CSIRO PUBLISHING

International Journal of Wildland Fire
http://dx.doi.org/10.1071/WF13214

Fine-scale factors influence fire regimes in mixed-conifer forests on three high mountains in Mexico

Larissa L. Yocom[A,G], *Peter Z. Fulé*[A], *Donald A. Falk*[B], *Celia García-Domínguez*[C], *Eladio Cornejo-Oviedo*[D], *Peter M. Brown*[E], *José Villanueva-Díaz*[F], *Julián Cerano*[F] and *Citlali Cortés Montaño*[A]

[A]School of Forestry, PO Box 15018, Northern Arizona University, Flagstaff, AZ 86011, USA.
[B]School of Natural Resources and the Environment, 325 Biological Sciences East, University of Arizona, Tucson, AZ 85721, USA.
[C]Department of Ecology, School of Biology, University of La Laguna, 38206 San Cristóbal de La Laguna, Tenerife, Spain.
[D]Department of Forestry, 'Antonio Narro' Autonomous Agrarian University, Calzada Antonio Narro 1923, 25084 Saltillo, Mexico.
[E]Rocky Mountain Tree-Ring Research, 2901 Moore Lane, Fort Collins, CO, 80526 USA.
[F]National Institute of Forest, Agriculture, and Fisheries Research, National Center of Research on Water, Soil, Plants, and Atmosphere, Km 6.5 Margen Derecha Canal de Sacramento, C.P. 35140, Gómez Palacio, Durango, México.
[G]Corresponding author. Email: larissa.yocom@gmail.com

Abstract. We investigated the influence of broad- *v.* fine-scale factors on fire in an unusual landscape suitable for distinguishing the drivers of fire synchrony. Our study was conducted in the Sierra Madre Oriental mountain range, in north-eastern Mexico. We worked in nine sites on three parallel mountains that receive nearly identical broad-scale climatic influence, but between which fires are unlikely to spread. We collected and cross dated samples from 357 fire-scarred trees in nine sites in high-elevation mixed-conifer forests and identified fire dates. We used Jaccard similarity analysis to evaluate synchrony among sites and quantified relationships between climate and fire occurrence. Fires were historically frequent (mean fire interval ranged from 8 to 16 years in all sites) and dates of fire exclusion ranged from 1887 to 1962. We found low fire synchrony among the three mountains, indicating a strong influence of fine-scale factors on fire occurrence. Fire regime attributes were similar across mountains despite the independence of fire dates. La Niña events were associated with fire over time, although not significantly since the 1830s. Our results highlight the importance of scale in describing fire regimes and suggest that we can use fire history to understand controls on complex ecosystem processes and patterns.

Additional keywords: climate, dendrochronology, fire history, fire synchrony, Sierra de Arteaga, Sierra Madre Oriental.

Received 17 December 2013, accepted 9 May 2014, published online 11 September 2014

Introduction

Factors that affect fire occurrence operate on a continuum of scales, from fine-scale microsite variation in fuels and topography to broad-scale global climate oscillations. Fine-scale factors interrupt fire synchrony and create heterogeneity across landscapes, whereas broad-scale factors are influential in synchronising fire across landscapes and even continents. The relative importance of broad-scale and fine-scale controls on fire regimes depends on the scale of analysis and on the strength of the influences in a given area (Falk *et al.* 2007; Kellogg *et al.* 2008). Climate is a significant broad-scale driver of wildfire synchrony at regional to continental scales (e.g. Swetnam and Betancourt 1990; Taylor and Beaty 2005; Kitzberger *et al.* 2007; Heyerdahl *et al.* 2008). Synchronous regional fire years, in which widely separated sites burn in the same year, can result from periods of widespread drought associated with regional-scale climate patterns, as illustrated in the south-western USA by high synchrony across mountain ranges separated by deserts (Swetnam and Baisan 2003).

Fine-scale variation in factors such as ignitions, topography, and fuel type, amount and connectivity may reduce synchrony in fire between sites because they exert independent influence on a site-by-site basis, increasing heterogeneity in burn patterns (Brown *et al.* 2001; Kellogg *et al.* 2008; Iniguez *et al.* 2009; Ireland *et al.* 2012). Controls may shift depending on the relative strength of forcing factors. Fine-scale topographic influences, for instance, may be stronger in years with mild climate, but severe fire weather can override local factors and result in widespread synchrony of fire occurrences (Taylor and Skinner 2003; Flatley *et al.* 2011).

Human activity has been described as a broad-scale influence on fire (Brown *et al.* 2001). For example, large areas of the south-western USA were affected by humans between 1870 and 1900 when surface fire regimes were interrupted due to the introduction of livestock, logging, predator control, land use changes and fire suppression (Swetnam and Baisan 2003). However, human influences can also be expressed at more local scales. Although fire regimes in Mexican forests have received limited scientific attention (Rodríguez Trejo 2008), studies in Mexico have documented sites that experienced fire exclusion at different points throughout the twentieth century or not at all (e.g. Fulé and Covington 1999, Stephens *et al.* 2003, Poulos *et al.* 2013).

