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Dating the origins of persistent oak shrubfields in northern New Mexico using soil charcoal and dendrochronology

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Abstract

Megafires in dry conifer forests of the Southwest US are driving transitions to alternative vegetative states, including extensive shrubfields dominated by Gambel oak (*Quercus gambelii*). Recent tree-ring research on oak shrubfields that predate the 20th century suggests that these are not a seral stage of conifer succession but are enduring stable states that can persist for centuries. Here we combine soil charcoal radiocarbon dating with tree-ring evidence to refine the fire origin dates for three oak shrubfields (<300 ha) in the Jemez Mountains of northern New Mexico and test three hypotheses that shrubfields were established by tree-killing fires caused by (1) megadrought; (2) forest infilling associated with decadal-scale climate influences on fire spread; or (3) anthropogenic interruptions of fire spread. Integrated tree-ring and radiocarbon evidence indicate that one shrubfield established in 1664 CE, another in 1522 CE, and the third long predated the oldest tree-ring evidence, establishing sometime prior to 1500 CE. Although megadrought alone was insufficient to drive the transitions to shrub-dominated states, a combination of drought and anthropogenic impacts on fire spread may account for the origins of all three shrub patches. Our study shows that these shrubfields can persist >500 years, meaning modern forest-shrub conversion of patches as large as >10,000 ha will likely persist for centuries.

Keywords

alternative stable states, anthropogenic pyrodiversity, ponderosa pine

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Introduction

Fire-driven type conversion may be on the rise in southwest US forests. These profound, extensive, and enduring (Coop et al., 2020; Keyser et al., 2020) biome changes can occur abruptly in mid-elevation dry conifer forests dominated by ponderosa pine (*Pinus ponderosa*) and other conifer species. Type-converted areas transition to dominance by grasses or resprouting shrubs that are often better adapted to hot and dry post-fire environments (Savage et al., 2013). This loss of forest triggers substantial changes in carbon storage and emissions, suggesting that these pyrogenic type conversions also have climate feedbacks (Hurteau et al., 2008). Recent vegetative transitions are driven by human factors. Fire suppression has led to substantial fuel build up and infilling of young trees (Fulé et al., 1997). Within these overly dense forests, anthropogenic climate change is amplifying drought effects, tree mortality, and uncharacteristically intense fire behavior (Higuera and Abatzoglou, 2021; Roos et al., 2020; Williams et al., 2013). Yet, relatively large patches (>100 ha) of grasses or shrubs with no known origins are embedded within many forests of the region, raising the possibility that these forests may have long been capable of transitions to enduring alternative stable states. For example, Gambel oak (*Quercus gambelii*) shrubfields in the Jemez Mountains of northern New Mexico have persisted in their current composition and structure since at least the seventeenth century, although a precise reconstruction of the shrubfield transitions has not been possible because tree-ring evidence lacked the "fingerprint" of type conversion (Guiterman et al., 2015, 2018). Accurate dating of biome switching events would improve our understanding of their causal mechanisms (Coop et al., 2020), providing context for whether recent fire-driven type conversion events are as profound and enduring as they seem.

Here we refine the dates for historical forest-to-shrub type conversion events in the Jemez Mountains of northern New Mexico to evaluate their driving mechanisms. We revisited three of the five shrubfields sampled by Guiterman et al. (2018) to infer the timing of high-severity fire leading to vegetative change from radiocarbon dates on soil charcoal. In stable soils, charcoal can preserve for millennia (De Lafontaine and Asselin, 2011; Ohlson and Tryterud, 2000). Long fire histories from previously forested areas have been reconstructed from soil charcoal (Talon, 2010), as have long periods without fire (Lertzman et al., 2002). The easily distinguished contrast between conifer and angiosperm wood mean that finer taxonomic analysis of soil charcoal, as is common in pedoanthracology (Nelle et al., 2013; Robin et al., 2015), was unnecessary for our research problem. Spatial analysis of the contexts of shrubfields and forest indicate that they occupy similar soils, microclimates, and topographic positions (Guiterman et al.,

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2018). Therefore, we assume that shrub patches in the Jemez Mountains had been dry conifer forests prior to a transition to oak dominated shrubfields. Furthermore, we assume that the event that catalyzed the transition to shrubs was a tree-killing fire event. Such moderate-to-high-severity fire events often produce surface erosion, sediment mobilization, and alluvial fan formation (Fitch and Meyer, 2016; Orem and Pelletier, 2015) that can remove some or all of the prior soil charcoal record, meaning that most, if not all, of the extant shrubfield soil charcoal record post-dates the most recent high-severity fire event.

Pre-suppression fire regimes in the southwestern U.S. dry conifer forests are among the best known in the world. A network of thousands of fire-scar samples across the region indicate that fires were frequent (<20-year fire intervals) and primarily occurred in abundant grassy fuels and needle litter. These frequent fires thinned forest stands by burning many seedlings and saplings but rarely killed mature trees, some of which record fire damage at their base that can be cross-dated with dendrochronology. This frequent, low-severity surface fire regime made these forests resilient to drought and large fires by maintaining open stands with elevated crowns. After more than a century of fire suppression, these same forests are choked with young conifers that now allow fires to burn from the surface into the canopy, generating large areas of continuous canopy mortality and opening previously forested sites to biome shifts. In the modern scenario both climate (Abatzoglou and Williams, 2016; Higuera and Abatzoglou, 2021) and land use (Fulé et al., 1997; Roos et al., 2020) are implicated in the fire regime shift and transition to alternative vegetative states. It remains unknown whether climate, land-use, or both could have reduced forest resilience for past transitions. In the modern scenario, the altered stands and fuels are critical to tree-killing and type-converting fires. Could interannual or decadal-scale climate reduce fire spread sufficiently to allow some stands to infill with young trees? Or could decadal-scale megadroughts lower live fuel moisture sufficiently to permit tree-killing fires? Or could land use by Native American communities have interrupted fire spread sufficiently to inadvertently create fire refugia that became vulnerable to high-severity fire?

We test three hypotheses regarding the primary drivers of high-severity fire leading to type conversion in the past: (1) that megadrought events led to high-intensity fire behavior (megadrought hypothesis); (2) that decadal scale variability in fire-climate drivers created periods of reduced wildfire spread (fire interval hypothesis); or (3) that human caused heterogeneity in landscape fuels indirectly reduced fire activity in some areas (anthropogenic hypothesis). The megadrought hypothesis presumes that high fuel flammability during intense drought conditions produced high-intensity, tree-killing fire regardless of forest and fuel structure. Drought is often implicated in paleofire studies across the western U.S. (Marlon et al., 2012), including in the Jemez Mountains (Fitch and Meyer, 2016), although we are doubtful that live fuel aridity in a low-density stand (<200 tree ha^{-1}) with elevated canopy could have generated crown fire patches between 100 and 300 ha (the size of some the largest historical shrubfields in the Jemez).

