

## Spatiotemporal variability of human–fire interactions on the Navajo Nation

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**Abstract.** Unraveling the effects of climate and land use on historical fire regimes provides important insights into broader human–fire–climate dynamics, which are necessary for ecologically based forest management. We developed a spatial human land-use model for Navajo Nation forests across which we sampled a network of tree-ring fire history sites to reflect contrasting historical land-use intensity: high human use, primarily in the Chuska Mountains, and low human use, primarily on the central Defiance Plateau. We tested for and compared human- and climate-driven changes in the fire regimes by applying change point detection, regression, and superposed epoch analyses. The historical fire regimes and fire–climate relationships reflect those of similar forests regionally and are similar between the two Navajo landscapes until the early 1800s. We then determined that a previously identified, localized, early (1830s) decline in fire activity was geographically widespread across higher human-use sites. In contrast, fires continued to burn uninterrupted through this period at the lower use sites. Though the 1830s included significantly wet and cold periods that could have contributed to fire regime decline, human factors pose a more spatiotemporally consistent explanation. A rise in Navajo pastoralism in the 1820s–1830s was concentrated seasonally in the heavy use sites. By the 1880s, livestock numbers more than doubled, grazing became far more spatially widespread, and frequent fire regimes of Navajo forests collapsed. The last widespread fire recorded on either landscape was in 1886. In the Chuska Mountains, livestock and fire coexisted for over 50 yr between the initial 1832 fire decline and the end of frequent fires after 1886, an exceptional pattern in the western United States. Though unique in its timing, character, and spatial dynamics, the collapse of historical fire regimes in Navajo forests contributed to now over a century without frequent surface fire, leaving Navajo forests at risk for large, uncharacteristic high-severity fires.

**Key words:** dendrochronology; Diné; fire history; natural disturbance regimes; Navajo; pastoralism; ponderosa pine; transhumance; tree rings.

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### INTRODUCTION

Recent increases in wildfire activity have triggered devastating impacts on human communities and natural resources, raising awareness that

anthropogenic climate change combined with past fire management is increasing the vulnerability of western U.S. forests (Stephens et al. 2013). Fire seasons are getting longer, and area burned is increasing, driven in large part by

warmer temperatures (Westerling et al. 2006, Abatzoglou and Williams 2016). Over a century of fire exclusion has increased fuel loads and raised the probability of uncharacteristic high-severity fire across many dry conifer forests (Covington and Moore 1994, Allen et al. 2002). Consequently, high-severity fire has been increasing in recent decades in many regions (e.g., southwestern United States; Singleton et al. 2019). These changes highlight the influence of both humans and climate on fire regimes (Abatzoglou and Williams 2016, Balch et al. 2017) but represent only a small snapshot in time for understanding interactions of multiple complex processes. For example, many modern wildfire analyses rely on satellite-derived fire products, many of which begin in 1984 or later (e.g., MTBS, Eidenshink et al. 2007). Paleo records of fire provide multi-century insights into human–fire–climate dynamics that can inform current fire management and restoration and help to calibrate projections of future fire regimes.

The modern era of fire exclusion began asynchronously across the western United States with most fire regimes collapsing by the early 20th century (Swetnam et al. 2001). This spatial and temporal variability of declining fire regimes has generated multiple hypotheses regarding causal factors, including the removal or decline of Native American populations and fire use (Spoon et al. 2015), intensive livestock grazing and industrial logging associated with settlement by Euro-Americans and arrival of the railroad (Leopold 1924), active fire suppression (Pyne 1982), and climate variability (Biondi et al. 2011). It is challenging to disentangle the relative effects of each factor because they roughly coincide in time, interact, and vary in importance geographically. Unraveling the human and climatic factors that influenced historical fire regimes and those that ultimately led to fire regime collapse is important for projecting future fire regimes and informing fire and forest restoration (Swetnam et al. 1999).

Climate variability is a primary driver of fire activity through regulation of the production and availability of fuels to burn. In the fuel-limited semiarid forests of the southwestern United States, historical surface fire activity was strongly associated with seasonal, inter-annual, and decadal moisture variability (Swetnam and

Betancourt 1990, 1998, Kitzberger et al. 2007, Margolis et al. 2017) and decadal-to-centennial variability in temperature (Trouet et al. 2010). Ecologically significant widespread fires were largely synchronized with drought episodes that followed multiple years of above-average moisture (Swetnam and Betancourt 1998). Antecedent wet conditions were necessary for the buildup and continuity of herbaceous fuels that enable fire spread. Humans can interrupt this link between climate and fire by altering the abundance and continuity of surface fuels (Bowman et al. 2011).

The influences of humans on historical fire regimes have long been debated (Roos et al. 2014). The idea that forests of the western United States were pristine natural areas wherein fire activity was driven solely by climate contends with a view that nearly all western fire regimes were anthropogenic, in which fires were set to manipulate forests for human benefits (Denevan 1992, Vale 2002a, b, Kay 2007). A more nuanced perspective on historical human–fire interactions among Native American groups is emerging in the western United States (Stan et al. 2014, Spoon et al. 2015, Swetnam et al. 2016, Taylor et al. 2016, Azpeleta Tarancón et al. 2018, Whitehair et al. 2018). Many Native American groups used landscape fire for hunting, for agricultural land clearing, for food production, and in conflict (Williams 2002, Swetnam and Baisan 2003, Fulé et al. 2011, Sullivan and Forste 2014, Spoon et al. 2015). Yet, the region also has some of the highest rates of lightning ignitions: “lots of lightning, plenty of people” (Allen 2002). Nonetheless, multiple studies point to localized, anomalous periods of change in the fire regimes that are likely indicative of human influence, including increased fire frequency (Seklecki et al. 1996, Kaye and Swetnam 1999, Meunier et al. 2014), unusually long fire-free periods (Heyerdahl and Alvarado 2003, Stephens et al. 2003), or changes in fire seasonality (Grissino-Mayer et al. 2004). Another fingerprint of human effects on fire regimes is high numbers of small fires (Swetnam et al. 2016, Taylor et al. 2016). Human ignitions can supplement natural ignitions, creating a more diverse and fragmented matrix of fuels on the landscape, and leading to self-limitation in fire extent. This phenomenon has been observed across the globe (e.g., Archibald et al. 2012,

Bliege Bird et al. 2012, Rolstad et al. 2017) and is documented in some areas of the southern and southwestern United States (Stambaugh et al. 2013, Swetnam et al. 2016, Taylor et al. 2016).

One difficulty of teasing apart human–fire–climate interactions is the rarity of historical documentation and proxy records pertaining to fire, climate, and humans for the same time periods and locations (Bowman et al. 2011). The Navajo Nation, located in the southwestern United States, presents a unique opportunity to study multi-century human–fire–climate interactions, because of a well-documented and unique human history that can be compared with tree-ring reconstructions of climate and fire regimes. Unlike most other regions in the western United States, the present-day Navajo Nation was never settled or used extensively by Euro-Americans. Apart from a four-year exile in the 1860s, which began with the “Long Walk” in 1863 forced by the U.S. military (Bailey 1964), the area has remained under the control of the Diné (Navajo) indigenous group since they began to settle in this particular area in the late 17th century (Towner 2008). Prior to circa 1700, the archaeological record suggests that the area was probably not well used and lacked any large settlements for centuries (McDonald 1976). The late arrival and permanent residency of the Navajo Native American population through the late 19th-century period of widespread fire decline contrasts with most other forested areas of the western United States (Pyne 2003).

The Navajo are famous for their sheep breeding and pastoral culture, which is well documented to have begun earlier than most livestock programs in the West (Bailey and Bailey 1986, Weisiger 2004). Large increases in sheep on the Navajo Nation began in the 1820s and 1830s (Denevan 1967, Bailey 1980, Bailey and Bailey 1986) as Diné pastoralism took on greater importance and Navajo acquired many animals during a period of back-and-forth raiding with other tribes and settlements in the region (McNitt 1972). Following establishment of the Navajo reservation in 1868, the U.S. government enforced a localized economic model upon the Diné, encouraging the rapid growth of livestock herds with provisions of more than one million animals, and facilitating the entry of dozens of trading posts after 1880 that were supplied by

nearby railroads (Bailey and Bailey 1986, Weisiger 2009). This timeline of Navajo culture, including (1) settlement in their current location beginning circa 1700, (2) the intensification of Navajo pastoralism in the 1820s and 1830s, and (3) the near-continuous presence on the land through the late 19th-century regional decline in fire activity, allows us to directly test for human effects on forest fire regimes.