Our understanding of the scales at which fine- and broad-scale factors influence fire occurrence is incomplete, although several studies have examined controls on fire at multiple scales (Falk *et al.* 2007). For example, Heyerdahl *et al.* (2001) explored influences on variations in fire regimes within and among watersheds and concluded that historically, both broad-scale factors such as regional climate and fine-scale factors such as aspect and elevation influenced fire frequency, size and season in the interior western USA. Livestock grazing and fire suppression became the most important influences on fire occurrence in the twentieth century. Similarly, Hessl *et al.* (2004) found that in the state of Washington, climate (summer drought and the positive phase of the Pacific Decadal Oscillation) was linked to fire, but these relationships were overridden by land use changes in the twentieth century. In another example from the Klamath Mountains, variation in fire frequency was related to aspect. Topographic features that acted as barriers to fire spread were important in defining spatial patterns of fire on the landscape except during years of exceptional climate, when more extreme fire behaviour overcame barriers to fire spread that operated in more moderate conditions (Taylor and Skinner 2003).

Various studies have also explored the controls on fire using models. Parisien *et al.* (2010) found in a modelling exercise that weather-related variables had a larger effect on mean burn probability, whereas fuels and ignitions had a larger effect on the variability of burn probability. However, the authors noted that cleanly separating broad-scale and fine-scale factors is not possible. Other modelling exercises have demonstrated that broad-scale controls are more important in topographically simple landscapes, whereas fine-scale controls are more important in topographically complex landscapes (Kellogg *et al.* 2008; Kennedy and McKenzie 2010).

El Niño-Southern Oscillation (ENSO) is a significant broad-scale influence on fire in many parts of North America and globally. The phases of ENSO affect winter precipitation and thus fire differently in different regions of North America. La Niña is associated with drought and increased fire activity in the south-eastern USA and northern Mexico. The present study site is located close to the bipole in central Mexico where the effects of ENSO phases switch and La Niña brings wetter conditions (Caso *et al.* 2007, Yocom and Fulé 2012). In a previous fire–climate study at Peña Nevada in north-eastern Mexico, Yocom *et al.* (2010) found patterns of frequent fire and a strong relationship between drought and fire years. At this site, the relationship between ENSO and fire changed over time. Before the 1830s, La Niña events were strongly associated with fire occurrence, but the relationship disappeared after the 1830s and in recent years fires have burned at Peña Nevada during both strong El Niño and La Niña events. It is unknown whether this unstable relationship is unique to Peña Nevada or whether the relationship between ENSO and fire has become disassociated in other parts of northern Mexico as well.

The Sierra Madre Oriental is a region rich in biodiversity and endemic species, with 50 gymnosperm species, 10 of those endemic (Contreras-Medina and Luna-Vega 2007). The northern end of the Sierra Madre Oriental is called the Sierra de Arteaga. The area is useful as a 'natural experiment' to investigate the relative influences of broad-scale and fine-scale controls. This part of the Sierra consists of a series of east–west-oriented, high, parallel, forested mountains separated by deep, non-forested valleys used for settlements and agriculture (Fig. 1). The distinctive topography allowed us to examine fire patterns in sites on mountains separated by only ~10 km. Because the mountains are in such close proximity, they experience the same broad-scale climatic influences such as ENSO and regional drought. However, we can assume that fires on individual mountains come from separate ignitions because surface fires would be unlikely to cross between them due to topography and vegetation patterns. Quantifying fire synchrony among mountains thus allows us to differentiate between broad-scale and fine-scale controls on fire regimes. Broad-scale influence would be indicated by high fire synchrony among mountains, suggesting that climate events strongly affect fire occurrence. Fine-scale control would be indicated by highly asynchronous fire occurrence among mountains, suggesting that fine-scale factors are more important in determining the occurrence of fire. Intermediate levels of synchrony would indicate combinations of controlling factors at a given scale.

Our objectives were to (1) characterise the historical fire regime of each mountain and describe the occurrence of low-severity and high-severity fire in our sites; (2) assess the relative influence of broad-scale and fine-scale factors by quantifying synchrony of fire dates among sites and mountains, and (3) determine the influence the ENSO on fire occurrence, and assess the stability of the relationship over time.

Methods

Study area

We sampled sites on three different mountains: San Antonio (southernmost), La Viga (middle) and Rancho Nuevo (northernmost; Fig. 1). Average elevation of sites ranged from 3081 to 3464 m and average slope ranged from 22 to 52% (Table 1). San Antonio sites were dominated by a mixture of *Abies vejarii* (Martínez), *Pinus hartwegii* (Lindl.), and *P. strobiformis* (Engelmann); La Viga sites were dominated by *P. hartwegii*; and Rancho Nuevo sites were dominated by *Pseudotsuga menzesii* (Mirb.) Franco with a large amount of *A. vejarii* in the understorey (Farjon 1990; Farjon and Styles 1997). We also found small pockets of *P. culminicola* (Andresen & Beaman), an endangered pinyon pine endemic to the Sierra Madre Oriental, as well as isolated populations of *Populus tremuloides* (Michx.),

