ANTHROPOLOGY

Indigenous fire management and cross-scale fire-climate relationships in the Southwest United States from 1500 to 1900 CE

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Prior research suggests that Indigenous fire management buffers climate influences on wildfires, but it is unclear whether these benefits accrue across geographic scales. We use a network of 4824 fire-scarred trees in Southwest United States dry forests to analyze up to 400 years of fire-climate relationships at local, landscape, and regional scales for traditional territories of three different Indigenous cultures. Comparison of fire-year and prior climate conditions for periods of intensive cultural use and less-intensive use indicates that Indigenous fire management weakened fire-climate relationships at local and landscape scales. This effect did not scale up across the entire region because land use was spatially and temporally heterogeneous at that scale. Restoring or emulating Indigenous fire practices could buffer climate impacts at local scales but would need to be repeatedly implemented at broad scales for broader regional benefits.

INTRODUCTION

Fire is a fundamental ecological process with impacts across geographic scales from ecosystems (*1*) to the Earth system (*2*). In recent decades, wildfires across the globe have stressed human societies and infrastructure and driven biome transformations often resulting in reduced ecosystem services including carbon storage (*3*), runoff control (*4*), and biodiversity (*5*). This is the result of a century of land-use changes, including active fire suppression and accelerating climate changes. By contrast, Indigenous people coexisted with wildfire for centuries or millennia before Euro-American colonization (*6*). Improved understanding of Indigenous fire histories may support growing calls for integration of traditional and modern fire management practices wherever and whenever possible (*7*).

Paleoecological, neo-ecological, and anthropological research indicates that in at least some contexts, Indigenous fire management includes benefits to biodiversity (*8*, *9*), weakening of climate linkages with fire activity (e.g., the importance of climate effects on fuel types, accumulation, and moisture content) (*10*, *11*), and reductions in fire intensity (*12*). These studies have tended to focus on local- to landscape-scale impacts of traditional fire management. However, the geographic and temporal scales of human activities are variable and heterogeneous (*13*). Some paleoecological studies have suggested that climate, not cultural burning, was the key driver of fire activity at regional to continental scales (*14*, *15*) and that Indigenous influences on fire were ephemeral in particular areas (*16*, *17*). An assessment of cross-scale impacts of Indigenous fire management on fire-climate relationships would assist contemporary fire policy and management strategies by benchmarking our expectations of supporting cultural burning by Indigenous practitioners or increasing anthropogenic (prescribed and deliberate) burning in general. We use the term "fire-climate relationships" to describe the mechanistic way by which properties of interannual climate influence fuel production and fuel aridity. We assess the strength of these relationships by testing for statistically significant patterns in interannual hydroclimate relative to tree-ring dated fire years across periods of varying Indigenous cultural influence.

Here, we use a network of 4824 fire-scarred trees in the Southwest United States (Arizona and New Mexico) to explore the patterns of fire-climate relationships across geographic scales and across traditional territories of three different Indigenous cultural groups (Fig. 1). Dry conifer forests dominated by ponderosa pine (*Pinus ponderosa*) and related species in the Southwest United States are one of the most sampled contexts for tree-ring–based fire histories. Fire scars are created at the base of these thick-barked trees when fire raises temperatures high enough to kill the cambium on only part of the tree. After the damage, the tree heals by growing new tissue from the margins of the damaged area, thus enabling the annual dating of the fire damage via dendrochronological examination (*18*). Regional syntheses of tree-ring climate and fire history reconstructions of widespread fire years across the Southwest (*19*), California (*20*), and the entire western United States (*11*) indicate that fire activity in fuel-limited dry pine forests was strongly driven by the broad-scale, regional controls of hydroclimate, at least partially entrained by the El Niño Southern Oscillation (ENSO) (*21*). Specifically, one to three wet years before a dry fire year produced sufficient fuels for fire to spread (prior wet) and cured them to burn (fire-year drought). Although