Paleo-charcoal records indicate that fires have burned in Navajo forests for millennia (Paklaian 2017). Pioneering tree-ring fire history research by Savage and Swetnam (1990) documented an early (1830s) decline in fire in a small study area in the central Chuska Mountains of the Navajo Nation. A similar 1830s decline in fire was documented in an area of the northern Chuska Mountains (Whitehair et al. 2018). Yet, in both study areas, fires did not stop completely and continued to burn at a lesser extent into the early 20th century. Savage and Swetnam (1990) attributed the early fire decline to sheep pastoralism but raise the possibility that climate played an important role, though they did not test this hypothesis. The 1830s–1840s were wet and cold regionally (Salzer and Kipfmüller 2005), which would have shortened the fire season, reduced vegetative flammability, and also supported growing numbers of livestock that could have both reduced herbaceous fuel loading and interrupted fuel continuity.

The goal of this study is to evaluate the relative roles of human land use and climate on spatial and temporal variability of forest fire regimes on the Navajo Nation. We developed a spatial model of human land use to explain the variability in fire regimes across two adjacent landscapes. Our model is derived from the locations of home site structures and surface water, combined with knowledge of Diné pastoral practices and transhumant patterns (e.g., Jett 1978). Our objectives are to (1) reconstruct the fire regimes of two adjacent landscapes with contrasting Navajo settlement and land-use intensity: the Chuska Mountains, high human use, and the Defiance Plateau, low human use; (2) test for temporal changes in climate and fire regimes over multiple centuries; and (3) assess the climatic and human roles in fire regime variability by evaluating the fire–climate relationship over the full reconstruction period and for both

landscapes. We base interpretations of human–fire interactions on the spatial model of land use and key periods in Navajo cultural history, including the 18th-century settlement era, early 19th-century pastoralism, and the late 19th- to early 20th-century reservation and intensive live-stock grazing era (Weisiger 2009).

## MATERIALS AND METHODS

### Study area

This study is located on the Navajo Nation along the northern part of the border between Arizona and New Mexico (Fig. 1). The montane forests of the Navajo Nation cover 280,000 ha and are primarily located in two adjacent landscapes, the Chuska Mountains and the Defiance Plateau. The Chuska Mountains are defined by a relatively narrow north-west-trending Oligocene sandstone crest of the Chuska Erg (Wright 1956, Cather et al. 2008) that includes dozens of shallow perennial lake basins (Wright 1964). The Defiance Plateau is largely composed of more permeable Triassic sandstone, is lower in elevation, is broader, has less topographic variability, and has relatively little perennial surface water. The mean elevation of sample sites is 2670 m in the Chuska Mountains and 2330 m on the Defiance Plateau (Table 1). Forests of both landscapes are predominantly ponderosa pine (*Pinus ponderosa*). Gambel oak (*Quercus gambelii*) is common in the understory, or occasionally as a codominant. On the higher elevation Chuska Crest, Douglas-fir (*Pseudotsuga menziesii*) and aspen (*Populus tremuloides*) are present in more mesic settings. Both landscapes grade rapidly into piñon-juniper (*Pinus edulis-Juniperus* spp.) woodlands at lower elevations.

The climate of the study area is continental and semiarid. The precipitation regime is bimodal, with most of the annual rainfall occurring July–September during the North American Monsoon, and the remainder occurs as snow in winter (Sheppard et al. 2002). The mean annual precipitation is 332 mm (1900–2010; based on the Precipitation-Elevation Regression on Independent Slopes Model, PRISM [Daly et al. 2008], averaged for the study area). Average minimum temperatures range from  $-8.6^{\circ}\text{C}$  in January to  $10.2^{\circ}\text{C}$  in August, and average maximum

temperatures range from  $4.9^{\circ}\text{C}$  in January to  $27.0^{\circ}\text{C}$  in July (1900–2010; PRISM 2016).

### Spatial land-use model

We used the locations of modern home sites and perennial lakes to estimate potential early and high human land use across the two study area landscapes. These location data were provided to us by the Navajo Nation Forestry Department. We applied spatial kernel density distributions to generate surfaces of relative density for each data set. Perennial lakes in the study area were a vital component for historical Navajo settlement and pastoralism. We hypothesized that areas with surface water would have been the loci for the largest sheep herds, particularly in the 19th century. Access to water for human use remains important, since many of the home sites in the forested areas do not have running water. Our decision to use modern home sites to estimate locations of historical human settlement and use is based on two assumptions: (1) Home sites currently near natural surface water would have been particularly sought after in the 19th century; and (2) Navajo traditionally pass down settlement locations through generations (Weisiger 2009), so areas of greater home site density have probably been used or occupied the longest. Structures and corrals spanning multiple generations are often present at home sites.

The spatial distributions of home sites and surface water are similar, and both are heavily concentrated in the Chuska Mountains (Fig. 1). The Chuska Mountains have abundant surface water in perennial lakes (Wright 1964), whereas the Defiance Plateau does not. Settlement clusters on the Defiance Plateau are associated with modern communities such as Sawmill, Arizona (AZ), near our Kailcheebito Spring (KCS) site that was built for logging in the 1920s, and houses to the south of the Natural Bridges Canyon (NBC) site that were built along the paved highway between Ft. Defiance and Ganado, AZ, to the west. We used the results of this spatial model to a priori locate and compare fire history sites that were likely most heavily used, primarily in the Chuska Mountains, with less used areas across the Defiance Plateau. The one exception to this design was Pine Canyon South (PCS), a high-use site located on the southern Defiance Plateau (Fig. 1) near a small community associated with

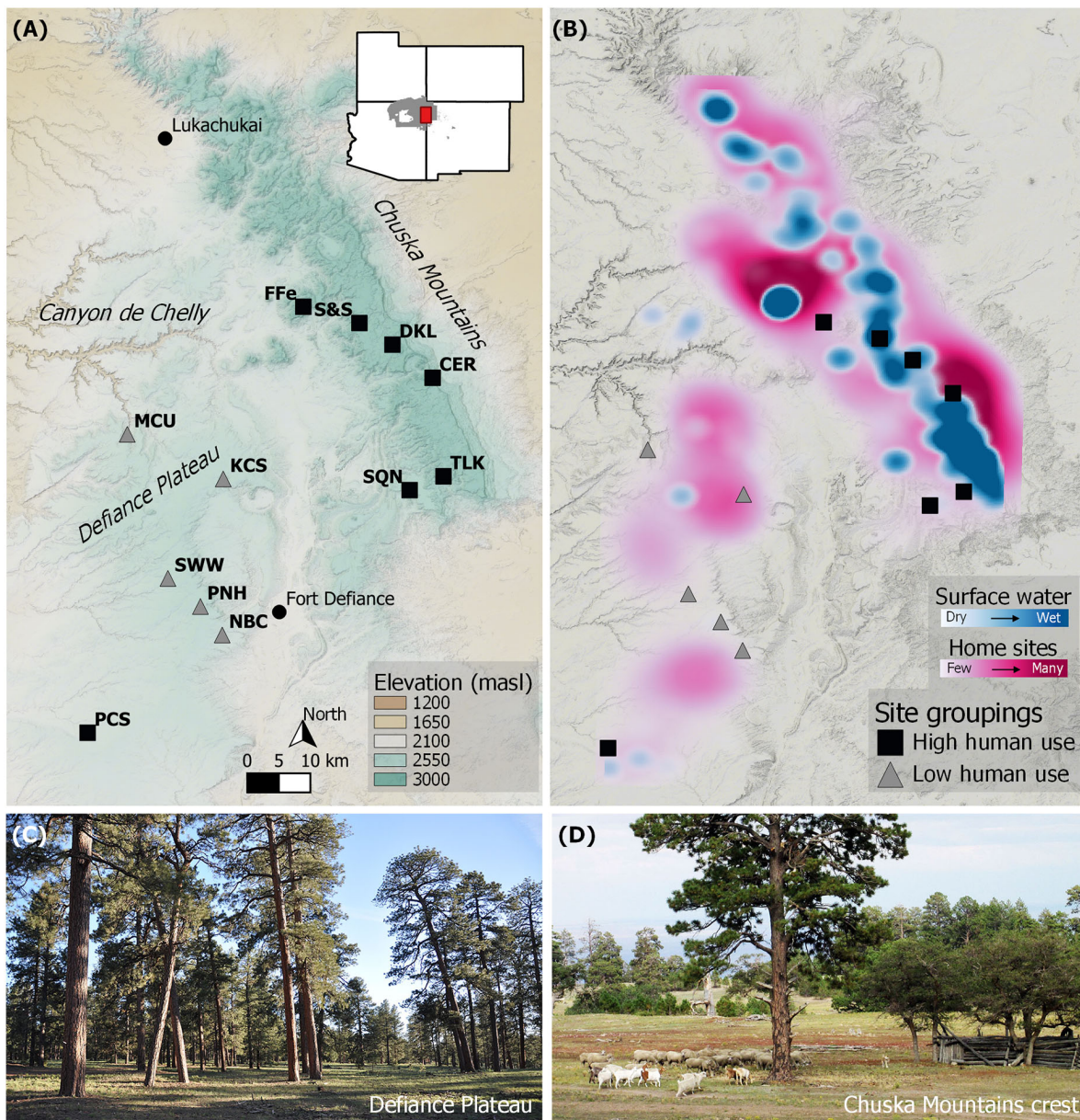


Fig. 1. Locations and human-use categories of tree-ring-based fire history sites on the Navajo Nation in the southwestern United States (A). Fire history site locations are superimposed on a spatial model of land-use intensity, inferred as historically higher human use where there is more abundant surface water (perennial lakes) and are more numerous modern home sites (B). Representative photographs for low human-use areas on the Defiance Plateau (C) and high human-use areas in the Chuska Mountains (D). See Table 1 for site names. Photos by C. Guiterman.

a reliable spring and several larger communities west of the plateau (Ganado and Wide Ruins, AZ). After it was initially sampled in 2015, we learned that PCS was also located near the

Pueblito of *Kin Náázíní*, a mid-18th-century defensive Navajo structure (Gilpin 1996). The area served as a travel corridor between Zuni and Hopi Pueblos to the east and west, and is

Table 1. Fire history sites in ponderosa pine-dominated forests of the Navajo Nation.