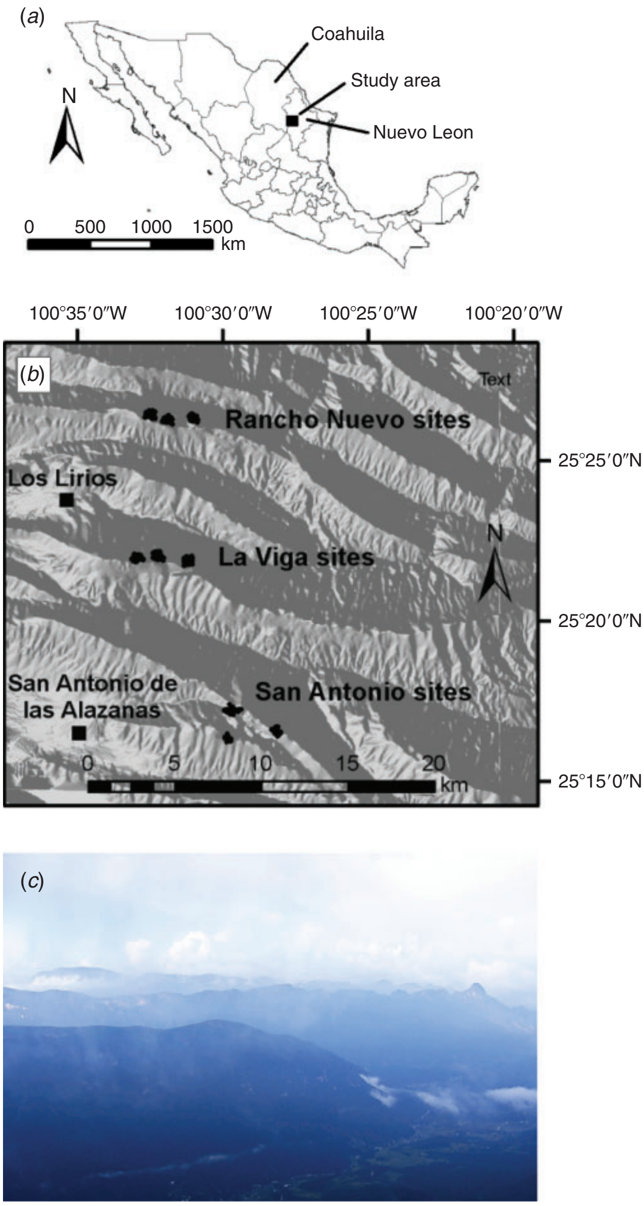

Fig. 1. Location of study area in Mexico (*a*), with nine sites on three mountains (*b*). Elevations of the sites on the three mountains average 3259 m (San Antonio), 3388 m (La Viga) and 3144 m (Rancho Nuevo). Two small towns are also shown on the map (Los Lirios and San Antonio de las Alazanas). Photograph (*c*) shows terrain with high mountains separated by deep valleys.

and *Quercus* and *Prunus* spp. The vegetation on the non-sampled south-facing slope of each mountain was quite different, being dominated by shrubs. The mountains in this region are the result of uplift and folding and the exposed rock is limestone (Ferrusquía-Villafranca 1993). Weather data from the closest weather station, San Antonio de las Alazanas (25°16′N, 100°37′W), near our study sites but at a lower elevation (2170 m), indicated an average yearly temperature of 13°C and average yearly precipitation of 499 mm (1955–1998; data extracted from the ERICIII database, IMTA 2006). Summer precipitation (June–August) accounted for 43% of the precipitation. Applying the dry adiabatic lapse rate of 9.8°C per 1000 m in elevation, yearly average temperature at our sites was estimated at 1–3.5°C. Currently, there are small centres of human population in the valleys between mountains, and roads lead to the top of each mountain. Forests in this area have been used for centuries by local people for timber, fuelwood and resin production (Ortega-Jiménez 2008). Fire suppression efforts began in earnest with the publication in 1930 of regulations organising the suppression of wildfires in this region (Ortega-Jiménez 2008).

Field sampling

An initial collection of fire-scarred tree samples was made at one of the San Antonio sites in 2001 as part of the North American Dendroecological Fieldweek (Speer *et al.* 2006). The remaining collections were made in 2007 and 2008. We established three sites on each mountain, for a total of nine sites. Sites on San Antonio are referred to as SA1, SA2 and SA3; La Viga sites are LV1, LV2 and LV3; and Rancho Nuevo sites are RN1, RN2 and RN3. On each mountain, study sites of 25 ha each were spaced at a minimum of 0.5 km and a maximum of 2 km apart. Sites were selected based on the presence of old trees or old remnant wood, in an effort to compile the longest possible tree-ring record. In each site, using chainsaws, we primarily sampled dead trees of any species that appeared in the field to have the largest numbers of well-preserved fire scars (Van Horne and Fulé 2006; Farris *et al.* 2013). We also sampled some live trees, which often had few scars, to ensure that the fire history extended up to the present. We collected 383 fire-scarred samples in total, most from pines (*P. hartwegii* and *P. strobiformis*) and a minority from *Pseudotsuga menziesii* and *A. vejarii*.

Laboratory methods

After surfacing samples, we cross dated them using a local *Pseudotsuga menziesii* tree-ring chronology (Villanueva-Diaz *et al.* 2007). The cross dating of a 10% subset of the samples was confirmed by a second dendrochronologist. We also measured the ring widths of each sample and checked the cross dating with the COFECHA software program (Holmes 1983). We identified fire scars to the exact year of formation by noting the cross dated ring in which the fire injury occurred (Baisan and Swetnam 1990). When possible, we determined the position of fire scars within rings for seasonal evaluation. We assigned dormant-season fires to the subsequent calendar year, which corresponds to observed seasonality of fire occurrence in the region.