The fire interval and anthropogenic hypotheses both implicate the impacts of fire exclusion on fuel accumulation, stand infilling, and the subsequent loss of resilience when fire returns to overly dense stands (Savage and Mast, 2005). The difference is that the fire interval hypothesis implicates natural climate variability in reducing fire spread in some forest patches (Biondi et al., 2011; Roos and Swetnam, 2012). The anthropogenic hypothesis implicates human pyrodiversity or other human activities in allowing some forest patches to remain fire free for long periods (Trauernicht et al., 2015). Interannual moisture patterns are significantly correlated with fire activity in dry conifer forests across the western U.S. (Swetnam and Betancourt, 1998; Swetnam et al., 2016). Antecedent wet years support the growth of abundant and continuous surface fuels that burn in subsequent dry years. A 1400-year tree-ring based model of these patterns of wet-dry switching indicate that these conditions varied in their frequency in the past (Roos and Swetnam, 2012). When conditions for widespread fires were rare, it is possible that some forest stands became fire refugia and began infilling with small trees, thereby increasing forest vulnerability when fire returned.

Archaeology and oral tradition indicate that the southwest Jemez Mountains were home to large, densely settled Native American communities who were ancestral to the modern Pueblo of Jemez (Tosa et al., 2019). Beginning around 1100 CE, Jemez immigrants increased fire activity on the mesas surrounding the modern town of Jemez Springs, New Mexico. These fires created new agricultural lands and also favored habitat for preferred game animals (Roos et al., 2021). By 1300 CE, thousands of Jemez people settled the mesas, intensifying agricultural use and expanding fire use for hunting, wild resources, and religious purposes that were evident as small patch, frequent fires in tree-ring records up to 10 km from the agricultural landscape. In modeling scenarios, small patch burning indirectly created patches that were long fire free (Roos et al., 2021). Small, patch burning on the Jemez landscape may have inhibited fire spread, indirectly creating fire refugia where stands filled in with young trees and forests became increasingly vulnerable to fire when it returned.

Variability in topography could also create heterogeneity in fire activity and promote crown fire behavior leading to type conversion (Iniguez et al., 2009), but the shrubfields we sampled have consistent landscape characteristics and fire histories (since 1700) as their adjacent dry conifer forest areas (Guiterman et al., 2018), so we concentrate our attention on climate and land use explanations. Each of these hypotheses implicates drivers operating currently, and that are attributed to recent type conversion events throughout the western USA (Coop et al., 2020) as well as in the formation of shrubfields estimated at >10,000 ha in the eastern Jemez Mountains since 2011 (Allen, 2016).

Although these three hypotheses are not mutually exclusive, we treat them distinctly before discussing the potential interactions of the mechanisms involved. We compare the radiocarbon and tree-ring chronologies of shrubfield establishment to a local, Jemez Mountains precipitation reconstruction that identifies megadrought events (Touchan et al., 2011), a local model of climate-predicted widespread fire events (adapted from Roos and Swetnam, 2012), and to nearby archaeological records of large Native American populations (Kulisheck, 2005; Liebmann et al., 2016; Roos et al., 2021).

Materials and methods

The Jemez Mountains in north-central New Mexico are a diverse, semiarid, and conifer-dominated landscape with a rich cultural and natural history (Allen, 1989, 2007; Liebmann et al., 2016; Roos et al., 2021; Swetnam et al., 2016). Much of the landscape consists of deep canyons and flat-topped mesas of dry mixed-conifer forests dominated by ponderosa pine with components of Gambel oak, Douglas fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and southwestern white pine (*P. strobiformis*). Shrubfields embedded within these forests are often located on steep slopes and are dominated by Gambel oak with New Mexico locust (*Robinia neomexicana*), trumpet gooseberry (*Ribes leptanthum*), and various grass species, with some scattered conifer trees including ponderosa pine, piñon (*Pinus edulis*) and Rocky Mountain juniper (*Juniperus scopulorum*) as well as aspen (*Populus tremuloides*) and white fir in mesic settings. Guiterman et al. (2018) sampled five distinct shrubfields that had no known origins, and predated both 1935 aerial photographs and a local fire atlas that extends to 1910 (Snyderman and Allen, 1997). They

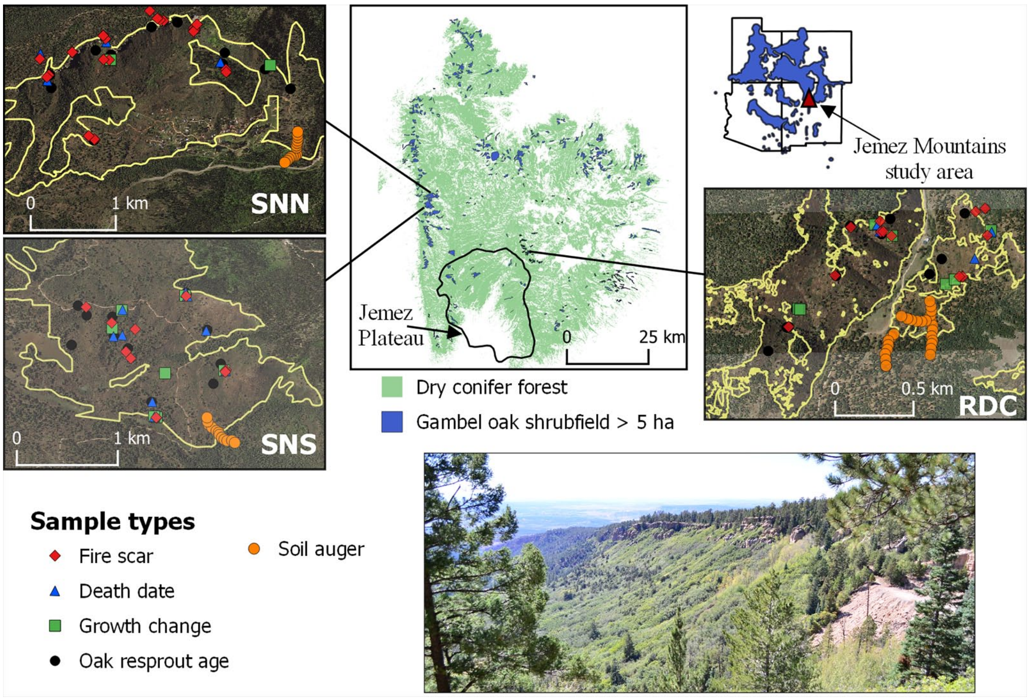

Figure 1. The locations of tree ring and soil charcoal samples for three shrubfields (Señorito North [SNN], Señorito South [SNS], and Redondo Creek [RDC]) in the Jemez Mountains, northern New Mexico. Blue polygons indicate the distribution of all shrubfields >5 ha embedded in dry conifer forests (green) in the Jemez Mountains prior to 2000 CE. The inset at top right shows the study area location, with blue polygons indicating the ecological range of Gambel oak (Little, 1971). Color is visible in the online version of this paper.

reconstructed Gambel oak age structures and disturbance histories, applying a multiple lines of evidence approach (Guiterman et al., 2015) using the burnr package in R (Malevich et al., 2018). Here, we assess three of these shrubfields, including Señorito North (SNN), Señorito South (SNS), and Redondo Creek (RDC), ranging in elevation from 2550 to 2670 masl.