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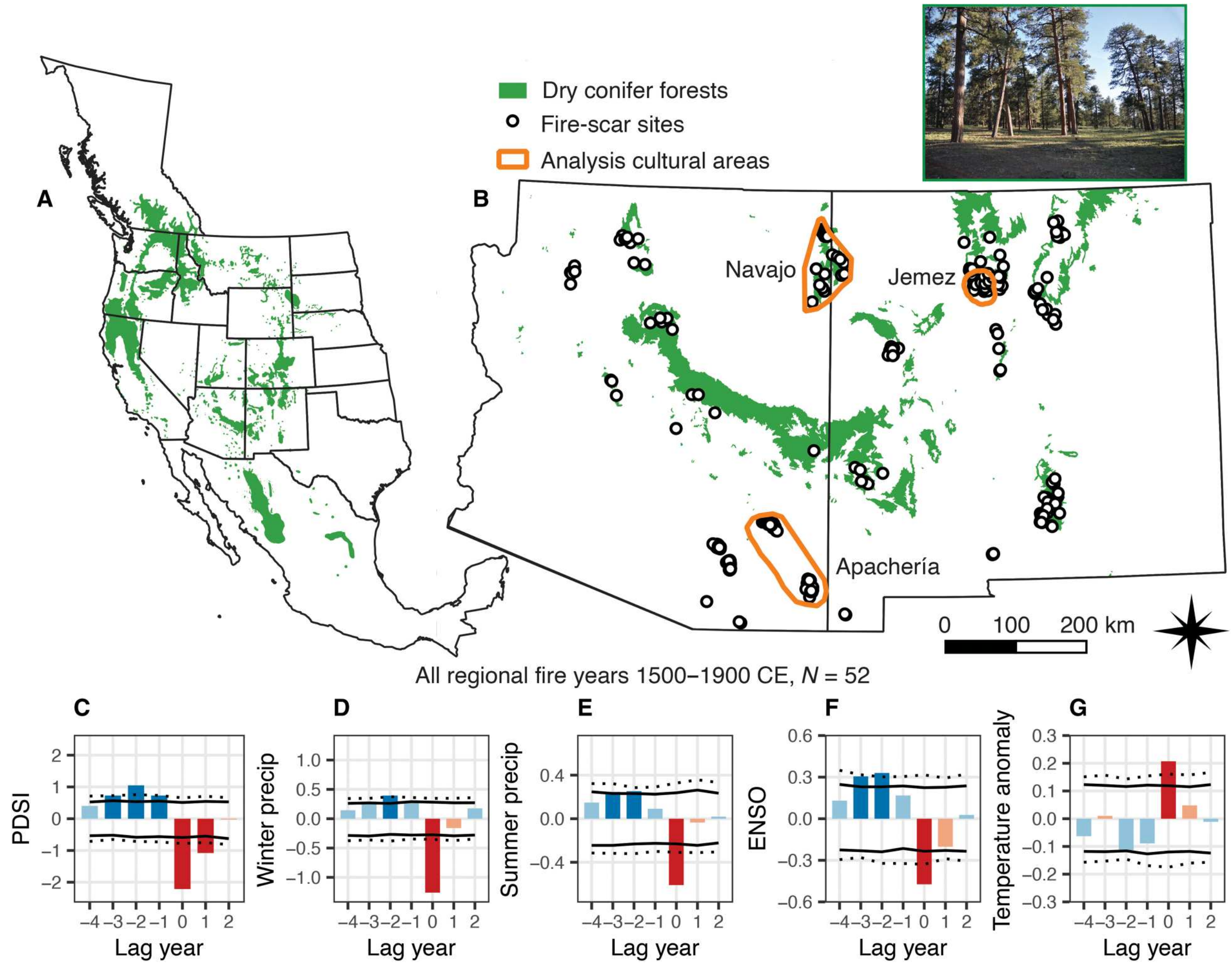

Fig. 1. Maps of the distribution of dry pine forests across western North America and the Southwest United States with regional fire-climate analyses. The distribution of dry pine and mixed conifer forests across western North America and the Southwest are indicated in (**A**) and (**B**). The location of tree-ring sites (dots; i.e., the local scale sites) and cultural areas (orange outlines; i.e., cultural landscapes) are indicated in (B). Superposed epoch analysis plots at the regional-scale for Palmer Drought Severity Index (PDSI) (**C**) (77), winter precipitation (**D**) (78), summer precipitation (**E**) (78), El Niño Southern Oscillation (ENSO) (**F**) (79), and temperature (**G**) (80) indicate the "canonical pattern" of prior wet and fire-year dry (and warm) conditions using the combined regional dataset for the entire record (1500-1900 CE). Solid line indicates significance at the $p < 0.05$ level, dotted line at the $p < 0.01$ level. Red/orange bars indicate dry/warm years. Blue bars indicate wet/cool years. Dark red/blue indicate years significant at the $p < 0.05$ level. Orange and light blue bars are not statistically significant. Photo of ponderosa pine (*Pinus ponderosa*) forest in the Chuska Mountains by C. Guiterman.

much recent attention has been drawn to the relationships between drought, vapor pressure deficit, and area burned in the western United States in recent decades (*22*, *23*), interannual climate drivers on fuel production are still evident in modern fire activity in the Southwest (*24*).

Here, we test the prevailing hypothesis that Indigenous societies had only local, ephemeral impacts on fire regimes and that these impacts were undetectable at landscape and regional scales. Previous studies that focused on measures of fire frequency have struggled to unambiguously identify Indigenous fire management in fire history data (*25*, *26*). We propose to test this by focusing on fire-climate relationships across geographic scales and three cultural landscapes (referred to as Navajo, Jemez, and Apachería). The primary mechanism by which Indigenous land and fire management could influence fire-climate dynamics is through impacts on fuels, affecting fuel patchiness and heterogeneity (through anthropogenic pyrodiversity) or fuel removal (via grazing). We further test the hypothesis that Indigenous impacts on fire regimes, when present, varied on the basis of cultural and economic practices. Human activities impinge upon fire and fuelwood uses and fuel removal. Specifically, large populations of settled farmers (Jemez) might supplement the burn area but decrease burn patch sizes (*6*, *11*, *27*), mobile pastoralists (Navajo) might reduce fire activity by removing fuels via grazing (*28*–*30*), and mobile hunter-gatherers (Apache) might have undetectable impacts because their populations were smaller and dispersed across a wide area, thereby affecting fuel loads the least (*26*, *31*).

Cultural landscapes

The Southwest United States has a rich and complex Indigenous cultural history. Native peoples of the Southwest maintain oral histories and traditions that connect culture, language, animals, people, plants, and other resources to home landscapes since time immemorial. History, ethnography, and archaeology document spatial and temporal variability in the timing, intensity, and character of land use and settlement by different groups across the region. Documentation of traditional fire knowledge and practices, however, is largely incomplete due to the historical and ongoing consequences of colonialism, hence the importance of long-term archaeological and paleofire studies in collaboration with Indigenous descendent communities. We concentrate on three subregional areas of the Southwest where distinct groups that have unique languages, cultures, and economies define cultural landscape study units. Three cultural landscapes (Navajo, Jemez, and Apachería) were used to define the landscape scale of analysis and to serve as units of observation to cluster tree-ring sites (table S1) for comparisons of local-scale records (Fig. 2). Historically or archaeologically defined periods of light and intensive Indigenous use are used to define time periods for comparative analysis at local, landscape, and regional scales.