Analysis

To quantify historical fire frequency, we calculated surface fire interval distributions for periods in which there was an adequate tree-ring record in each site, defined as beginning in the first fire year when at least three samples in that site were recording (Table 1). Recording trees are those that have been scarred at least once previously and are more likely to scar in subsequent fires. The period of fire interval analysis for each site ended on the last year when at least three samples were scarred in order to describe the historical fire regime before fire exclusion in the

Table 1. Characteristics and fire scar information for nine forested sites sampled in the northern Sierra Madre Oriental, Mexico

Mountain	Code	Site	Average elevation (m)	Average slope (%)	Average aspect	Samples dated	Number of fire scars	First fire scar recorded (year)	Period of fire interval analysis (year)
San Antonio	SA1	La Armenia	3270	41	SW	39	248	1572	1614–1918
	SA2	Las Bateas	3253	22	SW	29	141	1566	1648–1887
	SA3	Las Manzanas	3253	22	S	22	80	1572	1666–1962
La Viga	LV1	La Viga	3463	34	N	54	200	1422	1654–1917
	LV2	Musgoso	3414	52	N	42	159	1696	1696–1917
	LV3	Paraíso	3286	46	N	44	150	1557	1709–1917
Rancho Nuevo	RN1	Rancho Nuevo	3140	35	N	48	135	1610	1729–1909
	RN2	El Tarillal	3081	47	NE	31	122	1666	1755–1909
	RN3	Puerto El Tarillal	3211	44	N	48	122	1622	1710–1952
Total						357	1357		

19th or 20th centuries. The only exception to this procedure was for one site on Rancho Nuevo: although eight samples were scarred in 1982, this fire followed an unusually long period of 73 years without a fire that scarred more than one tree; this interval was not included in the analysis of fire intervals because it probably reflected human modification of the fire regime. To assess the possibility of historical high-severity fire occurrence, which would have killed trees and opened up growing space for seedling establishment (e.g. Veblen *et al.* 1994), we identified periods in each site with multiple trees recruiting, by identifying pulses of regeneration (multiple trees with pith dates clustered in 30-year periods).

We calculated fire interval statistics with FHX2 ver. 3.2 software (Grissino-Mayer 2001). For each site, we calculated the composite mean fire interval (MFI) between all fires (hereafter referred to as 'all fires'), and also between fires that scarred at least 25% of recording trees ('widespread fires'). We used the Kolmogorov–Smirnov goodness-of-fit test ($\alpha = 0.05$) to determine whether the Weibull median probability intervals (WMPI) fit the data adequately. The WMPI is the fire interval associated with the 50% exceedance probability of a modelled Weibull function fit to an empirical fire interval distribution (Grissino-Mayer 2001). We used Tukey's honest significant difference test ($\alpha = 0.05$) to determine whether there were differences in MFIs among sites and among mountains.

To test whether fires occurred synchronously among sites and among mountains more often than would be expected by chance, we used Chi-square tests. To compare synchrony of fire among mountains, we compared observed *v.* expected values of fire co-occurring on zero, one or two+ mountains. Expected values were estimated from joint probabilities of fire occurring or not occurring on the mountains. To test synchrony between pairs of sites within each mountain, we used a 2×1 analysis in FHX2 version 3.2 software (Grissino-Mayer 2001) because fire could easily spread between sites on each mountain (Grissino-Mayer 1995).

We used similarity analysis to assess persistent (a)synchrony among pairs of sites over the period of record. Each fire history was converted to a binary (fire, no fire $\times$ year) series at the site scale; fire years recorded at a site on only one tree were excluded. We calculated the Jaccard similarity coefficient ($S_j = a \div [a + b + c]$) for each *m,n* pair of sites for their period of common record, where $a =$ the number of fire years in common between two sites, and b and $c =$ number of years unique to one site or the other. The Jaccard coefficient is preferred for fire history analysis because it excludes the large number of (0,0) cases (i.e. non-fire years in both sites), which tend to inflate similarity values because most years are non-fire years. We used the resulting pairwise Jaccard distance ($1 - S_j$) matrix to drive a divisive clustering algorithm (Jain *et al.* 1999) based on shared fire history.

To evaluate the influence of ENSO on fire occurrence at our study sites, we used superposed epoch analysis (SEA) in FHX2 (Grissino-Mayer 1995) to compare 'widespread' fire occurrence with an independently derived ENSO index. The SEA compared reconstructed December–February NINO3 values (1408–1978; Cook 2000) during fire years, 5 years before fire years, and 2 years after fire years. To address temporal autocorrelation in the NINO3 index, we fit autoregressive integrated moving average models based on lowest Akaike's information criterion and significant but uncorrelated parameter estimates (Brown *et al.* 2008*a*) and used the resulting white noise residuals in our analyses. To assess statistical significance of the SEA results, we calculated 95% confidence intervals using bootstrapped distributions of climate data in 1000 trials. We analysed ENSO association with fire before 1831 and after 1832 to evaluate whether the relationship changed at the same time that the ENSO–fire relationship changed 200 km to the south at Peña Nevada (Yocom *et al.* 2010). We also analysed ENSO association with years in which zero, one, two or all three mountains recorded fire.

Results

Fire regime

We were able to cross date 357 (93.2%) of the samples; 26 could not be cross dated. The earliest fire scar identified was from 1422 and the last fire scars formed in 1998. Of the fire scars where intra-ring position could be determined, 88% were formed in the dormant season and 7% were found in earlywood.