In July 2018, we collected soil samples from the uppermost 15–18 cm of soil in ~200 m transects across the ecotone at the SNN, SNS, and RDC shrubfields (Figure 1). The intention of the transects was to assess the stability of the ecotone boundary since shrubfield establishment by quantifying the relative abundance of angiosperm versus gymnosperm wood charcoal across the transect. Practical limitations during the COVID-19 pandemic meant that only a subset of the samples (from the shrubfield side of the ecotone) were processed (16 of 26 shrubfield samples). Subsamples of soil (~200 g) were washed through a 500 µm sieve to remove finer particles after pretreatment to disaggregate the soil (Whitlock and Larsen, 2001) and make charcoal easier to distinguish from other tissues (Rhodes, 1998). Under low magnification (10–40×), wood charcoal fragments were identified as either angiosperm or conifer based on the presence of vessels in the xylem using a reference collection of scanning electron microscope images of conifer and angiosperm wood specimens from the Jemez Mountains. Angiosperm wood charcoal and charred conifer needles, when present, were collected for radiocarbon measurement. Prior to the pandemic, total charcoal >500 µm was weighed dry ($N=10$) and subsample weights of angiosperm and gymnosperm wood charcoal were also weighed when dry ($N=4$).

At least three angiosperm wood charcoal pieces from each shrubfield were selected for radiocarbon measurement. When present, pine needles from augers without nearby mature conifers were selected for radiocarbon dating. The working assumption was that the oldest dated angiosperm wood would provide a *terminus ante quem* age (TAQ; "date before which") for the establishment of the shrubfield, whereas the youngest pine needle would provide a *terminus post quem* age (TPQ; "date after which") for the establishment of the shrubfield.

Calibrations were made using IntCal20 (Reimer et al., 2020) in the BCal program (Buck et al., 1999). Where appropriate, angiosperm dates were assumed to be younger than pine needle dates to model Bayesian posterior probabilities of shrubfield establishment in BCal. In the absence of pine needle TPQ ages, the oldest TAQ angiosperm radiocarbon dates were used to model posterior probabilities of shrubfield establishment. This is based on our working assumption that the tree-killing fire event and subsequent post-fire erosion (Orem and Pelletier, 2015; Roering and Gerber, 2005) may have removed much of the prior soil charcoal and that the oldest TAQ age is closest to the establishment age. Posterior probabilities for each shrubfield were compared to tree-ring growth change and fire-scar indicators of possible shrubfield establishment. The tree-ring data used here come from the prior study of these shrubfields by Guiterman et al. (2018), where details on methods and results can be found. Here we inferred shrubfield origin dates when multiple paleoecological indicators aligned (e.g. peak radiocarbon probability with fire scars, growth changes, and/or tree mortality).

We tested our three hypotheses by comparing the reconstructions of shrubfield origins to independent datasets of climate, fire, and human history. For climate, we employed a local tree-ring reconstruction of October-June precipitation that extends to 824 CE (Touchan et al., 2011). We defined "megadroughts" within the reconstruction as periods of acute aridity (below average standardized precipitation in 25 year moving averages) that lasted more than two decades (Cook et al., 2007). This filter identified megadroughts between 866–886, 912–933, 979–1007, 1074–1103, 1127–1160 ("Chaco Drought"), 1234–1266, 1338–1372, 1406–1431, 1445–1488, 1527–1592 (16th century megadrought), 1652–1679, 1719–1741, and 1943–1967 CE.

Because our fire-scar chronologies were not sufficiently long to identify long fire-free intervals, we created a local model of interannual climate suitability for spreading surface fires, adapted from the regional methods used by Roos and Swetnam (2012). We built a split calibration-verification multiple regression model using fire synchrony (% scarred) for 1654 fire scarred trees across

Table 1. Radiocarbon measurements and 2σ calibrated age ranges of soil charcoal samples from Señorito North (SNN), Señorito South (SNS) and Redondo Creek (RDC) shrubfields (organized from North to South).

Sample (material)	Keck AMS no.	^{14}C age	cal CE (2σ)	cal CE (95% CI) Bayesian
Señorito North (SNN)				
SNN.s6.w1 (wood)	216689	300 ± 25	1495–1507, 1513–1599, 1617–1650	
SNN.s6.w2 (wood)	216691	170 ± 25	1661–1697, 1724–1814, 1927–1939	
SNN.s3.w3 (wood)	216692	**420 ± 35**	**1422–1520, 1593–1618**	
SNN.s6.w4 (wood)	216693	230 ± 25	1641–1680, 1764–1800	
SNN.s5.w5 (wood)	216694	235 ± 25	1638–1680, 1776–1799	
SNN.s5.w6 (wood)	216695	380 ± 90	1405–1665	
Señorito South (SNS)				
SNS.s4.n1 (needle)	216683	280 ± 25	1518–1593, 1619–1663	1515–1593, 1620–1659
SNS.s4.n2 (needle)	216684	260 ± 60	1466–1685, 1735–1756, 1758–1802	1465–1602, 1607–1667
SNS.s4.n3 (needle)	**216685**	**265 ± 25**	**1522–1574, 1628–1667, 1784–1795**	**1520–1578, 1630–1665**
SNS.s1.w4 (wood)	216686	130 ± 25	1684–1710, 1717–1765, 1800–1893, 1908–1935	1670–1777, 1800–1888
SNS.s4.w5 (wood)	**216687**	**190 ± 25**	**1664–1683, 1730–1810, 1927–1948**	**1652–1687, 1730–1807**
SNS.s4.w6 (wood)	216688	170 ± 25	1669–1689, 1727–1814, 1836–1869, 1919–1945	1661–1697, 1723–1814, 1927–1938
Redondo Creek (RDC)				
RDC.s6.n2 (needle)	216678	Modern	1957–1958, 2005–2010	
RDC.s8.n3 (needle)	216679	Modern	1956–1957, 2008–2010	
RDC.s8.w4 (wood)	216680	180 ± 25	1648–1695, 1727–1812	
RDC.s8.w5 (wood)	216681	190 ± 30	1655–1694, 1727–1811	
RDC.s8.w6 (wood)	**216682**	**280 ± 35**	**1491–1601, 1614–1665**	
Bayesian age probabilities for shrubfield establishment				
	Señorito North			355–1520 (67% CI)
	Señorito South			1535–1730 (95% CI)
	Redondo Creek			460–1660 (67% CI)