Diné (Navajo) people have traditional homelands and contemporary reservations in the Four Corners area of northwestern New Mexico, northeastern Arizona, southwest Colorado, and southeast Utah (*32*). Historically, Diné lived in small, family-based communities organized around sheep pastoralism, hunting, gathering, gardening, and domestic dwellings called *hogans* (*33*). Earliest archaeological and historical evidence suggest that, by 1500 CE, the center of *hogan*-building, pastoral Diné life, and culture was in an area called the Dinetah in the Largo and Gobernador basins of northwestern New Mexico. By the mid-1700s, the cultural center for pastoral Diné populations shifted westward with increased use of the Chuska and Lukachukai mountains, partially in response to overhunting in the Dinetah and the abundance of large game and good forage for domestic sheep in the forested mountains, among other factors (*34*). Previous studies have suggested that Navajo pastoralism reduced fire activity in pine forests (*28*), although burning practices may also have kept fires burning frequently in heavily traveled areas (*29*). For our analysis, the Navajo landscape includes the Defiance Plateau, Chuska, and Lukachukai Mountains, which have 394 fire-scarred tree samples from 62 sites (median area = 5 ha per site, mean area = 9.0 ± 15.6 ha per site) across dry conifer forests dominated by ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*) with widespread fire years between 1520 and 1879 CE (Fig. 2A) (*29*, *30*).

Hemish (Jemez) people have lived in the region of the southwestern Jemez Mountains since migrating to the area from an ancestral homeland in southern Colorado (*35*). Hemish people were farmers and hunters who were organized into dozens of pueblo villages across the pine forests and woodlands on the south-facing mesas of the Jemez Plateau. Archaeological and paleoecological evidence indicates that at least some Hemish people were living, farming, and burning in the area since 1100 CE (*6*). By the mid-17th century, Hemish people were forced off the forested mesas by a Spanish colonial policy of *Congregación* (*27*). In the wake of this active colonialism and missionization, Hemish populations were reduced by more than 85%. Previous studies indicated that Hemish fire management (ignitions and fuel use) resulted in a fire regime characterized by small fires and may have reduced fire-climate relationships (*6*, *11*). For our analysis, the Jemez landscape includes the area of Hemish agricultural activity and greatest land-use intensity, in the southwestern quarter of the Jemez Mountains, which has 456 fire-scarred tree samples from 48 sites (median area = 1 ha per site, mean area = 12.3 ± 35.3 ha per site) with widespread fire years between 1516 and 1896 CE (Fig. 2B) (*6*, *11*, *36*–*38*).

Ndée (Apache) people have traditional homelands stretching from central Arizona across New Mexico and into Texas and through southeast Arizona into northwest Mexico (*39*). Ndée are generally grouped into loosely connected bands that varied in their degree of reliance upon gardening and raiding (*40*). Western Apaches and Chiricahua Apaches have overlapping homelands in the western part of Ndée traditional territories (Fig. 2C) (*41*). In Apachería, Ndée were mobile hunter-forager-gardeners who seasonally lived in and used pine forests for hunting, gardening, and wild plant management. Fire use in gathering, gardening, and hunting is well documented among Western Apaches because these practices persisted into the 20th century (*42*). Apaches were often the subject of colonial military persecution from the Spanish, Mexican, and American governments, which drove them to be even more highly mobile and minimize evidence of their presence to reduce pursuit. We concentrate on two mountain ranges (Chiricahua and Pinaleño Mountains) as areas of Apachería that were important loci to Western Apaches (*43*) and Chiricahua Apaches (*44*) and that remained at a distance from Euroamerican settlement until after the establishment of the San Carlos and Fort Apache Indian Reservations in the 1870s. Together, Chiricahua and Pinaleño Mountains have 502 fire-scarred tree samples from 72 sites (median area = 100 ha per site, mean area = 83.9 ± 34.3 ha per site) and widespread fires between 1573 and 1894 CE (*45*–*50*).

Here, we use archaeological and historical evidence to define periods of (i) intensive land use and settlement when Indigenous fire management would have been most pronounced and (ii) periods with light, qualitatively different, or undetectable land use when Indigenous fire management would have been least influential (Table 1). For the Navajo landscape, we identify a period of intensive use by pastoral Diné people as they moved westward out of the Dinetah area after 1760 CE (*34*). For the Jemez landscape, we identify a period of intense use before *Congregación* and population decline (i.e., before ca. 1650 CE) (*27*). In the sky island landscapes of Apachería, Ndée land use likely varied on the basis of the intensity

Table 1. Cultural periods of the fire-climate analysis. The years for which intensive and light use were defined for each cultural landscape and the primary sources for defining these periods. Only fires after 1500 and before 1900 CE were included in the analysis, and this is reflected in the periodization below.

Cultural landscape	Intensive use	Light use	Sources
Navajo (Diné)	1760–1900 CE	1500–1759 CE	Archaeology and history (*32*, *34*)
Jemez (Hemish)	1500–1650 CE	1651–1900 CE	Archaeology and history (*27*)
Apachería (Ndée)	1500–1679, 1711–1747, 1791–1830, and 1887–1900 CE	1680–1710, 1748–1790, and 1831–1886 CE	History (*51*)