Table 2. Measures of fire frequency in nine sites in the Sierra Madre Oriental, Mexico

Fire intervals are for fire dates recorded at each site during each site's period of analysis. 'All fires' refers to any fire regardless of size, and 'widespread fires' refers to fires that scarred ≥25% of recording trees. WMPI, Weibull Median Probability Interval

Site	Number of intervals	Mean fire interval: all fires (years)	WMPI: all fires (years)	Mean fire interval: widespread fires (years)	Minimum fire interval (years)	Maximum fire interval (years)
SA1	39	7.8	6.7	12.7	1	28
SA2	25	9.6	7.9	14.1	1	29
SA3	23	12.9	11.4	17.4	2	32
LV1	16	16.4	13.9	23.9	2	47
LV2	14	15.8	11.1	27.6	1	79
LV3	19	11.0	9.0	16.0	1	37
RN1	14	12.9	12.0	13.9	3	28
RN2	12	12.8	12.3	15.4	4	24
RN3	25	9.7	8.7	20.2	1	19

MFI for 'all fires' ranged in individual sites from 7.8 to 16.4 years (Table 2). The Weibull function fit the data adequately in every site; WMPI ranged from 6.7 to 13.9 years. For 'widespread fires', MFI per site ranged from 12.7 to 27.6 years. Minimum fire interval in sites ranged from 1 to 4 years and maximum fire interval ranged from 19 to 79 years. On average, MFI and WMPI for 'all fires' and for 'widespread fires' were longest on La Viga and shortest on San Antonio. However, the differences in MFI between mountains were not significant. The only significant difference in MFI among sites was found for 'all fires' between SA1 (MFI 7.8) and LV1 (MFI 16.4; $P = 0.04$).

Several of our sites had pulses of tree regeneration in the past, defined and identified as multiple pith dates of fire-scarred samples clustered within a 30-year period. San Antonio had the fewest pulses of regeneration, with few clusters of pith dates and only three to six trees per cluster (Fig. S1 of the Supplementary material). Pulses were most pronounced in sites on La Viga (LV1, LV2 and LV3). Each of the sites had a pulse of regeneration in the mid-1700s (Fig. 2). Thirteen samples in site LV1 had pith dates between 1745 and 1758, 11 samples in site LV3 had pith dates between 1736 and1763, and four samples in site LV2 had pith dates between 1741 and 1754. In addition, site LV1 had a pulse of regeneration between 1564 and 1593 (nine samples) and site LV2 had a pulse of regeneration between 1636 and 1662 (13 samples). There was evidence of clumps of regeneration on Rancho Nuevo as well, but there were fewer trees in each pulse (Fig. S2).

Fire synchrony

Across the entire record, in only 6 years did all three mountains record a fire (1622, 1654, 1689, 1785, 1797 and 1838) (Fig. 3) out of 126 total fire years during that period (~5%). The years of highest synchrony among sites were 1785 and 1797, when eight of the nine sites recorded fire. The three mountains were not consistent in the timing of fire exclusion. Sites on La Viga were uniform; the last multi-scar fire at all three sites was in 1917. However, sites on Rancho Nuevo had their last multi-scar fires in 1909 or 1952, and sites on San Antonio were the least consistent, with last multi-scar fire dates in 1887, 1918 and 1962 in the three sites. Results of Chi-square tests indicate that the level of synchrony among mountains and among sites is no higher than would be expected by chance (Tables S1, S2 of the Supplementary material). Consistent with the Chi-square results, clustering based on similarity analysis of fire dates among pairs of sites resulted in the strongest affinities being among sites on each mountain. The result is plotted as a dendrogram (Fig. 4).

Fire–climate

La Niña events were associated significantly with the occurrence of 'widespread' fire in our study region before 1831 and were associated strongly but not significantly after 1832 (Fig. S3). In an analysis of ENSO association with different levels of fire synchrony on the three mountains over the entire period (1411–1978), years when zero mountains recorded fire were associated significantly with El Niño; years when one or two mountains recorded fire were associated significantly with La Niña, and years when all three mountains recorded fire were not associated significantly with ENSO (Fig. 5).

Discussion

Low fire synchrony

Sites on the three mountains historically had similar fire regimes in terms of fire frequency and seasonality, despite the lack of synchrony of fire dates among mountains. The fire regimes on all three mountains were characterised by frequent surface fire, with little significant difference among sites or mountains. However, fire on the three mountains was highly asynchronous: very rarely did all three mountains record fire in the same year despite a frequent fire regime on each mountain. Our results suggest that at the scale of our study region, fine-scale factors influencing fire predominated. Although ENSO was correlated with fire occurrence over a long temporal scale, it was not strong enough to synchronise fire throughout the region any more than would be expected by chance.