Bold samples are those that mark the oldest wood or youngest pine needles used in the Bayesian modeling to estimate posterior probabilities of establishment ages (bottom).

the Jemez Mountains (Swetnam et al., 2016), and the Touchan et al. (2011) precipitation reconstruction in SPSS v26. To normalize the fire history data, we used $\log_{10}$ of annual synchrony values (plus 0.01% to deal with 0 years) as predict and with annual (year *t*) and lagged annual precipitation (years *t*-1, *t*-2, *t*-3, *t*-4, and *t*-5), as potential predictors in a stepwise multiple linear regression. Two independent calibration sets (1681–1780 CE and 1781–1880 CE) were used to build separate models that were tested for goodness of fit to each other. The final model used the full calibration period (1681–1880 CE) to predict landscape fire activity as $\log_{10}$ synchrony values. Predicted $\log_{10}$ synchrony values $\geqslant 1$ were considered a conservative indicator of climate-driven widespread fire years and intervals between widespread fire years were tallied cumulatively to identify multidecadal windows of reduced fire spread.

To evaluate the potential role of past human land use, we assessed our results relative to the population and land-use history for the Jemez Plateau, a distinct physiographic area in the southwestern corner of the Jemez Mountains with archaeological evidence of Ancestral Pueblo (Jemez or Hemish) occupation of pine forests from ca. 1100–1700 CE. Although initial settlement occurred in the 1100s, populations were small (ca. 100–500) and fire use may have been restricted to the Jemez Plateau. By the 1300s CE, a second wave of migration swelled the population to more than 3000 and likely pushed more remote fire uses (e.g. for hunting) outside of the Hemish agricultural footprint (areas of villages and farm fields), where preferred large game would have been rare (Schollmeyer and Driver, 2013). There is evidence in charcoal, alluvial fan, and tree-ring records that Hemish fire management had impacts on the fire regimes at least 10 km beyond the agricultural footprint (Roos et al., 2021). Hemish population collapsed by as much as 85% in the wake of Spanish-introduced diseases and colonialism in the 17th century, when Hemish people were forcibly moved off of the forested mesas and into the valley to the south (Liebmann et al., 2016). After Hemish population collapse, the historical surface fire regime switched from frequent, small patch burning under Hemish fire management to widely spreading, extensive surface fires (Swetnam et al., 2016).

Results

We analyzed 16 soil auger samples to identify charred wood and leaf materials as angiosperm versus gymnosperm and to obtain radiocarbon ages. While angiosperm charcoal was relatively common from shrubfield augers (ca. 60–100% of all wood charcoal by mass, $N=4$), charred gymnosperm wood was less common and conifer needles were extremely rare. Mindful of potential problems with “inbuilt ages” of wood from the inner portions of long-lived trees (Gavin, 2001), we avoided radiocarbon dating of conifer xylem with the expectation that TPQ ages from conifer wood could be up to several centuries earlier than the tree-killing fire that is the target of our analysis, therefore producing unusable information. We were able to obtain radiocarbon dates for six charred pine needles from the RDC and SNS sites (there were none encountered at SNN). Those from RDC dated to the 20th century, apparently washed downslope following the 2013 Thompson Ridge Fire that burned near but not within the sample area. The pine needles from SNS dated between the late-1400s and mid-1600s. Dates from angiosperm wood across all sites ranged from the early-1400s to the late-1800s (Table 1).

Radiocarbon age estimates, together with tree ring dates from the same sites (Guiterman et al. 2018), provide minimum ages of the shrubfields (Figure 2). Our strategy of paired TAQ/TPQ dating of a type conversion event is only appropriate at SNS, where three pine needle dates constrain the oldest angiosperm ages. At the other sites, a lack of older pine needles and the rarity of gymnosperm wood probably reflects post-fire erosion following high-severity fire events (Fitch and Meyer, 2016; Orem and Pelletier, 2015), removing the soil-based evidence for prior forest composition. Bayesian modeling of dates from SNS places the shrubfield

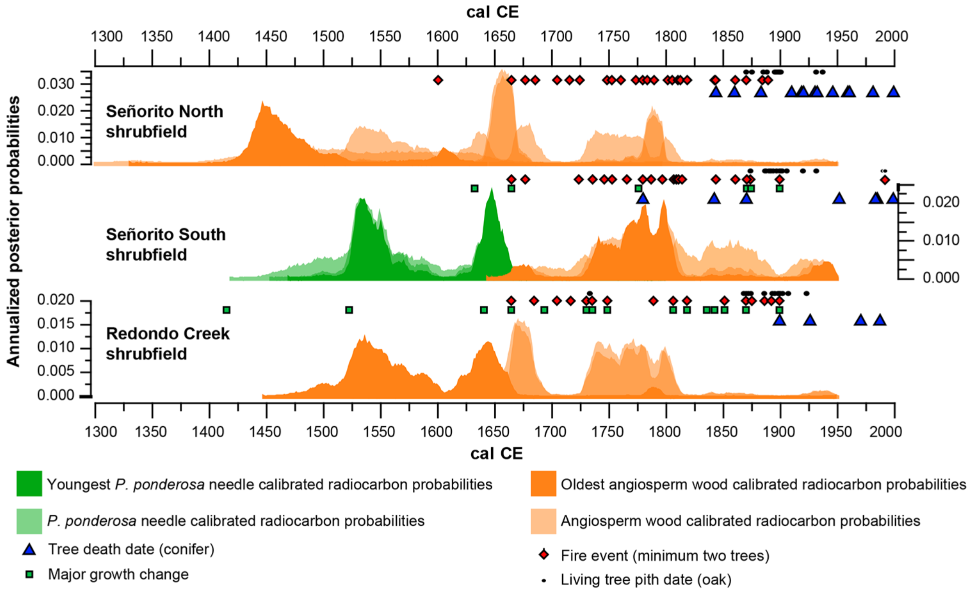

Figure 2. The posterior probability density functions for calibrated radiocarbon dates on angiosperm wood charcoal (orange) and ponderosa pine needles (green) for the three sampled shrubfields organized from north (top) to south (bottom). Dark orange or green indicate the oldest terminus ante quem (orange) or youngest terminus post quem (green) dates for each shrub patch. Superimposed on these distributions are the annual dates for conifer death dates (blue triangles), fire events (red diamonds), major growth changes (green squares), and oak germination (black circles) for each shrub patch. Color is visible in the online version of this paper.

establishment at 1535–1730 CE, with peak probabilities in the mid-1600s. Tree-ring dates for a spreading fire event (multiple fire scars) and a major growth change further suggest 1664 CE as the most likely date for this shrubfield origin. The growth change was a prolonged suppression of ring growth on a surviving ponderosa pine that likely experienced substantial root and/or crown damage in the fire (Guiterman et al., 2015).