Site name	Site code	Mean elevation (m)	Sample area (ha)	Number of trees	Fire dates	Tree-ring dates
High human use						
Chuska East Ridge	CER	2712	1.0	6	1504–1879	1309–1984
Duck Lake	DKL	2747	35.3	12	1476–1893	1336–1985
Falling Irons	FFe	2779	78.3	38	1510–1896	1468–1936
Pine Canyon South	PCS	2226	9.8	14	1323–1876	1072–1962
Savage and Swetnam	S&S	2738	1.4	4	1679–1870	1529–1986
Squirrel Springs North	SQN	2455	11.2	18	1462–2011	1384–2016
Tohatchi Lookout	TLK	2593	79.1	32	1337–1925	1293–2017
Low human use						
Kailcheebito Spring	KCS	2392	4.3	13	1481–1886	1372–2016
Monument Canyon Upper	MCU	2210	1.0	5	1595–1871	1446–1963
Natural Bridges Canyon	NBC	2307	1.3	9	1396–1902	1254–2016
Piney Hill	PNH	2433	67.0	22	817–1910	735–2017
Scattered Willow Wash	SWW	2391	18.0	21	1333–1879	1134–2016

associated with the *Ma'iideshgizhnii* Navajo clan (Coyote Pass People) that has strong ties to Jemez Pueblo. Upon revisiting the site in 2016, we determined that it was also near a small, perennial water pool in the canyon and had nearby evidence of old sheep corrals, which are relatively uncommon on the central Defiance Plateau. Finally, the fire history at PCS contains multiple anomalous fire gaps that we interpret as originating from localized early grazing. Given the evidence of nearby human use and interruptions to the fire regime, we grouped the PCS site with the other high human-use sites that are located in the Chuska Mountains. All of the other Defiance Plateau sites were confirmed as likely low human use and analyzed together.

#### Fire history reconstruction

We sampled fire history sites in the Chuska Mountains (high human use) and on the Defiance Plateau (low human use). Within each landscape, sample sites were distributed to provide broad spatial coverage. We only sampled in the southern half of the Chuska Mountains, because of an ongoing fire history study in the northern Chuska Mountains near Lukachukai (Whitehair et al. 2018). Final site locations were determined by road locations, permission to access the land, and abundance of fire-scarred material (i.e., targeted sampling).

At each of our sites, we used standard tree-ring fire history methods (Dieterich and Swetnam 1984) to collect samples primarily from

dead trees (stumps, logs, and snags) and occasionally from live trees. Partial cross sections were extracted from trees with multiple fire scars to obtain a complete inventory of all spreading fire events (Farris et al. 2013). We targeted old remnant and living trees, as identified by the number of rings, spiral grain, and weathering in order to extend the reconstruction back in time as long as possible.

In the laboratory, we prepared the samples using standard dendrochronological methods that included sanding to a fine polish in order to accurately see cellular structure (Speer 2010). Samples were precisely crossdated using local tree-ring chronologies (Guiterman 2016, Guiterman et al. 2016). In the event that a specimen could not be crossdated by visual and/or skeleton-plot techniques, we measured the growth patterns and used the program COFECHA (Holmes 1983) to aid in identifying dates that we checked visually. Once crossdated, we identified the year and intra-ring position of each scar (Baisan and Swetnam 1990) and assigned the year of dormant scars to the subsequent growth year (i.e., spring fires), based on regional analyses of fire season (Swetnam and Betancourt 1998). Initial assessments of the fire histories and quality control were performed iteratively by viewing plots in the FHAES computer program (version 2.02; Sutherland et al. 2015).

We located and verified the dating of existing samples from 16 fire-scarred trees in the Chuska Mountains (Savage and Swetnam 1990) to

include in our data set. These samples were collected as isolated individuals or in small groups of 2–4 trees across a relatively large area (~4000 ha). To boost estimates of historical fire activity on the Chuska Crest, we used the largest and northernmost Savage and Swetnam (1990) tree group (S&S,  $n = 4$  trees), supplemented two small groups (combined  $n = 5$ ) with our own additional sampling at Duck Lake (DKL,  $n = 7$ ), and added a southern site (Chuska East Ridge, CER,  $n = 6$ ). These three sites include over 37 ha of sampled area distributed over ~1000 ha in the central Chuska Mountains.

### Analyses

Fire history data were analyzed in R (version 3.6.1; R Core Team 2019) using the *burnr* fire history package (version 0.5.0; Malevich et al. 2018). We started our analyses after 1600, the year at which 20% of trees were recording fire. Trees were identified as recording following the scar that initiated the open cat face wound (Swetnam and Baisan 1996). Fire intervals were assessed at two spatial extents within individual sites: fires recorded by any tree, and fires recording by  $\geq 25\%$  of trees with a minimum of two trees recording and two trees scarred (hereafter, the 25% filter). The stringent percentage filter omits small fires that scar single trees, allowing us to concentrate analyses on well-replicated, spreading surface fire events (Swetnam and Baisan 1996). Studies by Farris et al. (2010, 2013) demonstrate the efficiency of targeted fire-scar sampling for reconstructing temporal and spatial patterns of fire history in southwestern ponderosa pine forests, and the strong correlation of percentage-filtered fire interval metrics with independent fire atlases (maps of observed fires) and total area burned.

We compared the fire history reconstructions between the two categories (high vs. low human use) with regard to fire frequency, extent, fire–climate relationships, and fire-scar seasonality. We tested the categories for different overall fire frequencies, as calculated using all scars and with the 25% filter, by performing two-sample *t*-tests (data are normally distributed but have unequal variances;  $\alpha = 0.05$ ).

As a metric of fire extent, we calculated fire index for each category (Taylor et al. 2008, 2016). Fire index represents the relative extent of past

events but does not indicate the exact size of individual fires. It is calculated as the sum of site-level percent-scarred time series divided by the number of sites recording fire. Individual site series were added only once they had two trees recording fire. Changes in fire index through time were identified by performing nonparametric change detection in R using the *cpm* package (version 2.2; Ross 2015). This method performs sequential Mann-Whitney tests by adding observations over time until a change is detected, and then repeats the analysis for a new set of years following a detected change point (Ross et al. 2011). To check the robustness of the change point years identified by *cpm*, we performed piecewise linear regression tests on cumulative fire-event time series (Brown and Sieg 1999, Brown et al. 1999, Meunier et al. 2014). The regression procedure detects break points in the regression slope caused by changes in fire frequency and was performed with the segmented library in R (version 3.0; Muggeo 2008).

We also tested for temporal changes in tree-ring reconstructions of historical temperature and drought, following the methods we applied to fire index. Drought data were obtained from the Living Blended Drought Atlas (Cook et al. 2010), which is a gridded reconstruction of June–August Palmer Drought Severity Index (PDSI; Cook and Krusic 2004). We averaged 16 PDSI gridpoints covering the study area between 109.75° W to 108.25° W and 35.25° N to 36.75° N. Temperature data were obtained from a reconstruction gridpoint near the Four Corners region, located at 107.5° W and 37.5° N (Wahl and Smerdon 2012).

We quantified the relationship between fire and inter-annual variability in PDSI with superposed epoch analysis (SEA; Swetnam 1993) in *burnr*. We performed SEA on fire years meeting the 25% filter and that were recorded synchronously at  $\geq 2$  sites. We split the data set into human-use categories, as described above, and into different historical periods. Our periods of analysis were the full post-1600 reconstruction period, the period of fire regime decline as identified by change point detection, and the 50 yr preceding the decline. We added the pre-decline period to assess the degree to which different fire–climate patterns during the decline era are related to the duration and timing of decline as

opposed to human influences. Our expectation was that the 50-yr pre-decline period would be very similar to the full reconstruction and that the decline period would be different due to human influences. Fire-scar seasonality was assessed across the same time periods and site categories as SEA.