Synchrony in our sites was lower than in comparable settings elsewhere. For example, in the Chiricahua Mountains in south-eastern Arizona, two areas (Sara Deming Canyon, Baisan and Morino 2000, also see http://hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1:0::::P1_STUDY_ID:1945; and Rustler Park, Seklecki *et al.* 1996) separated by 13 km of rugged terrain shared

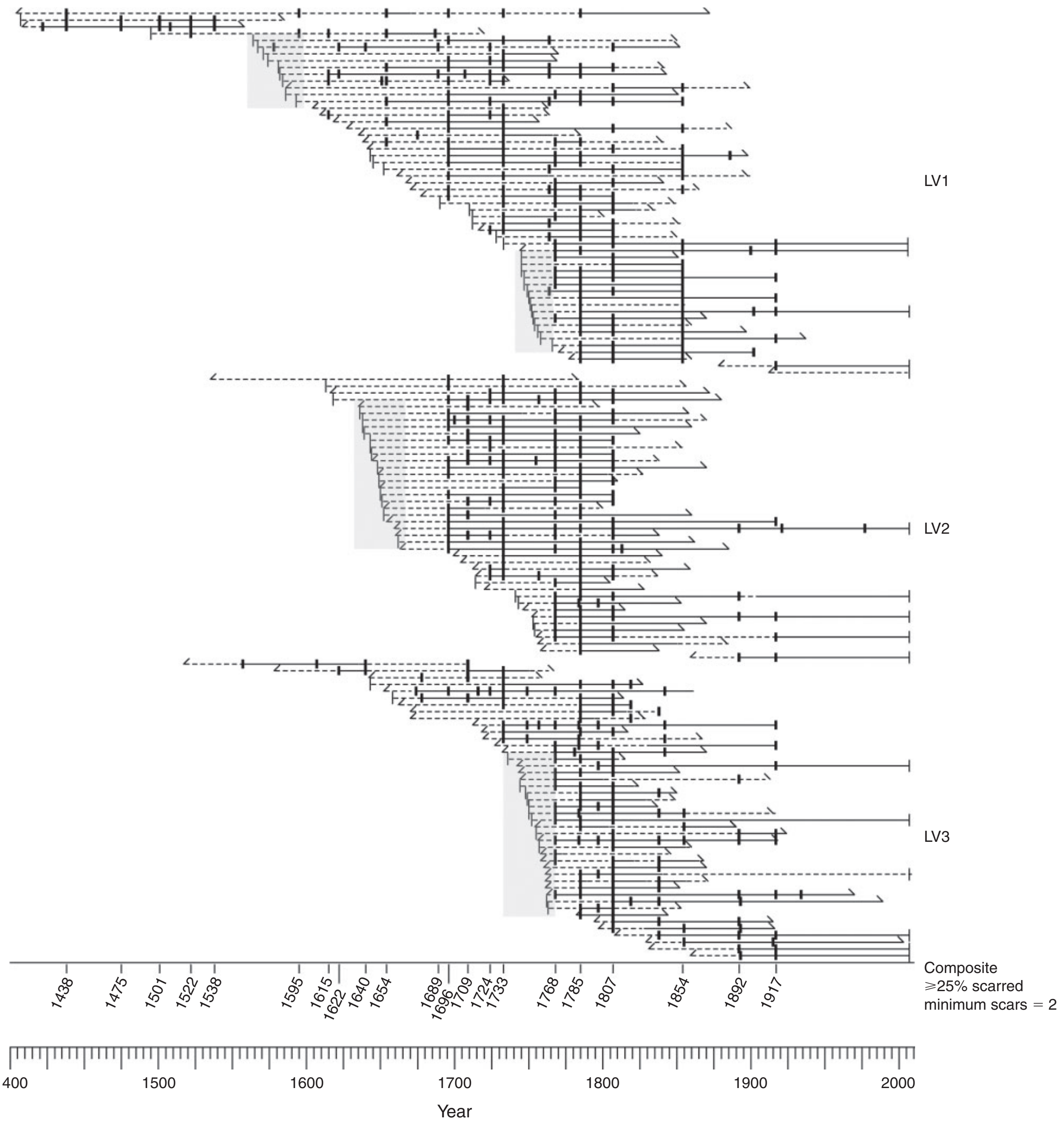

Fig. 2. Fire history graph for La Viga: top, LV1; middle, LV2; bottom, LV3. Horizontal lines represent individual tree samples; solid horizontal lines represent periods when the sample was recording and dashed horizontal lines represent periods when the sample was not recording. Bold vertical tick marks represent precisely dated fire scar dates. Vertical lines to the left represent pith dates and slanted lines to the left represent inside ring dates (i.e. unknown number of years to pith). Grey boxes indicate 30-year periods with pulses of regeneration (≥8 pith dates).

16 out of 66 total fire dates (24%) between 1708 and 1894. At a larger scale, a regional analysis of fire dates in the Madrean Archipelago (SE Arizona, SW New Mexico and NW Sonora) revealed that there were 30 years between 1648 and 1886 when at least five of 31 sites (16%) recorded fire (Swetnam 2005). This is a higher level of synchrony, over a much larger region, than we found in our study area. However, synchrony among sites in our study area was comparable to synchrony among sites in El Malpais National Monument in New Mexico, a study location where some sites were separated by lava flows that act as natural barriers. In a 230-year period, 13 fire years (5.7%) coincided at four or more of the nine sites (Grissino-Mayer and Swetnam 1997). In comparison, in a 218-year period at our study sites, 10 fire years (4.6%) coincided at four or more of the nine

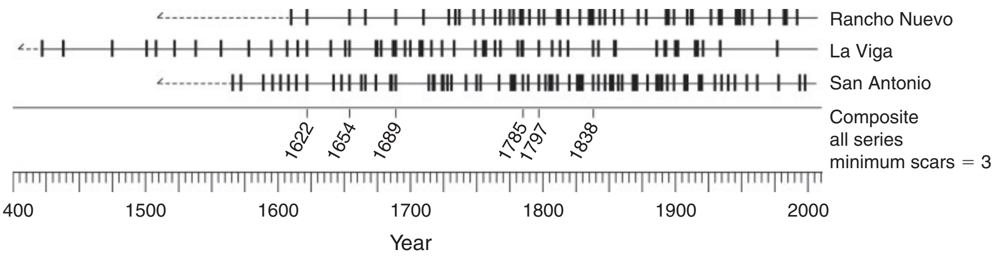

Fig. 3. Composite fire history graph for the three mountains in the study. The 6 years listed are the only years in which all three mountains recorded fire simultaneously.