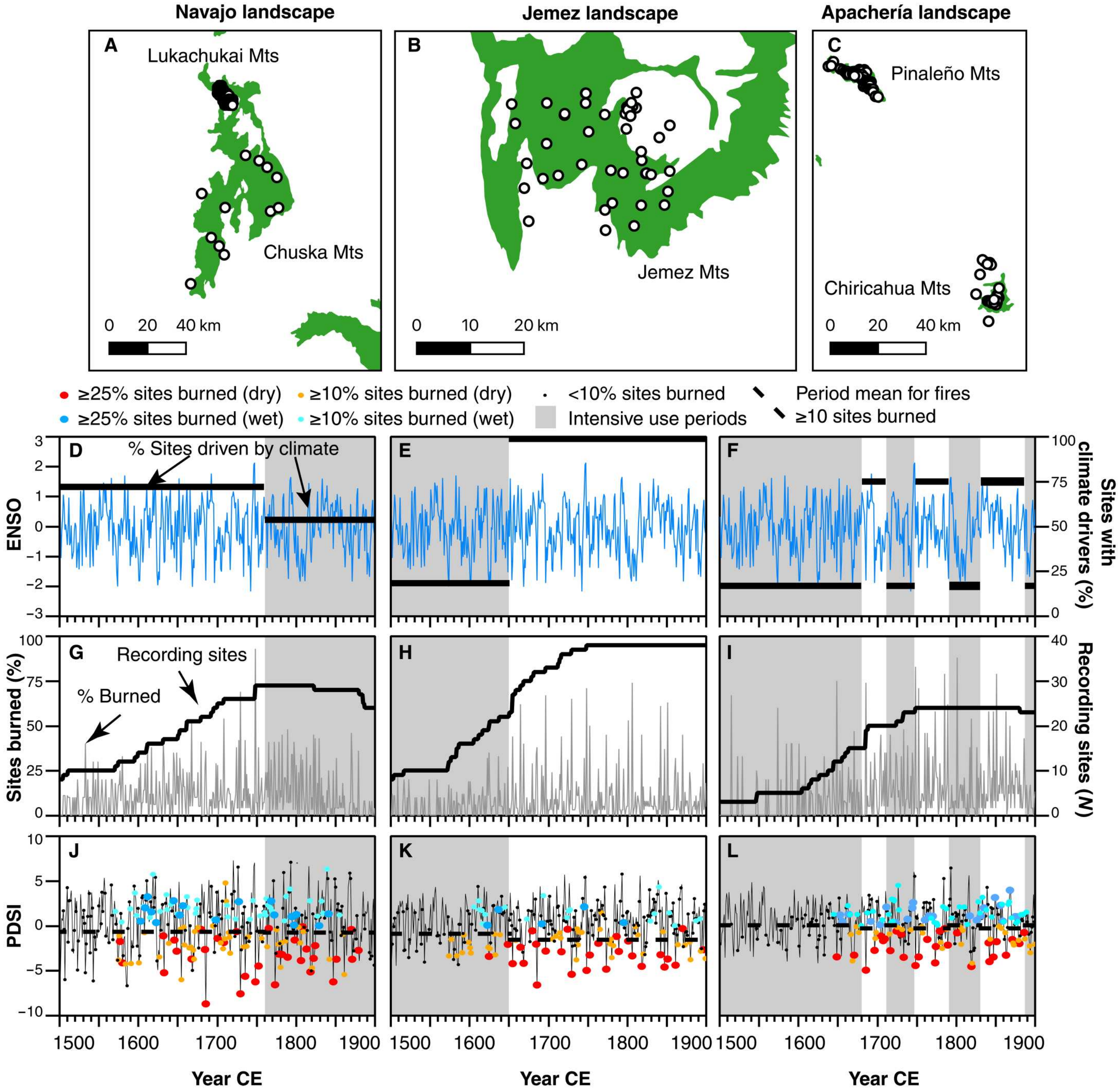

Fig. 2. Local-scale analysis within cultural landscapes. Maps of tree-ring sites in the Navajo (**A**), Jemez (**B**), and Apachería (**C**) cultural areas that also define the columns for time series data in subsequent rows. White dots indicate the location of tree-ring sites used in the analysis (see table S1 for a complete list of sites). The percentage of tree-ring sites with significant climate drivers in local SEA for intensive- and light-use periods is plotted on the Niño 3 reconstruction of ENSO (*79*) (**D** to **F**) (see Table 2). Sample depth (number of recording sites) and percentage of those sites that burned each year are in (**G**) to (**I**). These are restricted to the set of sites used in the local SEA (i.e., sites with at least five trees and at least five fires in one or both cultural periods). The bottom row plots annual PDSI with local fire years by percentage scarred (**J** to **L**) (*77*). Dotted lines in this row indicate the mean PDSI values for each cultural period. Note that fire year PDSI changed very little at the landscape scale across periods.

of warfare (*51*). We identify periods of light use during heightened warfare (*51*) when traditional cultural burning would have been risky because it would have exposed the locations of Apache bands, although fire may have been used to facilitate escape or destroy forage for pursuing cavalry. By contrast, intensive-use periods in Apachería occurred during peacetime when traditional land-use and burning practices would have been less risky (*51*).

Ethnography suggests some common forms of burning in wild plant management, hunting, and garden maintenance, as well as potential religious and other cultural uses of fire across Diné,

Table 2. Local-scale analysis and summaries of site, tree, and fire numbers for analyzed cultural landscapes. Total number of sites, trees, and fires in the intensive- and light-use fire periods for all cultural landscapes investigated in the paper. The percentage (and number) of local fire records that have significant climate drivers during each period, along with statistical significance at the $P = 0.05$ level for Fisher's exact tests, is also shown (significant patterns at $P = 0.05$ level are in bold). Only sites with at least five trees and periods with at least five fires were included in the Fisher's exact test.