## RESULTS

We reconstructed fire histories at 12 ponderosa pine-dominated sites in the Chuska Mountains and Defiance Plateau on the Navajo Nation from 194 trees and 1560 dated fire scars. Tree-ring chronologies extend longer than one millennium, with the earliest tree dating to 735 Common Era (CE), the earliest fire scar is in 817 CE, and the most recent scar is in 2011 (Table 1). All but one site (S&S) has at least one tree dating prior to

1500. The latest spreading fire event (i.e., 25% filter) recorded at any of our sites was in 1886.

Fire was historically frequent at all sites (Table 2). Mean fire intervals (MFIs) for all fires across all sites ranged from 3.7 to 11.4 yr and from 9.3 to 27.2 yr for 25% filter fire events. Much of the variability in MFI is related to sample area (Table 1). The MFI for high-use sites averaged 7.1 yr for all fires and 15.5 yr for 25% filter events, while at low-use sites, these averages were 7.0 and 11.8 yr, respectively. MFI values between high- and low-use sites did not differ across the spatial land-use model when testing for all scars ( $t$ -test,  $P = 0.94$ ) or 25% filter events ( $P = 0.19$ ).

At high-use sites, we note declining surface fire activity after ~1830 (Fig. 2), whereas fire activity at low-use sites remains stable through this period (Fig. 3). Change point detection of relative

Table 2. Historical fire return interval statistics for ponderosa pine-dominated forests of the Navajo Nation.

Site	Composite filter	Number of intervals	Mean fire interval (MFI)	Minimum	Maximum	Weibull median fire interval <sup>†</sup>
High human use						
CER	All fires	17	11.4	3	23	10.7
	25%	9	15.4	7	44	13.4
DKL	All fires	54	5.3	1	29	4.1
	25%	10	19.7	4	48	17.2
FFe	All fires	79	3.7	1	26	...
	25%	25	10.7	3	33	9.9
PCS	All fires	30	9.2	2	41	...
	25%	15	16.4	5	41	14
S&S	All fires	18	10.6	1	40	8.2
	25%	6	27.2	3	106	16.9
SQN	All fires	64	4.4	1	17	...
	25%	30	9.3	3	21	8.8
TLK	All fires	59	4.9	1	17	...
	25%	28	9.6	3	22	8.8
Low human use						
KCS	All fires	46	6.1	1	19	5.4
	25%	27	9.7	2	19	9.1
MCU	All fires	26	10.3	3	41	9.2
	25%	17	11	4	18	11
NBC	All fires	32	8.2	2	20	7.9
	25%	19	13.9	2	31	12.7
PNH	All fires	52	5.2	1	15	4.7
	25%	18	13.5	3	33	12.3
SWW	All fires	57	4.9	1	11	4.6
	25%	20	10.8	3	29	10.1

CER, Chuska East Ridge; DKL, Duck Lake; FFe, Falling Irons; KCS, Kailcheebito Spring; MCU, Monument Canyon Upper; NBC, Natural Bridges Canyon; PCS, Pine Canyon South; PNH, Piney Hill; S&S, Savage and Swetnam; SQN, Squirrel Springs North; SWW, Scattered Willow Wash; TLK, Tohatchi Lookout.

<sup>†</sup> Fits of the Weibull density function were assessed with a Kolmogorov-Smirnov test ( $\alpha = 0.10$ ). Ellipses indicate a poor fit (Grissino-Mayer 1999).



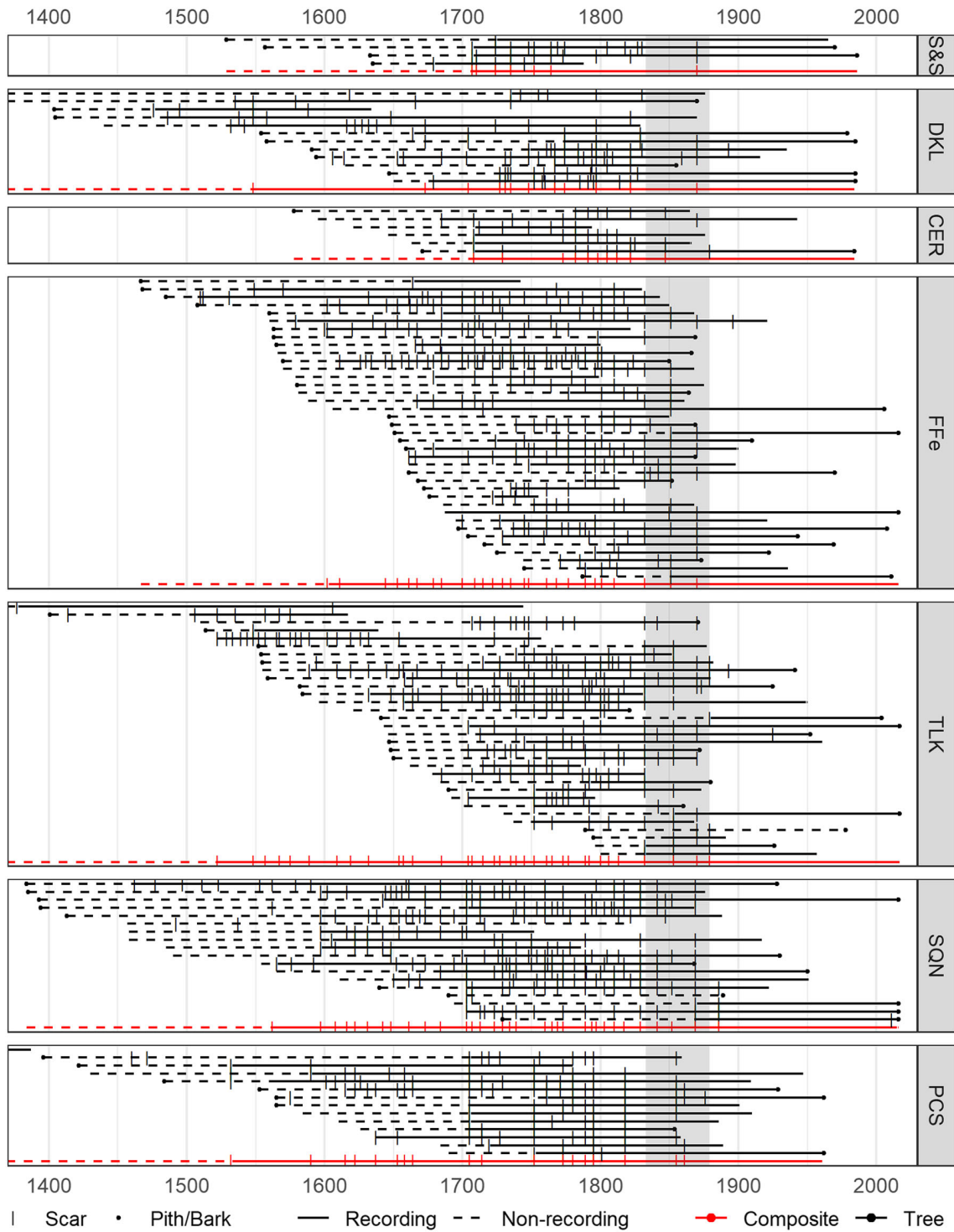


Fig. 2. Fire histories of high human-use sites on the Navajo Nation, representing much of the Chuska Mountains. Each horizontal line shows the time series of an individual tree, with vertical marks indicating fire scars. Composite fire-scar series (red) are based on the 25% filter. The gray shaded area encompasses the 1833–1879 period of fire decline across these sites. See Table 1 for site names.