Señorito North (SNN) yielded the oldest angiosperm dates, with Bayesian modeled ages suggesting the establishment prior to 1520 CE and most likely in the 1400s or before. No tree-ring evidence was available that far back in time, which further suggests a stable oak-dominated composition with frequent fire that consumed older tree-ring material (Guiterman et al., 2015, 2018). At RDC, a similar pattern suggests establishment prior to 1660 CE and most likely by the 1500s. Tree-ring evidence of major growth changes implicates 1522 or 1664 CE as possible establishment dates for RDC. Given the age of the oldest angiosperm charcoal, a 1664 CE establishment is very unlikely ($p=0.03$), but fire at that time could have acted to expand or reinforce the shrubfield. The growth change in 1522 CE is more consistent with the radiocarbon evidence that may record the establishment of this shrubfield. This tree-ring date of 1522 CE falls within the period of greatest probability of shrubfield establishment prior to the oldest angiosperm radiocarbon date, suggesting that this is the most likely date for RDC establishment (Figure 2).

In our tree-ring model, each calibration period of the fire-climate regression generated $r^2 \geq 0.436$ using precipitation year t, t-1 or t-2, and t-3, replicating the regional pattern of 1–3 antecedent wet years prior to a dry fire year with $r^2=0.436$ for the full calibration set (Roos and Swetnam, 2012; Swetnam et al., 2016) (Table 2 and Figure 3). Other variables were not significant contributors to the model. Periods between model-predicted widespread fire years were generally less than 34 years (92.7% of all intervals), with the median interval of 12 years meaning that interannual climate generally supported frequent, spreading surface fires going back to at least 825 CE. Three intervals longer than 60 years all cluster between 1244 and 1486 CE, suggesting that this 240-year period had several multidecadal periods when climate conditions were not suitable for many widespread surface fire events (Roos and Swetnam, 2012).

Discussion

Soil charcoal dating of three large Gambel oak-dominated shrubfields in the Jemez Mountains reveals multiple episodes of likely establishment, from the 15th century through the mid-17th century, although one of these shrubfields could be older still. These findings align with the conclusions of Guiterman et al. (2018), who asserted that the shrubfields have been an alternative stable state of oak dominance for at least the last 350 years. Our results for two of the shrubfields add weight to scant tree-ring evidence of high-severity fire up to 300 ha during the 1500s and 1600s (Figure 2). For two shrubfields, our combined tree-ring and soil charcoal evidence for shrubfield establishment allow us to evaluate their potential driving mechanisms based on three independent but potentially interacting hypotheses. The dating on our third shrubfield corroborates the antiquity of the shrub patch (>500 years), but we can only speculate on the timing of its origins.

The megadrought hypothesis implicates prolonged, acute drought in the intensification of fuel flammability to a level that would facilitate large high-severity fire events despite what was likely an open, low density canopy structure (Allen, 1989). Droughts are ubiquitous features of the Southwest US paleoclimate, but megadrought-influenced transitions would have been most likely in the 1100s, 1200s, 1400s, and 1500s (Cook et al., 2007, 2010; Stahle et al., 2007; Touchan et al., 2011). Although the late-1500s megadrought could have initiated the SNS shrubfield (Figure 4), it more likely transitioned during the mid-1600s drought. The age estimate for SNN is less certain, although the shrubfield is at least 500 years old. If SNN was established immediately prior to the oldest angiosperm charcoal age, then it would likely have occurred during the prolonged 1400s droughts. It is possible, however, that the SNN soil charcoal record was truncated in the 1400s by high-severity fire through an already established shrub patch or an erosion event. While we do not exclude severe drought as a factor in the fires that establish persistent oak shrubfields generally, severe drought alone does not seem to be a likely driver of altered fire behavior and associated shrubfield origins in Jemez dry conifer forests.

The fire interval hypothesis states that decadal-scale variation in climate drivers of fire activity may have promoted fuel build-up

Table 2. Regression statistics for split calibration-verification model of climate predicted fire activity using reconstructed precipitation. (a) Contains the statistics for the model calibrated with AD 1681–1780 and verified against AD 1781–1880. (b) Contains the statistics for the model calibrated with AD 1781–1880 and verified with AD 1681–1780. (c) Contains the statistics for the model calibrated against the full fire-scar record AD 1681–1880 with verification statistics.

(a)

Calibration, 1681–1780		*p*	*F*
r^2	0.436	<0.001	24.705
Precipitation	β	*p*	*t*
Constant	0.122	0.077	1.788
t	−0.520	<0.001	−7.938
t-2	0.172	0.012	1.626
t-3	0.153	0.025	1.096
Verification, 1781–1880			
r^2	0.439	<0.001	76.697
RE	0.430	CE	0.430

(b)

Calibration, 1781–1880		*p*	*F*
r^2	0.465	<0.001	27.783
precipitation	β	*p*	*t*
Constant	0.109	0.069	1.842
t	−0.492	<0.001	−8.094
t-1	0.176	0.006	2.809
t-3	0.175	0.007	2.775
Verification, 1681–1780			
r^2	0.333	<0.001	48.820
RE	0.321	CE	0.321

(c)

Calibration, 1681–1880		*p*	*F*
r^2	0.436	<0.001	50.427
precipitation	β	*p*	*t*
Constant	0.116	0.011	2.569
t	−0.491	<0.001	−10.830
t-2	0.143	0.002	3.139
t-3	0.145	0.002	3.158
Verification statistics			
Sign test	77.5% (155/200)	RE	0.436