	Jemez	Navajo	Apachería
Total sites	48	62	72
Total trees	456	394	502
Intensive-use fire years	13	25	32
Light-use fire years	36	41	26
Sites with significant climate drivers in intensive-use period, % (# sites)	**18.2% (2)**	53.6% (15)	**16.7% (4)**
Sites with significant climate drivers in light-use period, % (# sites)	**100% (38)**	72.0% (18)	**75% (18)**
P	**<0.0001**	0.2565	**0.0001**

Hemish, and Ndée groups despite different cultures, languages, and economies (*6*, *42*). We use the term "Indigenous fire management" to include all land-use practices by Indigenous people that affect ignitions, fuels, fire behavior, or fire spread, such as anthropogenic burning and wood harvesting for various cultural purposes (*6*), and pastoral land use (*29*). Discerning intentionality is a challenge for archaeologists, and whether these practices were done to deliberately manipulate fire regimes cannot be known with certainty. The importance here is that their net effect was to influence fuels, ignitions, and fire spread. In this way, the past century of grazing, logging, and active fire suppression are all part of recent fire management, even if these activities were not explicitly part of policy or performed to deliberately modify fire regimes (*52*). For all fire-climate analyses, we only use fires that occurred after 1500 CE and before 1900 CE to exclude periods of low sample depth due to the fading record problem (before 1500 CE) and after the impacts of widespread fire exclusion due to overgrazing, logging, curtailment of Indigenous fire practices and confinement to reservations, and fire suppression (after 1900 CE).

RESULTS

Across the entire Southwest U.S. dataset ($N = 4824$ trees and $N = 451$ sites; table S1) and over the entire record from 1500 to 1900 CE, climate exerted strong controls on fire activity. Seasonal climate was significantly wetter in 1 to 3 years before regional fires (>10% trees scarred) and significantly warmer and drier during the year of fires, corroborating previous observations (Fig. 1, C to G) (*11*, *21*). We call this the "canonical pattern" wherein wet years before fires were important for producing abundant and continuous fuels that would carry surface fires widely during unusually warm and dry years. These patterns were evident when using each of four different hydroclimate reconstructions and the temperature reconstruction, so we use the Palmer Drought Severity Index (PDSI), which integrates temperature and precipitation for our analyses. The canonical pattern is partly driven by ocean-atmospheric phenomena that create global-scale teleconnections, the epitome of broad-scale climate controls on fire regimes (*53*).

Local sites were grouped by cultural landscape to examine variability in site-level fire-climate patterns across the three different landscape contexts. At these small (ca. 5 to 100 ha) local scales, climate drivers of fire were rarely significant during periods of intensive cultural use but were more consistently significant at most sites during periods of light use (Fig. 2, D to F). This pattern was statistically significant at the $P < 0.05$ level for every landscape but the Navajo area (Table 2 and tables S2 and S3). In the Navajo area, sites with significant fire-climate relationships were more common during the light-use period (72%) than the intensive-use period (53%), but this difference was not significant at the $P < 0.05$ level. In aggregate, while climate drove local fire activity at nearly all cultural landscape sites during periods of light use (85.1% of all sites across cultural landscapes), significant climate drivers were only observed from a minority of sites during intensive cultural periods (32.3% of all sites; Fisher's exact test, $P < 0.0001$).

At the landscape scale (i.e., Navajo, Jemez, and Apachería study units), fire-climate relations differed during periods of intensive and light use, but not in the same ways as the local-scale patterns. In all cultural landscapes, periods with light use displayed statistically significant canonical wet-dry patterns (Fig. 3, B, E, and H). During intensive-use periods, prior-year wet conditions were not a significant driver of fire activity, but fire-year drought was, despite cultural, economic, and population size variability among the three cultural areas. This pattern of weakened prior wet conditions during intensive-use periods occurred across all climate variables, even as significant fire-year drought and warm conditions persisted (figs. S1 to S3). This suggests that the fire-year climate conditions that drove widespread landscape-scale fire years were similar across intensive- and light-use periods (Fig. 2, J to L) but that Indigenous fire management, by changing the timing of ignitions to periods of less abundant fuels, reduced the significance of wet conditions and fuel production before fire years.

The landscape-scale patterns are not unique features of the climate during these periods because *t* test comparisons of PDSI and ENSO across intensive- and light-use periods reveal no significant differences for all cultural areas (Fig. 2, B to D and J to L). The exception is at Jemez when examining ENSO ($t = -2.6844$, df = 132.35, $P = 0.008194$) where Niño 3 conditions during the intensive-use period were significantly cooler (-0.085 ± 0.848, $N = 151$) than during the light-use period (-0.056 ± 0.869, $N = 250$). The difference is slight and would actually suggest a more common role for La Niña and drought than is evident during the Jemez intensive-use period (Fig. 3, D and E).

Using cultural periods of intensive and light use to partition the Southwest U.S. regional-scale dataset (all 4824 trees across the region), every period demonstrated the canonical pattern of significantly wetter climate in the 1 to 3 years before fire, and significant drought during the fire year, regardless of the intensity of use (Fig. 4). Therefore, the influence of Indigenous burning on fire-climate relationships is undetectable at this scale. The dilution of human influences results from variability in the timing and locations of the most intensive Indigenous fire management. Land use was spatially heterogeneous because the resources that people

