously performed an analysis using the median fire return interval that produced virtually identical results as our MFI_{all} analysis (Table 2). Log–linear regressions were performed on MFI_{all} and N trees for each site to compare Ndee sites to regional sites from the International Multiproxy Paleofire Database. Because of the substantial differences in sample size (almost an order of magnitude) between the Ndee and regional sample sets, Wilcoxon Rank Sum tests were performed to assess whether differences between Ndee and regional fire return intervals (all filters and metrics) were statistically significant.

Lightning data were accessed from the NOAA Experimental Lightning Climatology data service (https://www1.ncdc.noaa.gov/pub/data/swdi/database-csv/v2/), which provides numerical data for daily lightning strikes gridded at 0.1° across North America. We trimmed this dataset to the boundaries of Arizona and New Mexico for each year from 1994 to 2023 to calculate 30-y averages for annual, April–June (summer drought), April–September (fire season) lightning densities and interpolate raster surfaces. Tree-ring site locations were used to subsample lightning and Parameter-elevation Regressions on Independent Slopes Model climate normal dataset raster surfaces (99) for mean annual temperature, mean annual precipitation, and monthly precipitation estimates. Linear regressions were done at different temporal scales to assess the impacts of lightning and precipitation on MFI_{all}—annual lightning/precipitation, fire-year (April–September) lightning/precipitation, and arid foresummer (April–June) lightning/precipitation.

SEA is a method to test the strength of associations between fire occurrence and climate variables before and during fire years. It has been widely employed in tree-ring fire scar and interannual climate association studies (20, 21, 58). SEA uses bootstrap resampling of a climate time series to assess the probability that average fire year climate (lag year 0) and prior years climate (years −1, −2, −3, etc.) would occur by chance. We conducted SEA with PDSI—a measure of summer moisture (100) on all Ndee fire history sites using all fire years and rendered a bivariate plot of fire-year PDSI (usually dry) on the x-axis as a measure of the importance of fire-year drought, and the maximum wet year in the three prior years on the y-axis, as a measure of the importance of prior moisture and fuel buildup. We used the average of grid points 88 and 104 from the North American Drought Atlas (101, 102) to represent PDSI for the Western Apache homelands. We also conducted SEA on fire years in which at least 10% of all Ndee fire history sites burned and years in which at least 25% of all Ndee fire history sites burned. We did the same thing for all years where at least 10% or 25% of regional sites burned for a comparison of Ndee climate influences vs. climate controls at the regional scale during the 1600 to 1870 CE period.

For the fire size analysis, we adapted the approach of Huffman (53) and Fulé (52) to our use of the MFI by calculating the ratio of MFI for those years with at least 25% of trees scarred (min 2 scarred trees; $MFI_{25\%}$) and the MFI for all fire years (MFI_{all}). Hypothetically, this should produce ratio values greater than 1 but because the 25% filter often removed fires at the beginning or end of a time series, it occasionally produced values less than 1, meaning $MFI_{25\%}$ had lower values than MFI_{all} at that site. In general, higher values indicate a greater prevalence of fires that scarred few (<25%) trees, although this is an imperfect proxy for fire size. Nevertheless, high $MFI_{25\%}$:MFI_{all} values indicate that many more fire years exclusively involved smaller fires. Log–linear regressions were used to explore the relationship between $MFI_{25\%}$:MFI_{all} ratios and MFI_{all} values. Wilcoxon rank sum tests were used to compare Ndee fire history sites with regional fire history sites.

We follow Swetnam and Baisan (57) in translating intraring scar placement into calendar estimates of fire seasonality. We used Fisher's exact test to compare Ndee fire seasonality histograms to all non-Apache Arizona fire history sites.

Data, Materials, and Software Availability. Tree-ring fire scar data used in this study are available from the International Multiproxy Paleofire Database housed at the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (https://www.ncei.noaa.gov/products/paleoclimatology/fire-history) (103). Data originating from the San Carlos Apache Tribe Reservation remain the sovereign data of the tribe but may be provided upon request made to the tribe.

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