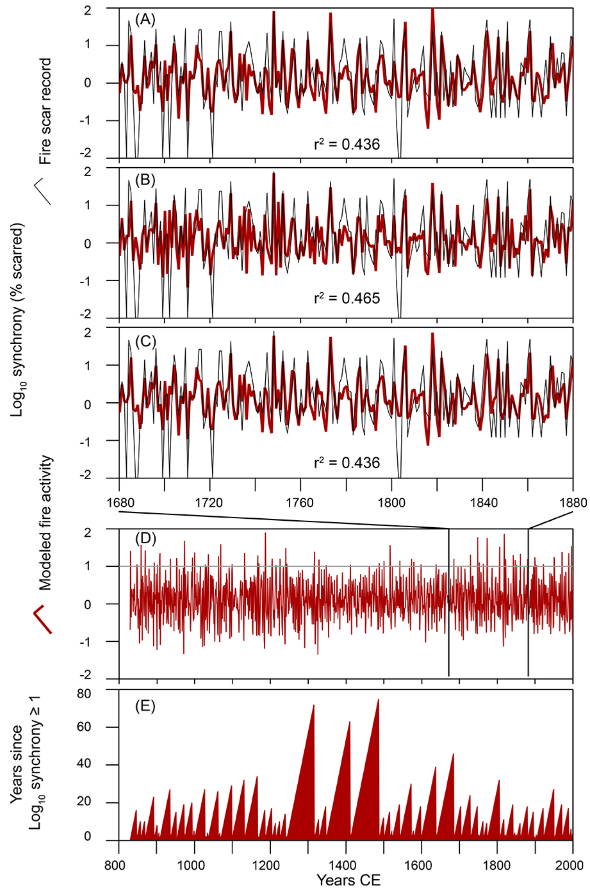

Figure 3. Original (black) and modeled (red) $\log_{10}$ fire synchrony (% scarred) for each of calibration 1 (A; 1681–1780), calibration 2 (B; 1781–1880) and the full calibration period (C; 1681–1880) with r^2 values for the calibration period. The full, annual reconstruction from 826 CE to 2000 CE with the threshold of values ⩾1 indicated (D). Sawtooth plot of time since last year ⩾1 in model predicted values. Color is visible in the online version of this paper.

in some stands through reductions in fire spread and enhanced vegetative growth (Roos and Swetnam, 2012). These conditions facilitated high-severity fire once fire did return. In the absence of sufficiently long fire scar chronologies for the Jemez Mountains, we modeled the frequencies of climate conditions that historically drove widely spreading surface fires. This model suggests that interannual climate variability may have reduced the frequencies of widespread fires between 1244 and 1486 CE (Figures 3 and 4). It is possible that one of our shrubfields (SNN) dates within this window of time, circa 1400 following at least two prolonged intervals with likely reduced fire activity. If RDC were to have established in 1522, the legacy of prior fuel accumulation and stand infilling from previous long fire intervals could have been a driving factor. The SNS site likely transitioned in 1664 CE following the early 17th century pluvial and associated reduced fire period (1599–1637) in which widespread tree establishment is recorded in the Jemez Mountains (Farella, 2015; Liebmann et al., 2016) and regionally (Swetnam and Betancourt, 1998). If it dates to 1664 CE, as both the radiocarbon and tree-ring dates suggest, then it established during a significantly dry individual year during a short period of reduced fire activity (1639–1684) and prolonged drought (1652–1697), although we doubt that this fire interval would have been long enough to substantially alter stand density and fuels.

The anthropogenic hypothesis implicates pyrodiversity created by small patch burning and other activities in altered spatial patterns of fire that may have brought more fire to parts of the landscape but indirectly reduced fire activity in others by inhibiting fire spread (Roos et al., 2019; Trauernicht et al., 2015). Through foraging, hunting, and other activities, a population of 3000–5000 Hemish people used fire on the Jemez Plateau 4–18 km south of our sampled shrubfields (Liebmann et al., 2016; Roos et al., 2021; Swetnam et al., 2016), although anthropogenic impacts on fire regimes were found up to 10 km from the Jemez Plateau (Roos et al., 2021). In our case, anthropogenic pyrodiversity provides a mechanism by which areas could remain fire free for long enough to have burned at high-severity when fire eventually returned. All three of our shrubfield establishment ages could be consistent with an anthropogenic hypothesis. The inferred origin date at RDC falls within the period of peak Hemish populations (1325–1650 CE), and if SNN established pre-1500 then it too could relate to human land use. If established in 1664 CE, SNS was not established during peak occupation but in the decades of Hemish population collapse and the rebound of widely spreading fires (Liebmann et al., 2016; Swetnam et al., 2016) when burning may have returned to previously sheltered parts of the landscape. Particularly given the relatively long distance between SNN, SNS, and the Jemez Plateau, the anthropogenic hypothesis has implications for how we think about the scale of

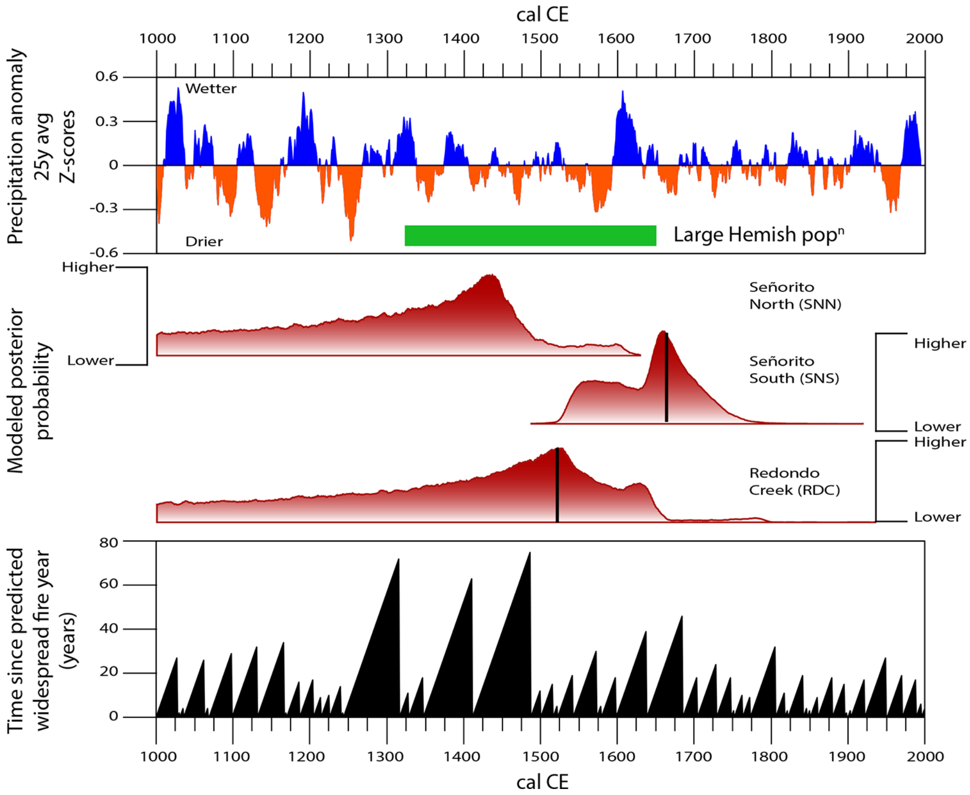

Figure 4. The Bayesian posterior probability density functions for the fire event that initiated the transition from forest to shrub patch based on radiocarbon data in Figure 2 and Table 1 for the three shrub patches organized from north (top) to south (bottom). Black vertical lines at SNS and RDC indicate the tree-ring evidence for establishment. These establishment ages are compared to decadally smoothed precipitation (orange and blue), the period when the Native American Hemish population was more than 3000 from 1325–1650 CE, and the sawtooth plot of modeled fire intervals from interannual climate variation (bottom). The sawtooth plot shows cumulative time since the last year predicted to have widespread fires. Color is visible in the online version of this paper.