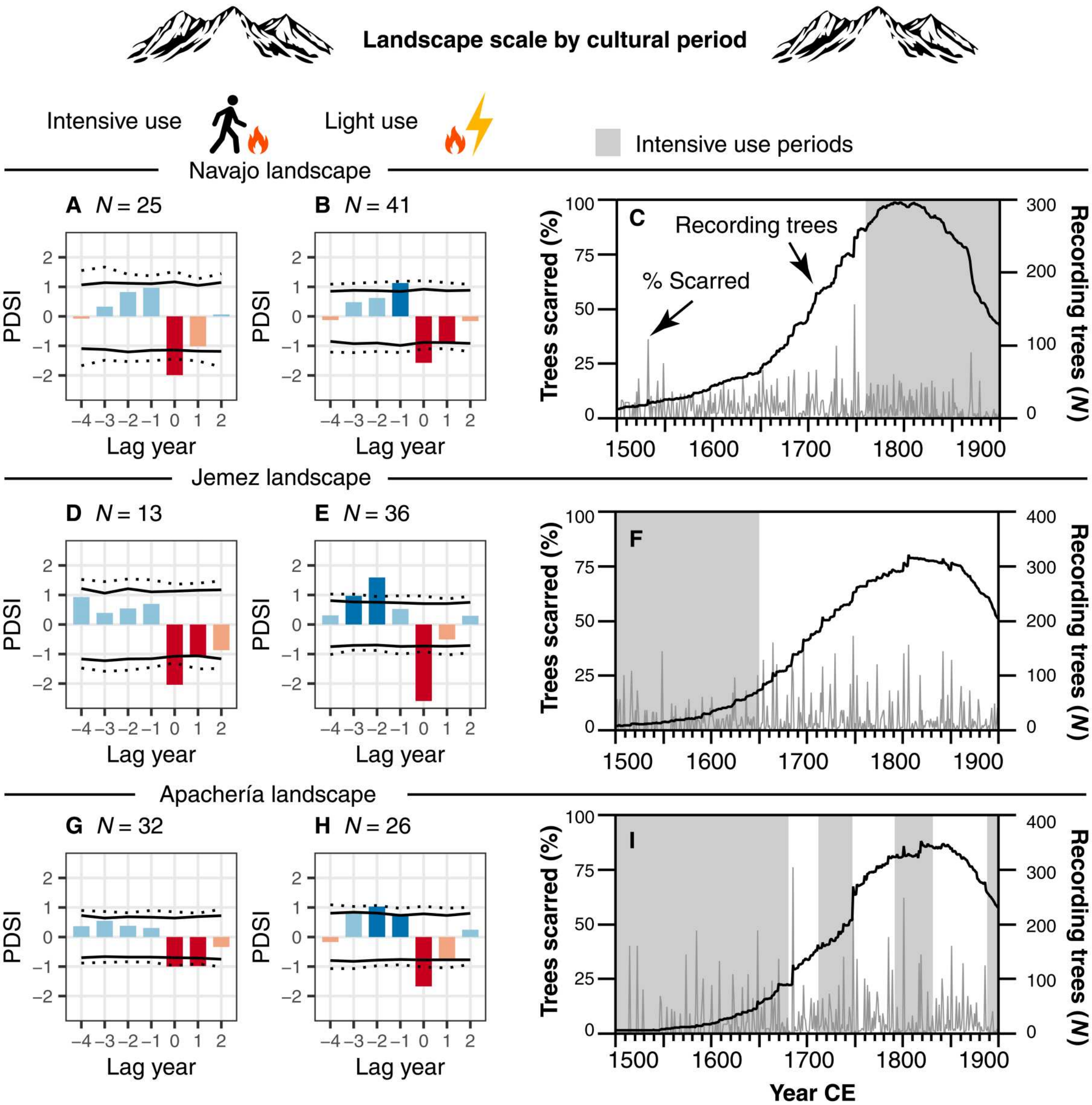

Fig. 3. Landscape-scale fire-climate analyses by cultural period. SEAs of the intensive-use (**A**, **D**, and **G**) and light-use (**B**, **E**, and **H**) periods for each of the culture areas (Jemez, Navajo, and Apachería) using PDSI (*77*). Sample *N* = the total number of widespread fire years for that period in that landscape. Solid line indicates significance at the $P < 0.05$ level, and dotted line indicates significance at the $P < 0.01$ level. Red/orange bars indicate dry years. Blue bars indicate wet years. Dark red/blue indicate years significant at the $P < 0.05$ level. Orange and light blue bars are not statistically significant. Percentage of recording trees scarred each year and total numbers of recording trees for each cultural landscape are plotted with each set of SEA plots (**C**, **F**, and **I**).

used and managed were not evenly distributed, generating considerable spatial variability in human impacts on ignitions and fuels. The intensive-use periods are different for the Navajo and Jemez landscapes, and each of these only partially overlaps with the intensive-use period in Apachería (Fig. 2 and Table 1). It follows that for any given period, the regional-scale record is composed of a mix of local sites with reduced climate influences and sites with significant fire-climate relationships, but even during periods of intensive use at a given cultural landscape, the number of local sites with muted climate drivers was always lower as the geographic scale broadened.

DISCUSSION

Our work further indicates the lessons that can be learned from the historical ecology of Indigenous burning practices over centuries or longer, particularly in contexts like the Southwest United States that have experienced centuries of colonial impacts on traditional ecological knowledge and practices (*27*). The past is full of lessons for contemporary society to coexist with wildfire (*54*–*56*). Integrations of archaeology, history, dendrochronology, and paleoecology offer unique opportunities to enrich our understanding of coupled human-natural fire regimes and their consequences. As climate change (*57*), land-use histories (*12*), and settlement patterns (*58*) make human communities more vulnerable to fire, the past can