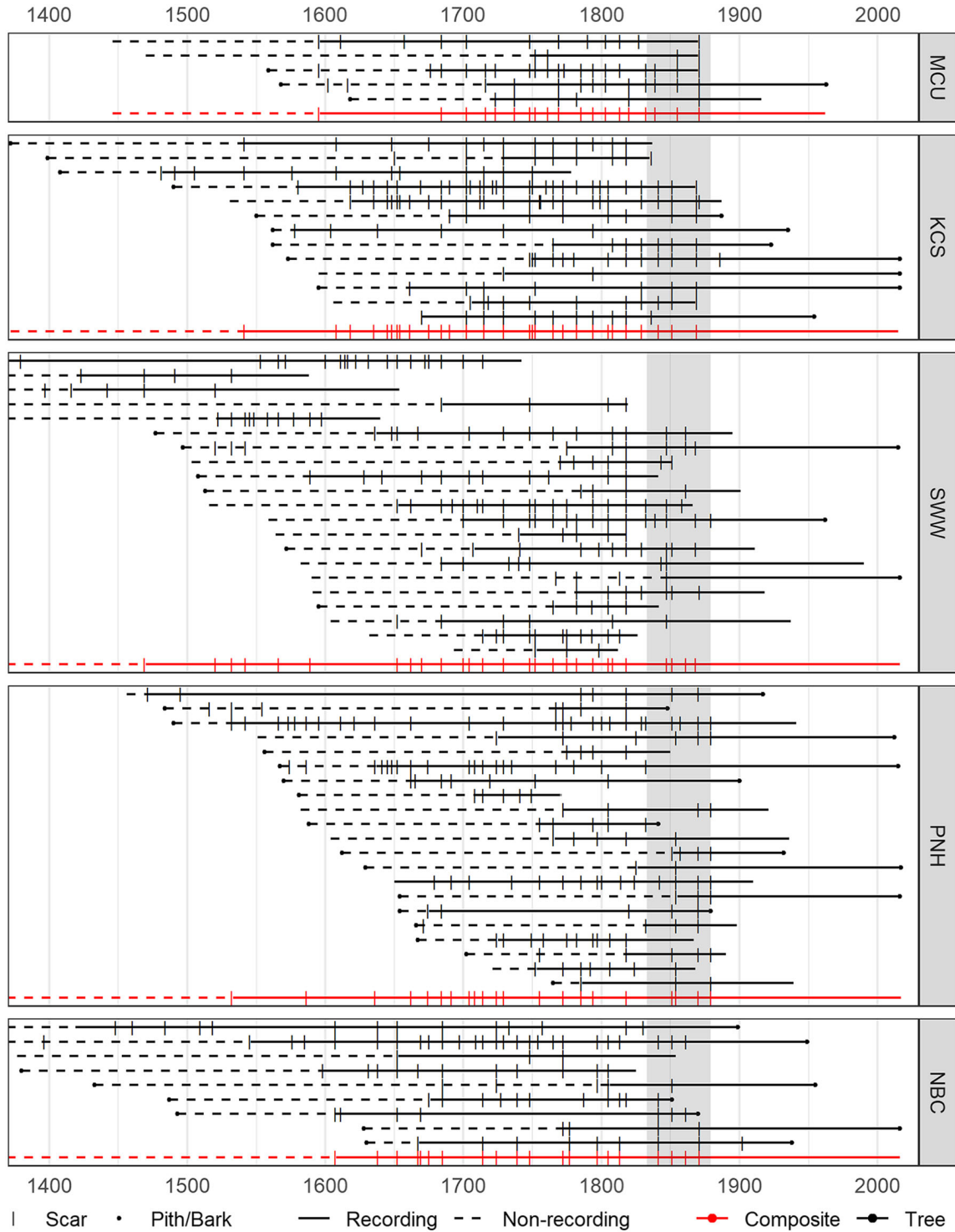


Fig. 3. Fire histories of low human-use sites on the Navajo Nation, representing forests of the central Defiance Plateau. Each horizontal line shows the time series of an individual tree, with vertical marks indicating fire scars. Composite fire-scar series (red) are based on the 25% filter. The gray shaded area encompasses the 1833–1879 period of fire decline across the high-use sites, shown in Fig. 1. See Table 1 for site names.

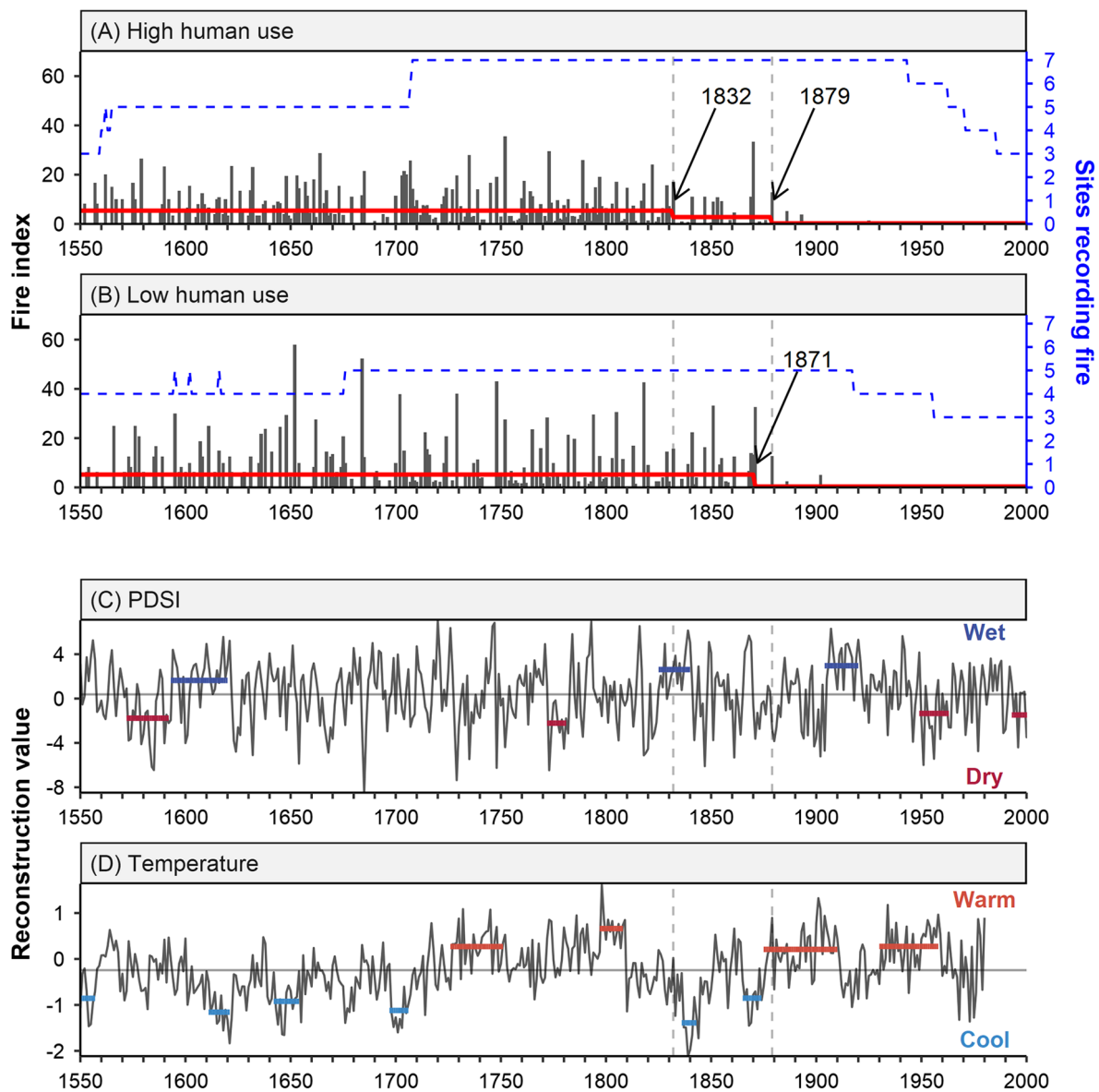


Fig. 4. Annual fire index (relative fire extent) for high human-use sites (A) and low human-use sites (B) compared to independent tree-ring reconstructions of drought (C) and temperature anomaly (D) for the Navajo Nation study area. A nonparametric change detection analysis was used to identify shifts in the running mean of each time series, shown as bold horizontal lines on each panel. In (C) and (D), only the most extreme periods are shown (defined as greater than one standard deviation above or below the mean). The reconstruction average for each series is shown as the gray horizontal line. Vertical dashed gray lines across all panels indicate the period of reduced fire activity (1832–1879) at high human-use sites as determined by change point detection.

fire extent (i.e., fire index) for each category identified significant declines in fire in 1832 and in 1879 for the high-use sites, and in 1871 for the low-use sites (Fig. 4A, B). Changes in fire

frequency determined by piecewise linear regression supported these findings, with declines in 1828 and 1887 at the high-use sites, and in 1868 at the low-use sites (Fig. 5).