Indigenous impacts on fire regimes (Bowman et al., 2011; Roos, 2020; Roos et al., 2014).

Although the megadrought hypothesis is not well supported on its own, the impact of severe drought on fuel flammability was important. SNN may have established during the chronically dry 1400s. If RDC was established in 1522 CE, that year was unusually dry, as was 1664 CE, when SNS was likely established (Touchan et al., 2011). Most fire years, and widespread fire years in particular, are typically dry in surface fire regimes of the Western US (Swetnam and Baisan, 2003; Swetnam and Betancourt, 1998; Swetnam et al., 2016), so this is not a sufficiently unique characteristic of these events. Other features would have been necessary to drive unusual fire behavior. Dry years during or in the decades following long periods of reduced fire spread, whether driven by climate (1522 CE following the 1348–1486 CE reduced fire periods) or anthropogenic pyrodiversity (1664 CE following peak Hemish populations) are likely intersections between these mechanisms. Although the fire interval hypothesis may explain the origins of two of the three shrubfields, the anthropogenic hypothesis might explain all three.

Conclusions

Integrated tree ring and soil charcoal radiocarbon evidence identify at least three distinct episodes of crown fires (100–300 ha) leading to type conversion from forest to shrubs in the 15th (or earlier), 16th, and 17th centuries CE. Comparisons of the estimated establishment ages of two shrubfields with independent records of climate and archaeology suggest interactions between climate and Native American land use may have contributed to altering fuel and stand density to support tree-killing fires and shifts to perennial shrubfields. A third shrubfield may further corroborate this interpretation but its dating is less secure. However, the total number of shrubfields with establishment ages is small and more research is needed to fully evaluate the climate and land-use mechanisms that contributed to the loss of forest resilience and transitions to alternative stable states in the past.

For 21st century shrubfield establishment, both climate and anthropogenic mechanisms are important and operating. Many forests in the western USA have not burned in over a century, a distinctly anthropogenic driver that has increased fuel loads and homogenized forest structures. Current drought conditions are also promoting fire intensity, with drought effects and fire sizes amplified by anthropogenic climate change (Abatzoglou and Williams, 2016; Williams et al., 2013). These factors make mountainous areas like the Jemez far more vulnerable to extensive and enduring type conversion than they were historically. Already a suite of fires since the 1970s have more than doubled the amount of Gambel oak-dominated shrubfield in the Jemez (Allen 2016). We hope that this work will stimulate future research on persistent shrubfields and the light they may shed on alternative stable states, and climatic and anthropogenic influences on forest vulnerability.

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References

Abatzoglou JT and Williams AP (2016) Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* 113: 11770–11775.

Allen CD (1989) *Changes in the Landscape of the Jemez Mountains, New Mexico*. Berkeley: University of California.

Allen CD (2007) Interactions across spatial scales among forest dieback, fire, and erosion in Northern New Mexico landscapes. *Ecosystems* 10: 797–808.

Allen CD (2016) Forest ecosystem reorganization underway in the Southwestern US: A preview of widespread forest changes in the anthropocene. In: Sample VA and Bixler RP (eds) *Forest Conservation and Management in the Anthropocene: Conference Proceedings*. Fort Collins, CO: U.S. Department of Agriculture: Rocky Mountain Research Station, pp.103–122.

Biondi F, Jamieson LP, Strachan S et al. (2011) Dendroecological testing of the pyroclimatic hypothesis in the central Great Basin, Nevada, USA. *Ecosphere* 2: art5.

Bowman DMJS, Balch JK, Artaxo P et al. (2011) The human dimension of fire regimes on Earth. *Journal of Biogeography* 38: 2223–2236.

Buck CE, Christen JA and James GN (1999) BCal: An on online Bayesian radiocarbon calibration tool. *Internet Archaeology* 7. Available at: http://intarch.ac.uk/journal/issue7/buck/

Cook ER, Seager R, Cane MA et al. (2007) North American drought: Reconstructions, causes, and consequences. *Earth-Science Reviews* 81: 93–134.

Cook ER, Seager R, Heim RR et al. (2010) Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context. *Journal of Quaternary Science* 25: 48–61.

Coop JD, Parks SA, Stevens-Rumann CS et al. (2020) Wildfire-driven forest conversion in Western North American landscapes. *BioScience* 70: 659–673.

de Lafontaine G and Asselin H (2011) Soil charcoal stability over the Holocene across boreal northeastern North America. *Quaternary Research* 76: 196–200.

Farella J (2015) *Terminus Ante Quem Constraint of Pueblo Occupation Periods in the Jemez Province, New Mexico*. School of Geography and Development. Tucson, AZ: University of Arizona.

Fitch EP and Meyer GA (2016) Temporal and spatial climatic controls on Holocene fire-related erosion and sedimentation, Jemez Mountains, New Mexico. *Quaternary Research* 85: 75–86.

Fulé PZ, Covington WW and Moore MM (1997) Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. *Ecological Applications* 7: 895–908.

Gavin DG (2001) Estimation of inbuilt age in radiocarbon ages of soil charcoal for fire history studies. *Radiocarbon* 43: 27–44.

Guiterman CH, Margolis EQ, Allen CD et al. (2018) Long-term persistence and fire resilience of oak shrubfields in dry conifer forests of Northern New Mexico. *Ecosystems* 21: 943–959.

Guiterman CH, Margolis EQ and Swetnam TW (2015) Dendroecological methods for reconstructing high-severity fire in pine-oak forests. *Tree-Ring Research* 71: 67–77.

Higuera PE and Abatzoglou JT (2021) Record-setting climate enabled the extraordinary 2020 fire season in the western United States. *Global Change Biology* 27: 1–2.

Hurteau MD, Koch GW and Hungate BA (2008) Carbon protection and fire risk reduction: Toward a full accounting of forest carbon offsets. *Frontiers in Ecology and the Environment* 6: 493–498.