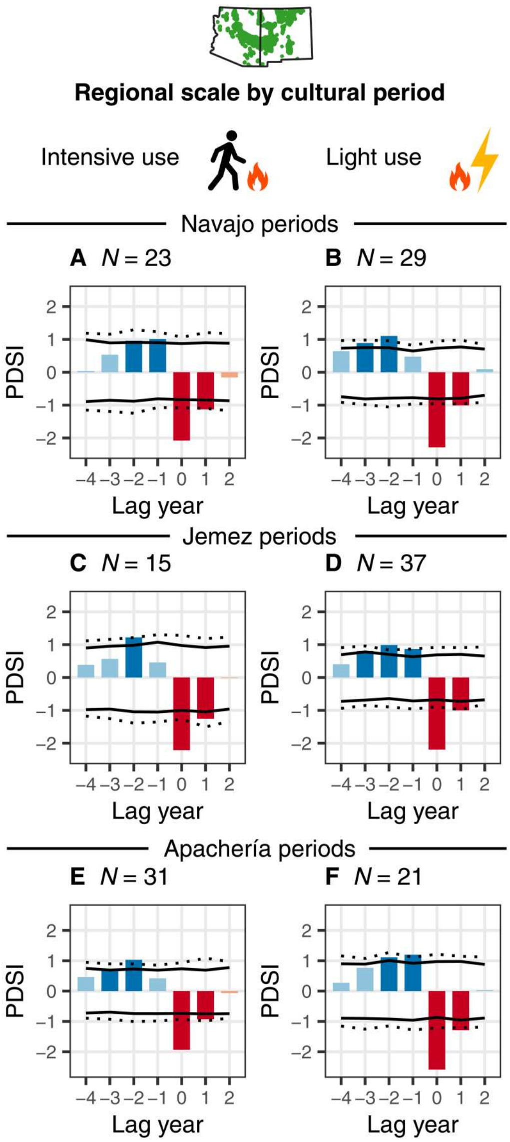

Fig. 4. Regional-scale fire-climate analyses by cultural period. SEAs of the intensive-use (**A**, **C**, and **E**) and light-use (**B**, **D**, and **F**) periods for each of culture area using the combined regional tree-ring dataset using PDSI (*77*). Sample *N* = the total number of fire years for that period in the regional dataset. Solid line indicates significance at the $P < 0.05$ level, and dotted line indicates significance at the $P < 0.01$ level. Red/orange bars indicate dry years. Blue bars indicate wet years. Dark red/blue bars indicate years significant at the $P < 0.05$ level. Orange and light blue bars are not statistically significant.

offer a spectrum of possibilities to reduce those vulnerabilities (*6*, *11*, *20*, *59*, *60*).

Fire-climate relationships across the western United States indicate that interannual wet-dry switching exerted strong controls on fire activity in dry pine forests for at least the past five centuries (*11*, *61*). Our regional synthesis of the Southwest United States corroborates these patterns. During all cultural time periods analyzed here, regional-scale fire activity was preceded by 1 to 3 years of above average moisture followed by significant drought during the year of burning. This was also true of local- and landscape-scale fire activity in periods when Indigenous land use, and presumably fire management, was light. However, in all cultural areas, regardless of differences in language, cultural practices, and economy, when Indigenous occupation and land management was most pronounced, fire-climate relationships were buffered at local and landscape scales. Local burning was probably in small patches, reducing surface fuel continuity but retaining unburned fuel capable of burning in future fires (*6*, *10*, *11*, *62*)—a classic feature of anthropogenic pyrodiversity (*62*). Previous research has observed that fires were more frequent during Hemish fire management, but fewer trees were scarred during fires (Fig. 3F) and fewer sites recorded fires (Fig. 2H) than during light-use periods (*6*, *11*, *27*). This indicates frequent but relatively small, patchy fires during intensive land use. A similar pattern may be evident in the Navajo dataset (Figs. 2G and 3C), whereas Apache wartime (light use) fires have been observed to be synchronous and widespread (*51*, *63*). Light grazing—predominantly on the Navajo landscape—may have had a similar effect as Hemish patch burning on the heterogeneity of landscape fuel loads, although more intensive grazing would have substantially reduced fire spread (*28*, *30*).

At the landscape scale, drought remained a potent driver of fire activity even during intensive use, suggesting that even in heterogeneous fuelscapes created by Indigenous patch burning, climate could overcome limitations in fuel continuity and promote spreading fires. These observations corroborate prior research that Indigenous patch burning can buffer—but not entirely eliminate—local- to landscape-scale climate influences on widespread fire activity (*10*). We show that this effect is scale dependent. Locally, the buffering of climate influences was strongest. At the landscape scale, climate impacts were moderated, but drought persisted as an important influence on fire activity. At the regional scale, the canonical climate pattern continued to be the primary driver of fire activity through time. The repetition of this cross-scale variation in fire-climate drivers across all cultural regions and periods hints at a common cause—human impacts on fire regimes were scale dependent, in space and time (*13*). This scale dependency means that paleofire records composited and assessed at regional scales can mask important, localized Indigenous influences on fire activity and the ecological and social influences of this management (*13*).

This study highlights both the lacuna of our knowledge about Indigenous fire management practices in the western United States and the benefits of collaborative research between archaeologists, paleoecologists, and Indigenous communities and scientists (*54*, *56*). Colonialism by Euro-Americans has affected access to traditional lands and, in many cases, traditional fire practices of Indigenous people around the world (*64*). Working together, scientists and Indigenous communities can develop new approaches to reconstruct traditional practices and document the ecological effects of Indigenous practices (*64*).

These results also have implications for modern fire management and policy. In the wake of recent wildfire disasters—fires that damages homes, infrastructure, water sources, and kill humans—there have been calls to restore traditional Indigenous burning practices in western North America (*7*, *65*) and elsewhere (*66*). Indigenous-managed pyrodiversity offers the opportunity to reduce fire hazard (*6*), support fire-sensitive plant and animal species (*8*), reduce carbon emissions (*67*), and empower Indigenous people (*7*, *65*, *68*). Our results show that a further benefit of supporting, restoring, or emulating Indigenous burning practices, including modern prescribed burning efforts, would be the buffering of the impact of increasing fuel aridity on fire activity. To achieve landscape and regional scale fire-climate buffering, however, these applied burning practices would need to be conducted often and at the scales of interest or in strategic locations that have particularly important influence on landscape-scale fire behavior (*69*). Land managers have struggled to accomplish this goal (*70*), but future management aims for increasing prescribed burning by more than an order of magnitude (*56*, *71*). As was the case in recent centuries, climate will continue to play a strong role in influencing fire activity even in the best-case management scenarios. However, Indigenous burning, prescribed burning, and managed wildfire at the appropriate scales (*7*, *65*) can all contribute to undermine climate as a "force multiplier" in our wildfire challenges as we endeavor to get more "good fire" on the ground (*22*, *72*).