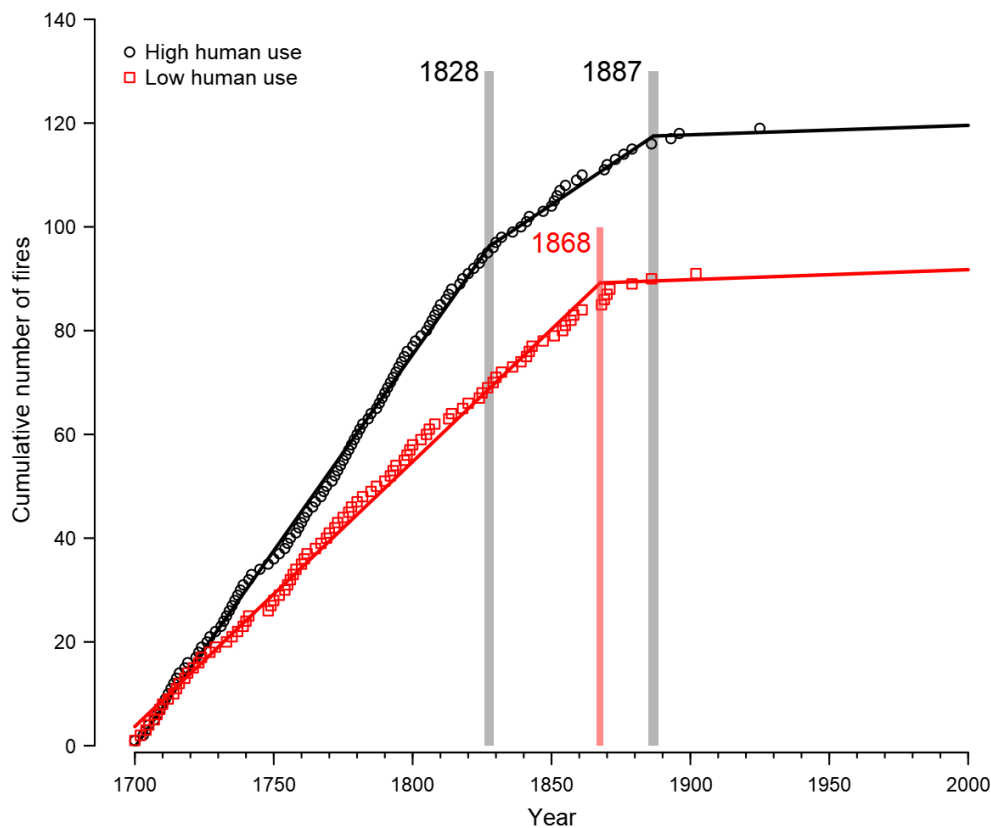


Fig. 5. The cumulative number of fires for high human-use sites and low human-use sites on the Navajo Nation. Changes in slope indicate shifts in fire frequency through time. The timing of the changes in fire frequency is indicated by the year; the widths of the vertical shaded bars represent the confidence interval around change years.

The climate reconstructions also include significant changes in running mean in the middle and late 1800s (Fig. 4C, D). The period 1825–1840 was anomalously wet (Fig. 4C) and 1836–1843 was anomalously cold (Fig. 4D), coinciding with the fire decline at high-use sites that began after 1832 (Fig. 4A). Another cold period occurred from 1865 to 1874. An increase in temperature beginning in 1875 was coincident with the final decline in fire at the high-use sites (1879; Fig. 4A) and the low-use sites (1871; Fig. 4B). Other periods of anomalous climate in the late 1500s (drought), early 1600s (pluvial), and early to middle 1700s (warm) did not coincide with changes in fire activity.

The long-term historical fire–climate relationship across both human-use categories underscores the importance of inter-annual climate variability in promoting fuel conditions for synchronous fire activity (Fig. 6). Fires were

recorded in years with significant drought conditions, marked by below-average PDSI. Over the full post-1600 reconstruction, fire-event years were preceded by a significantly wet year. The fire–climate relationship during the 50-yr pre-decline period mirrors the pattern of the full reconstruction, but some lag-year averages did not exceed their bootstrap confidence intervals. This most likely relates to the relatively low numbers of fire-event years, leading to wider confidence intervals around mean PDSI (note the widening vertical axes in Fig. 6). The SEA results for the decline period (1833–1879) also indicate drought and antecedent wet years in association with fire events, but drought levels were not significant. During the decline era, however, antecedent wet conditions were significant two to three years prior to a fire year, which were longer lags than over the full reconstruction.

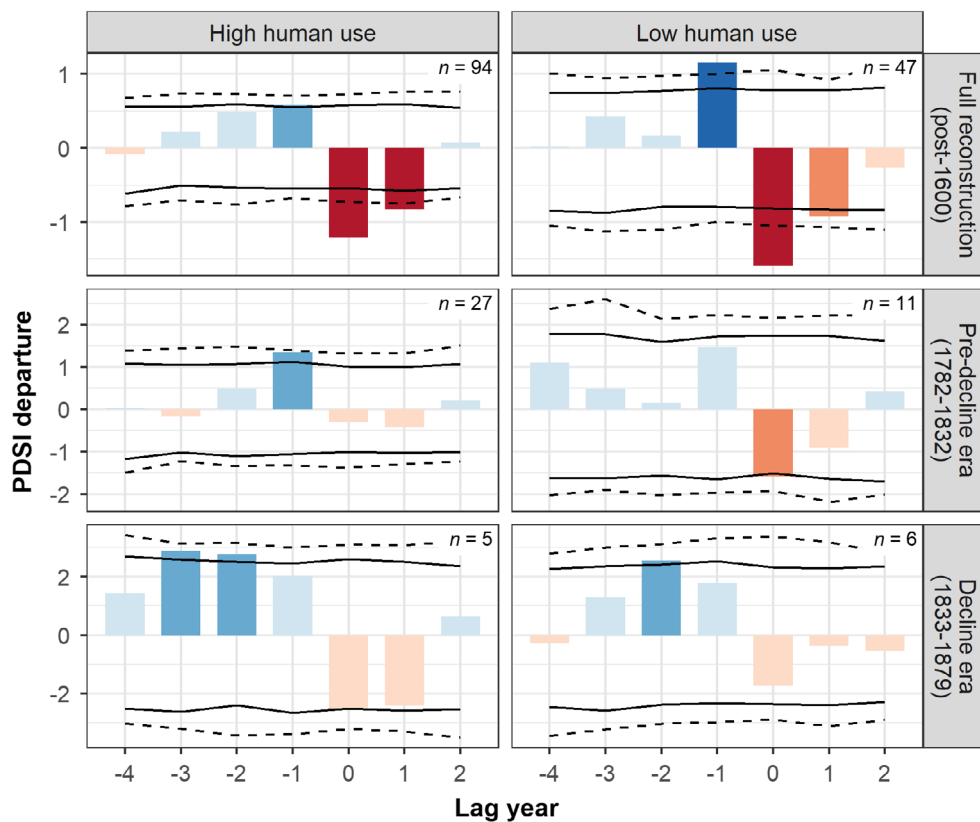


Fig. 6. Fire-climate relationship in Navajo forests. Superposed epoch analyses between synchronous ( $\geq 2$  sites) widespread fires (25% filter) and Palmer Drought Severity Index (PDSI) were split between the site categories and for different periods (full reconstruction, 50 yr prior to 1832 fire decline, and the fire decline period). The year of the fire in the superposed epoch analysis (SEA) is indicated as lag-year zero. Bootstrap confidence intervals are provided at the 95% (solid) and 99% (dashed) levels for the mean departures of PDSI. The number ( $n$ ) of unique fire-event years is provided for each SEA.

The predominant season of fire in Navajo forests was spring and early summer, recorded as dormant and early-earlywood fire scars (Fig. 7). This pattern is consistent across use areas. During the fire decline period (1833–1879), however, there was an increase in spring dormant fires that occurred at the high-use sites.

## DISCUSSION

### *Historical fire regimes of the Navajo Nation*

The general pattern of historical fires in ponderosa pine-dominated forests of the Navajo Nation reflects that of similar forest types in the region (Fulé et al. 2003, Rother and Grissino-Mayer 2014, Guiterman et al. 2018). Recurrent surface fires burned at individual sites every

seven years on average. At the scale of our fire history network across the Chuska Mountains and Defiance Plateau, fire was recorded somewhere on the landscape in nearly every year historically. We also found multiple years of extensive burning. For example, in 1748 and 1870, trees spanning more than 55 km of the Chuska Mountains were scarred by fire. This included multiple trees at our sites and also at existing sites in the northern Chuska Mountains (Whitehair et al. 2018). Fires were also recorded on the Defiance Plateau in the same years, indicating the strong possibility for multiple ignitions and independent fires burning synchronously during favorable climatic conditions. Fire activity predominantly occurred in spring and early summer during the foreshummer