Iniguez JM, Swetnam TW, Baisan CH et al. (2009) Spatially and temporally variable fire regime on Rincon Peak, Arizona, USA. *Fire Ecology* 5: 3–21.

Keyser AR, Krofcheck DJ, Remy CC et al. (2020) Simulated Increases in fire activity reinforce shrub conversion in a southwestern US forest. *Ecosystems* 23:1702–1713.

Kulisheck J (2005) *The archaeology of pueblo population change on the Jemez Plateau, A.D. 1200 to 1700: The effects of spanish contact and conquest*. Department of Anthropology. Dallas, TX: Southern Methodist University.

Lertzman KP, Gavin D, Hallett DJ et al. (2002) Long-term fire regime estimated from soil charcoal in coastal temperate rainforests. *Conservation Ecology* 6: 5.

Liebmann MJ, Farella J, Roos CI et al. (2016) Native American depopulation, reforestation, and fire regimes in the Southwest United States, 1492–1900 CE. *Proceedings of the National Academy of Sciences* 113: E696–E704.

Little EL (1971) *Atlas of United States Trees, Vol. 1. Conifers and Important Hardwoods*. Washington, DC: U.S. Government Printing Office.

Malevich SB, Guiterman CH and Margolis EQ (2018) Burnr: Fire history analysis and graphics in R. *Dendrochronologia* 49: 9–15.

Marlon JR, Bartlein PJ, Gavin DG et al. (2012) Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences* 109: E535–E543.

Nelle O, Robin V and Talon B (2013) Pedoanthracology: Analysing soil charcoal to study Holocene palaeoenvironments. *Quaternary International* 289: 1–4.

Ohlson M and Tryterud E (2000) Interpretation of the charcoal record in forest soils: Forest fires and their production and deposition of macroscopic charcoal. *The Holocene* 10: 519–525.

Orem CA and Pelletier JD (2015) Quantifying the time scale of elevated geomorphic response following wildfires using multi-temporal LiDAR data: An example from the Las Conchas fire, Jemez Mountains, New Mexico. *Geomorphology* 232: 224–238.

Reimer PJ, Austin WEN, Bard E et al. (2020) The IntCal20 Northern hemisphere radiocarbon age calibration curve (0–55 Cal KBP). *Radiocarbon* 62: 725–757.

Rhodes AN (1998) A method for the preparation and quantification of microscopic charcoal from terrestrial and lacustrine sediment cores. *The Holocene* 8: 113–117.

Robin V, Talon B and Nelle O (2015) Charcoal: Resource and ubiquitous proxy. *Quaternary International* 366: 1–2.

Roering JJ and Gerber M (2005) Fire and the evolution of steep, soil-mantled landscapes. *Geology* 33: 349–352.

Roos CI (2020) Scale in the study of Indigenous burning. *Nature Sustainability* 3: 898–899.

Roos CI, Bowman DMJS, Balch JK et al. (2014) Pyrogeography, historical ecology, and the human dimensions of fire regimes. *Journal of Biogeography* 41: 833–836.

Roos CI, Rittenour TM, Swetnam TW et al. (2020) Fire suppression impacts on fuels and fire intensity in the Western U.S.: Insights from archaeological luminescence dating in Northern New Mexico. *Fire* 3: 32.

Roos CI and Swetnam TW (2012) A 1416-year reconstruction of annual, multi-decadal, and centennial variability in area burned for ponderosa pine forests of the southern Colorado Plateau region, Southwest US. *The Holocene* 22: 281–290.

Roos CI, Swetnam TW, Ferguson TJ et al. (2021) Native American fire management at an ancient wildland-urban interface in the Southwest United States. *Proceedings of the National Academy of Sciences* 118: e2018733118.

Roos CI, Williamson GJ and Bowman DMJS (2019) Is anthropogenic pyrodiversity invisible in paleofire records? *Fire* 2: 42.

Savage M and Mast JN (2005) How resilient are southwestern ponderosa pine forests after crown fires? *Canadian Journal of Forest Research* 35: 967–977.

Savage M, Mast JN and Feddema JJ (2013) Double whammy: High-severity fire and drought in ponderosa pine forests of the Southwest. *Canadian Journal of Forest Research* 43: 570–583.

Schollmeyer KG and Driver JC (2013) Settlement patterns, source–sink dynamics, and artiodactyl hunting in the prehistoric U.S. Southwest. *Journal of Archaeological Method and Theory* 20: 448–478.

Snyderman D and Allen C (1997) *Fire in the mountains: analysis of historical fires for Bandelier National Monument, Santa Fe National Forest and Surrounding Areas 1909 through 1996*. Unpublished report on file at USGS research station, Santa Fe, NM.

Stahle DW, Fye FK, Cook ER et al. (2007) Tree-ring reconstructed megadroughts over North America since A.D. 1300. *Climatic Change* 83: 133–149.

Swetnam TW and Baisan CH (2003) Tree-ring reconstructions of fire and climate history of the Sierra Nevada and Southwestern United States. In: Veblen TT, Baker CM, Montenegro G et al (eds) *Fire and Climate Change in Temperate Ecosystems of the Western Americas*. New York, NY: Springer, pp.158–195.

Swetnam TW and Betancourt JL (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate* 11: 3128–3147.

Swetnam TW, Farella J, Roos CI et al. (2016) Multiscale perspectives of fire, climate and humans in western North America and the Jemez Mountains, USA. *Philosophical Transactions of the Royal Society B: Biological Sciences* 371: 20150168.

Talon B (2010) Reconstruction of Holocene high-altitude vegetation cover in the French southern Alps: Evidence from soil charcoal. *The Holocene* 20: 35–44.

Tosa P, Liebmann MJ, Ferguson TJ et al. (2019) Movement encased in tradition and stone: Hemish migration, land use, and identity. In: Duwe S and Preucel RW (eds) *The Continuous Path: Pueblo Movement and the Archaeology of Becoming*. Tucson: Amerind Foundation and University of Arizona Press, pp.60–77.

Touchan R, Woodhouse CA, Meko DM et al. (2011) Millennial precipitation reconstruction for the Jemez Mountains, New Mexico, reveals changing drought signal. *International Journal of Climatology* 31: 896–906.

Trauernicht C, Brook BW, Murphy BP et al. (2015) Local and global pyrogeographic evidence that indigenous fire management creates pyrodiversity. *Ecology and Evolution* 5: 1908–1918.

Whitlock C and Larsen CPS (2001) Charcoal as a fire proxy. In: Smol JP, Birks HJB and Last WM (eds) *Tracking Environmental Change Using Lake Sediments*. Dordrecht: Kluwer Academic Publishers, pp.75–97.

Williams AP, Allen CD, Macalady AK et al. (2013) Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change* 3: 292–297.