MATERIALS AND METHODS

All fire-scar chronologies used in the analysis are archived in the International Multiproxy Paleofire Database (IMPD) and were compiled as part of the North American Fire Scar Network (NAFSN) (*73*, *74*). All Superposed Epoch Analyses (SEAs) were conducted using the burnr (*75*) library [function *sea()*] in the R programming environment (*76*). SEA isolates the climate reconstruction values for each fire event year (lag 0), and prior (lags −1 to −4) and posterior years (lags 1 and 2), calculates mean values for these lag years for all fire events in a particular period, and then assesses their statistical significance against bootstrapped resampling of a random set of "event" years of the same sample size from the entire dataset. In this fashion, SEA reveals the statistically significant patterns of prior-year and fire-year climate for any single temporal or spatial domain. At each spatial scale and for time periods analyzed, we used SEA (*21*, *75*) of fire years and four reconstructions of hydroclimate: (i) summer PDSI (*77*), (ii) standardized winter precipitation anomalies (*78*), (iii) standardized summer precipitation anomalies (*78*), and (iv) the Niño 3 index of ENSO (*79*), as well as regional temperature anomalies (*80*), to analyze fire-climate relationships. Interpolated drought and seasonal precipitation were delimited to the geographic extent of the landscape defined by the extent of tree-ring sample locations.

Fire-scar chronologies were aggregated from individual tree-ring sites for landscape- and regional-scale collections of individual tree records. Individual fire scar sites (i.e., the local scale) were overwhelmingly, but not exclusively, small (mean area = 48 ± 247.1 ha, median area = 3.5 ha), representing individual tree stands to patches of forest. Local, landscape, and regional groupings were filtered to isolate all presuppression fire years (1500 to 1900 CE), and archaeological and historical records (*27*, *34*, *51*) were used to define intensive- and light-use periods for the Hemish, Diné, and Ndée (Table 1). The composite record for analyses at the regional scale included 4824 individual trees for 451 sites in Arizona and New Mexico (table S1). Landscape-scale datasets had between 48 and 72 sites and 394 and 502 trees for each cultural landscape (Table 2).

For the local-scale analyses, the tree-ring site was the fundamental unit of analysis and observation, but sites were grouped by cultural landscape for comparison and aggregate analysis. For sites, all fire years were analyzed with SEA using the PDSI paleoclimate dataset (*77*) for intensive- and light-use periods. The presence/absence of statistically significant departures from average climate conditions was classified into three categories: (i) one to three prior years of above average moisture, (ii) above average drought in the fire year, or (iii) canonical wet-dry switching. These three types of fire-climate relationship were then tallied for all sites that had at least five trees, had at least five fires, and had undergone rigorous quality control to reduce the impact of misdated fire years for the cultural period of interest (tables S2 and S3). Sites were grouped by landscape-scale cultural areas (Navajo, Jemez, and Apachería; see Figs. 1 and 2), and the number of sites with and without significant climate relationships was summed for each cultural period for four-cell Fisher's exact tests for each landscape to determine whether fire-climate relationships were significantly more common in light-use periods than in intensive-use periods at $P < 0.05$. We calculated percentages of sites with significant climate drivers for each period and each landscape using these tallies. Table 2 reports the percentage (and number) of sites with statistically significant climate drivers for the intensive- and light-use periods, and the Fisher's exact test results for that landscape. Tables S2 and S3 present the tallies for sites/periods with or without significant climate drivers used in the Fisher's exact tests.

At the landscape and regional scales, trees were the fundamental unit of measure. For analysis, these were aggregated by cultural landscape (for the landscape-scale) or the entire region (regional scale). For landscape and regional analysis, widespread fire years were those years represented by at least 10% of recording trees scarred within the entire landscape when a minimum of 11 recording trees were present in the aggregate record. A recording tree is one that was scarred that year or had been previously scarred. Thus, a fire year at the landscape and regional scales refers to fires at a larger spatial extent than that represented in local-scale fires. SEA was done for each cultural period for landscape- and regional-scale aggregations to identify the presence/absence of significantly wet years before widespread fire events and significantly dry fire years. SEA with all climate variables can be found in figs. S1 to S3.

Supplementary Materials

This PDF file includes:
Figs. S1 to S3
Tables S1 to S4
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All fire-scar data were compiled by the North American Fire Scar Network (https://doi.org/10.5066/P9PT90QX) (*74*) and are available via the International Multiproxy Paleofire Database (www.ncei.noaa.gov/products/paleoclimatology/fire-history). DOI for each fire history site used can be found in table S1. All climate data are available through the NOAA paleoclimate database (www.ncei.noaa.gov/products/paleoclimatology). Specific paleoclimate datasets include the following: PDSI (https://doi.org/10.25921/0qmn-2k23), seasonal precipitation data (https://doi.org/10.25921/phr4-1961), ENSO (https://doi.org/10.25921/d2pw-qm53), and temperature (https://doi.org/10.25921/hx0x-m820). The burnr package and related code for conducting SEAs with fire-scar and climate data are available at https://cran.r-project.org/package=burnr.

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