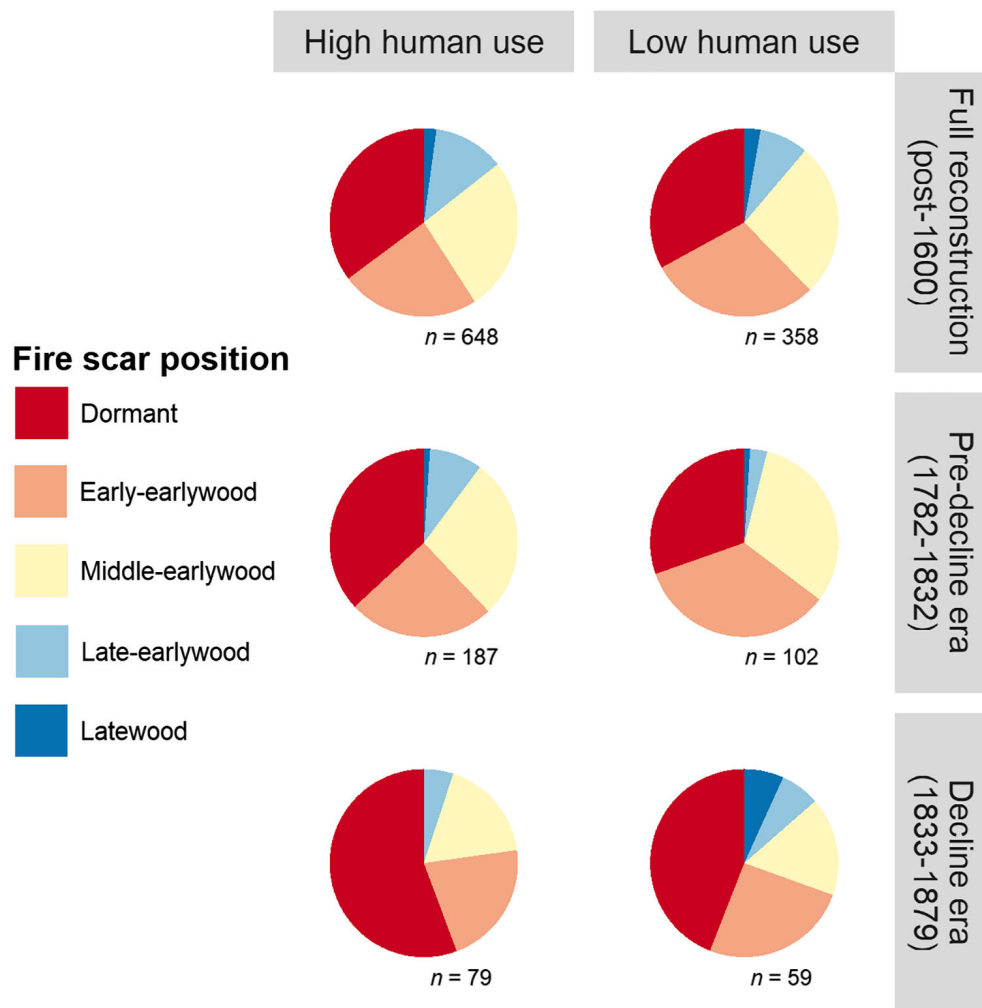


Fig. 7. Intra-ring position (seasonality) of fire scars in Navajo forests. The number of individual fire scars ( $n$ ) with a determined season is provided for each pie chart. Dormant fires likely occurred prior to the onset of growth in the late spring/early summer.

drought (likely April–June), especially following one to two years of above-average winter precipitation. This pattern is common to dry conifer forests of the region (Swetnam and Betancourt 1998) and is indicative of a necessary buildup of fine fuels to form a continuous surface fuel layer that enables fire to spread at stand to landscape scales. The fire–climate relationship also underscores sensitivity of historical fire regimes to both bottom-up and top-down influences that could disrupt fuel loading and continuity.

Across our spatial land-use model, patterns of surface fire activity were quite similar, until the mid-19th century. The two landscapes—Chuska

Mountains and Defiance Plateau—have similar forest types, topography, and climate, but differ in their geology, which leads to contrasting surface-water resources and thus their desirability for livestock grazing. This fact is well documented in the ethnographic, archaeological, and historical record of the Diné (Navajo) and of the landscapes themselves. The spatial densities of perennial surface water and home sites are in strong accord with the historical record of cultural practices among the Diné, including seasonal transhumant migrations ranging as far as 100 km to grazing areas and summer sheep camps in the Chuska Mountains (Jett 1978). The

strength of our study design to sample across this historical spectrum of land-use intensity is that it enabled us to tease apart drivers of change in historical fire regimes that are often conflicting (Bowman et al. 2011).

Fire regimes of the Navajo Nation share many characteristics with similar forests of the southwestern United States, but are unique in the timing, patterns, and mechanisms of mid- to late 19th-century declines in fire activity. Many other landscapes in the region experienced collapse of frequent fire regimes in the late 19th century, attributed to land-use changes associated with Euro-American arrivals and settlement (Swetnam and Baisan 1996). The Navajo Nation, by contrast, was never settled by Euro-Americans. Historical land-use patterns in Navajo forests created a different and dynamic human–fire relationship that to our knowledge is unique in the western United States.

#### *Contrasting fire regime declines*

We found that the historical fire regimes differed along axes of relative historical land-use intensity in the early 19th century. At higher use areas, predominantly in the Chuska Mountains, fire activity significantly declined in extent and frequency after circa 1830. In contrast, the fire history of lower use areas on the central Defiance Plateau showed no interruptions from the mid-1500s until 1871. Ultimately, historically frequent fire regimes collapsed across all sampled Navajo forests in the late 19th century. The last fire event to scar multiple trees across any site occurred in 1886, over 130 yr ago.

The Chuska Mountains had one of the earliest fire regime declines of the western United States, as was first reported by Savage and Swetnam (1990). Our new and supplemental fire-scar collections reinforce their findings and further define its spatial scope. Our findings are also supported by Whitehair et al. (2018), who report declined fire activity after 1830 across half of their 5000-ha study area in the northern Chuska Mountains. As noted by Savage and Swetnam (1990), climate variability may have contributed to the initial (early) fire decline. We found that it was both significantly wet and cool in the 1830s (Fig. 4). This combination would have contributed to a shorter fire season, reduced vegetative flammability, and an abundance of grasses

that would have aided in rapidly increasing livestock herd sizes. Though such environmental conditions would have affected the Defiance Plateau as well, albeit to a lesser extent given its warmer, drier position at lower elevation, fire activity at low-use sites did not change through this period.

Importantly, the early (1830s) decline in fire activity across the Chuska Mountains was not a cessation in fire, but a reduction in fire: Our reconstructions and those by Whitehair et al. (2018) include fire for another 50 yr. This is a unique pattern to the Navajo forests, and particularly to the Chuska Mountains. It reflects a rarely observed double threshold in the interruption of frequent surface fire regimes. As the fuel layer is disrupted, by livestock grazing for example, fire activity initially slows. As the disruption intensifies, the ability of fires to spread ceases. In Navajo forests, there was a slow transition from spatially concentrated livestock grazing by small herds in the early and mid-1800s to more intense, landscape-scale grazing pressure after the 1870–1880s. This caused the step-down in fire activity beginning circa 1830 when livestock grazing surpassed an initial threshold. After 1886, grazing had intensified enough to surpass the second threshold in fuel abundance and continuity, and the fire regime completely collapsed. Across most forests in the western United States, the initial introduction of livestock was so great that it surpassed both thresholds and immediately initiated the 20th-century fire exclusion era.

Interestingly, the landscape-scale fire of 1870 that burned across the Navajo Forests was an exception to the trend of gradually declining surface fire activity (Fig. 4). This fire followed four years of forced exile for the Diné and their livestock in the 1860s. The mid- to late 1860s were also cool and wet. The combination of these two factors allowed herbaceous fuels to recover in abundance and continuity to support landscape-scale fire in 1870. Despite active and concentrated grazing for decades in the 1800s, this fire demonstrated the latent resilience of herbaceous fuels at that point in time.

The contrasting fire regime patterns we document across our spatial land-use model convincingly point to human influences over climate in the disruption of frequent surface fire regimes here and elsewhere. To emphasize this point, we

can look to areas with either continued frequent fire regimes or those with early interruptions. For example, forested islands in volcanic flows (kipukas) in central New Mexico (Grissino-Mayer and Swetnam 1997) and multiple montane sites in northern Mexico that were never grazed or had delayed grazing continued to burn into at least the late 20th century (Swetnam et al. 2001, Stephens et al. 2003, Fulé et al. 2011, 2012, Meunier et al. 2014). The opposite is true for areas that were grazed prior to Euro-American settlement, which often show early fire interruptions or declines in frequent fire activity (Touchan et al. 1995, Baisan and Swetnam 1997). Differing elevations among our sites could not explain different fire history patterns, as the Chuska Mountains sites (averaging 2670 m) and the Defiance Plateau sites (averaging 2330 m) have similar fire regimes prior to 1832. Differences in fire frequency during this period (e.g., Fig. 5) result from different sample areas and numbers of fire-scarred trees (Falk et al. 2007) and not from intrinsically different fire regimes. This leaves human factors as the likely contributor to the interruption of surface fuels that led to fire regime decline, a finding that is in accord with several studies from the general region (Fulé et al. 2012; Margolis 2014; Taylor et al. 2016). The Navajo Nation has a rich, spatially variable, unique human history, and that history helps to explain the unique character and pattern of fire regime decline in Navajo forests.