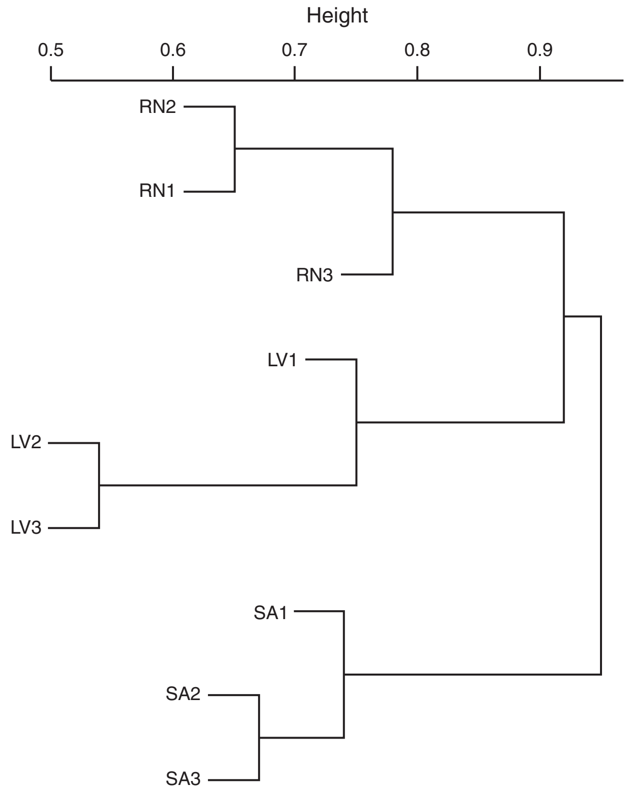

Fig. 4. Dendrogram from divisive hierarchical analysis of fire dates in study sites. SA sites are on San Antonio, LV sites are on La Viga and RN sites are on Rancho Nuevo.

sites. In another example from north-western Arizona, low synchrony of fire found among sites was probably due to a lack of fuel continuity, with patches of ponderosa pine separated by a matrix of less flammable vegetation types (Ireland *et al.* 2012).

Although the fire regimes were similar among mountains, there was some variation. MFI for 'all fires' and 'widespread fires', WMPI and maximum interval were all longer on average in La Viga sites than in sites on the other two mountains. San Antonio tended to have the shortest intervals of the three mountains. The mountain highest in elevation, La Viga, had more pulses of regeneration, which could be evidence of small patches of high-severity fire, but we found no evidence of high-severity fire at the scale of our sites (25 ha) or greater. Brown *et al.* (2008*b*) did not consider multi-aged stands with recruitment pulses that overlapped living trees (as was the case at our sites) to indicate evidence of high-severity fire. However, we suggest that small patches of high-severity fire may have opened up gaps within our sites at the scale of <25 ha. We acknowledge the limitations of using pith dates of fire-scarred trees instead of full stand age data to assess recruitment pulses and the possibility of historical high-severity fire, but we believe the results are still useful to report. The fire scars were collected from trees of multi-century age that had survived numerous fires. These scarred, fire-surviving trees represented an average of 40 trees per 25-ha site (357 trees over nine sites), providing evidence that a stand-replacing fire or other disturbance at a patch size of 25 ha had not occurred for at least several centuries.

Several fine-scale factors varied among the three mountains as well, including elevation, topography and forest species composition. First, elevation varied slightly among mountains: sites on La Viga were on average 130 m higher than sites on San Antonio and 244 m higher than sites on Rancho Nuevo. Other studies have found longer fire intervals, more synchronous fires and more stand-replacing disturbance with increasing elevation (Brown *et al.* 2001; Fulé *et al.* 2003; Margolis and Balmat 2009). In terms of topography, sites on La Viga and Rancho Nuevo were arranged on steep north-facing slopes, and sites on San Antonio were on three flatter, mostly south-facing sides of a wet meadow. Average slopes varied: San Antonio sites were the least steep with average slopes of 28%, whereas sites on La Viga and Rancho Nuevo averaged 44 and 42% slope. Slope and aspect have both been shown to affect fire history patterns (Gavin *et al.* 2003, Iniguez *et al.* 2008). All of these interlinked factors could have had an influence on the local fire regime.

Kellogg *et al.* (2008) hypothesised that broad-scale controls are stronger in topographically simple landscapes, whereas bottom-up controls are more important in more topographically complex landscapes. This hypothesis was supported by modelling work by Kennedy and McKenzie (2010) using fire scar data, and it is supported by our findings of strong bottom-up controls in a topographically complex area. Flatley *et al.* (2011) concluded that topography is an important influence on fire but also that it can be overridden by climate. In our study region, there were only 6 years in which all three mountains recorded fires, suggesting that here the synchronising effect of climate has rarely overridden the strong influence of the complex topography.