#### *Societal factors led to fire regime decline*

Pastoralism is a deep cultural tradition among the Diné (Weisiger 2009). Navajos first acquired livestock (horses, sheep, and goats) in the 1600s after these animals were imported to the region by the Spanish (Weisiger 2004). Early on, sheep were not kept long before they were consumed, but as wool became important to the Navajo economy, raising larger herds took on greater importance (Andrews 1991). During the 18th century, there was a diaspora among Navajos, who were slowly leaving their homelands along the Colorado–New Mexico border and emigrating south and west, including to the present-day Navajo Nation (Towner 2008). By the late 1700s, several settled areas around the Chuska Mountains and Defiance Plateau accounted for most of the approximately 10,000-person Diné

population (Bailey 1980, Andrews 1991). From these growing settlements, small herds of livestock were first brought into the Navajo forests of the Chuska Mountains (Bailey 1980, Kemrer and Lord 1984).

The general historical practice of pastoralism consisted of seasonal transhumance from low-elevation winter homes to summer grazing areas in the Chuska Mountains to take advantage of plentiful grazing and surface water (Jett 1978). Shepherdling was often the responsibility of children and elders, who made daily rounds within a short distance (1–10 km) of the home site to water and grazing areas, returning each night to corrals (Adams 1963). The legacy of historical pastoralism is largely preserved in the forests, where one can find old home sites and corrals near lakes and meadow areas in the Chuska Mountains, many of which are still used seasonally (Fig. 1).

Through the mid-1800s, herd sizes grew rapidly as families bred their sheep to be passed to younger generations. Livestock and horses were also acquired from neighboring tribes and settlements during an era of back-and-forth raiding and skirmishes (McNitt 1972, Bailey and Bailey 1986). These growing herds led to the partial interruption of surface fire activity. Livestock consume grasses and forbs and also create trail networks that disrupt fuel continuity, especially in areas where herds travel routinely on drive-ways (Belsky and Blumenthal 1997, Allen 2007).

Historical observations of the forests in the Chuska Mountains during the mid-19th century support the idea that grazing impacts were relatively localized. During the late 1840s and 1850s, U.S. military reconnaissance recorded the abundance of understory grasses and large, old trees in park-like stands (cited in Savage 1991). Despite nearly two decades of reduced fire activity (and only three small fires recorded during the 1830s), any effect of grazing on the landscape and forests was not apparent to American travelers.

As the U.S. Government exerted greater control of the region in the 1850s, tensions rose between the Navajos, New Mexican settlements, and other tribes. This culminated in the 1863–64 U.S. military campaign to subdue and remove Navajos to the Bosque Redondo Reservation in eastern New Mexico (NM). In 1868, a signed treaty gave back much of the present-day Navajo



Nation, and roughly 4000 Diné began to return from Bosque Redondo. They were provisioned with sheep and encouraged to rebuild their herds (Hoover 1937). By the 1880s, herd sizes had more than doubled from the pre-1863 numbers (see Savage 1991), including large herds under individual ownership, which were previously rare (Kelley 1986, Weisiger 2009). These changes were in response to a growing Navajo population and a more stable political situation given the reservation boundaries. The railroad arrived to Gallup, NM, in 1881, establishing a trading depot just southeast of the Chuska Mountains, bringing with it new access to distant markets for provisions that Navajos desired and an avenue to trade prized Navajo wool products. With this, the number of small but economically important trading posts on the reservation rose from one in 1870 to over a dozen by the mid-1880s (Kelley 1985, Bailey and Bailey 1986).

Driven by market demand and products coming from the east via the railroad, the Navajo economy grew in the 1880s. Livestock remained the key source of economic wealth for Diné, intensifying and broadening land-use patterns in the forests of the Chuska Mountains and Defiance Plateau. The intensification of pastoralism there, as in nearly every other mountain range of the American West, led to the final collapse of frequent surface fire regimes. Though unique in its patterns of decline, fire regimes of the Navajo forests experienced the same cross-scale collapse of historical surface fire regimes in the late 19th century as did other forests in the West. This legacy is ongoing, with now over 130 yr without recurrent surface fires across most of a large dry conifer forest.

#### *Navajo fire use*

The traditional ecological knowledge of the Diné regarding forest fires is not well recorded. Thus, there is no evidence to date for historical human-set landscape fires among Navajos (Williams 2000). Many Diné informants felt that fire was a natural process, not to be disturbed (Whitehair 2017). And yet, fire activity has been recorded during times and in areas of known human land use (livestock grazing), and in one area, some fire continued until 1916, nearly a century after the initial human-caused fire decline (Whitehair et al. 2018).

Human fire use over long periods can create a distinctive pattern in fire regime reconstructions. Studies from multiple semiarid and fuel-limited areas show that when a society includes landscape fire as a normal cultural practice, fire frequency increases and fire extent decreases as the fuel matrix gains complexity and fire spread becomes self-limiting (Taylor et al. 2016). Some areas of the Southwest with similar forest types showed this pattern historically (Swetnam et al. 2016). Our tests for changes in fire extent and frequency did not identify obvious changes in human fire-use patterns in Navajo forests (Fig. 4). Our reconstructions extend to an era before any large-scale settlement of the area in the 18th century, allowing us to distinguish between eras of free-range fire (*sensu* Swetnam et al. 2016) and potential cultural burning after Navajo immigration. There was no change in fire frequency circa 1700. We interpret this finding as originating from two factors: (1) Navajos may not have used fire commonly and extensively enough to augment the already high-frequency fire regime driven by lightning, or perhaps they did not set landscape fires at all; and (2) though people lived in, used, and traveled extensively through our study area, these impacts were seasonal and localized to specific grazing areas close to individual use areas (Adams 1963). This pattern of land use is in stark contrast to nearby forest lands, such as the Jemez Mountains where a large population lived year-round in forested areas for hundreds of years and affected fire regimes both locally and at landscape scales (Liebmann et al. 2016, Swetnam et al. 2016).

#### CONCLUSIONS

An early (1830s) decline in extensive, frequent, low-severity fire in Navajo forests closely followed the timeline and spatial patterns of Diné cultural dynamics. Fire activity in mid-elevation ponderosa pine-dominated forests remained stable from at least 1600 until the mid-1800s, through variable climate patterns and the settlement of a relatively large Native American group. As the Diné intensified pastoral practices into the 1830s, including long-distance seasonal migrations to grazing areas in the Chuska Mountains, fire activity became disrupted across higher use sites. The spatial variability of these

changes was captured by a human land-use model based on the distribution of perennial lakes and modern home sites (often locally referred to as sheep camps). This initial decline in fire activity, but not cessation, persisted for 50 yr, an exceptional pattern in the western United States.

By the late 1800s, fire regimes across the study area collapsed in response to further intensified livestock grazing. Following the establishment of the Navajo reservation in 1868, the U.S. Government enforced new economic models and provided new access to markets via the railroad. These changes spurred major increases in herd sizes, and livestock grazing intensified far beyond earlier levels. This intensified land-use practice surpassed the threshold at which herbaceous fuels could sustain frequent fire activity. After 1886, fire regimes of the Navajo forest had collapsed, mirroring much of the southwestern United States. Some have attributed decline of historical fire regimes to loss and removal of Native American populations. In this case, however, Diné populations grew through the period of fire exclusion, with the decline of fire clearly attributable to land-use change, and likely not reduced human ignitions.

New insights regarding the history of fire in Navajo forests reveal the strength of combining socioecological and environmental data to disentangle sources of variability in human–fire–climate interactions. It may be that other reconstructed fire regimes from the western United States include human-driven variability that can also be explained by understanding the patterns and drivers of settlement and land-use histories. Gaining these broader perspectives will help to improve our understanding of how human-driven changes in ecological process affect the structure and function of forests, and vice versa. Such insights are critical for managing the response of forest ecosystems to anthropogenic climate change because the legacy of human-induced changes to keystone disturbance processes such as fire is ongoing.

The deficit of fire over the last 130 yr across Navajo forests has increased the probability of uncharacteristic high-severity fire, especially under increasingly warm and dry conditions. In 2014, this risk became a reality. The 6000-ha Asaayi Lake Fire burned through an important

watershed of the central Chuska Mountains at moderate to high severity. Monsoonal rains followed the fire and triggered major sedimentation into a reservoir that is important for local recreation and water supply. Historical fires were likely more extensive than the Asaayi Lake Fire, but the fire-scarred trees we sampled survived up to 38 individual fires over centuries, indicative of relatively low-intensity fire behavior. As fires continue to be more extensive across southwestern forests (Singleton et al. 2019), applying lessons from the past—here that frequent surface fires promote resistance to extreme events (Allen et al. 2002)—is ecologically justifiable in Navajo forests.

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