Human influence on fire occurrence

This area has a long history of human use of the forest (Ortega-Jiménez 2008); certainly humans have used fire in this region

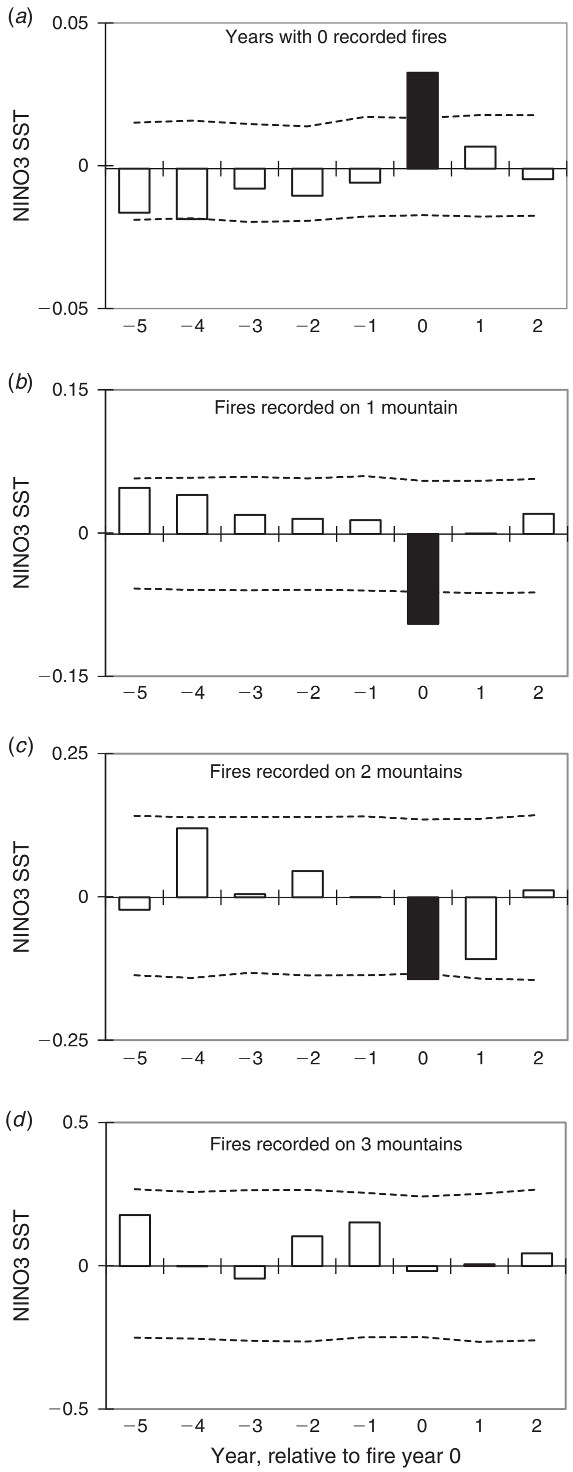

Fig. 5. Superposed epoch analysis showing departure from the mean value of NINO3 SST (sea surface temperatures; Cook 2000) years in which 0 (*a*; $n = 416$), 1 (*b*; $n = 113$), 2 (*c*; $n = 22$), and 3 (*d*; $n = 6$) mountains recorded fire (1411–1978). Typically in this region, positive NINO3 values tend to be correlated with above-average precipitation and negative NINO3 values tend to be correlated with below-average precipitation. Fire years are indicated by 0 on the *x*-axis, and values are also given for 5 years before fire years (negative values) and 2 years after fire years. Black bars are those that pass the 95% confidence interval. Here, NINO3 is a unitless index.

for various reasons over centuries. However, we do not have information about how many fires were started by humans (rather than lightning) throughout history, nor whether human ignition patterns were different among mountains. We also do not know the full history of logging on these mountains, although we know from plot measurements (L. L. Yocom, P. Z. Fulé, D. A. Falk, C. García-Domínguez, E. Cornejo-Oviedo, P. M. Brown, J. Villanueva-Díaz, J. Cerano and C. Cortés Montaño, unpubl. data) that the tree species most often cut was different on Rancho Nuevo from that on San Antonio and La Viga. The majority of stumps on Rancho Nuevo were from *Pseudotsuga menzesii* whereas *P. hartwegii* was the most commonly cut species on San Antonio and La Viga. This reflected the variation in dominant tree species on the three mountains. All three mountains had roads leading to the top. We saw evidence of grazing on San Antonio and seasonal homes on San Antonio and La Viga, but we lack information about current or historical grazing levels. All three mountains were close to small human population centres in the valleys below and have doubtless been visited and used for centuries (Ortega-Jiménez 2008). We did not see an increase in fire occurrence in the fire scar record that we can link to changed land use (e.g. Donnegan *et al.* 2001) or changes in seasonality that we can attribute to human fire ignitions (e.g. Grissino-Mayer *et al.* 2004).

The only change to the fire regime that we could attribute to human activity was the decrease in fire that began between 1887 and 1962. The lack of synchrony in the onset of fire exclusion was unusual in comparison to many fire history studies from the western United States, where the onset of fire exclusion was consistent not only across study areas but fairly so across much of the western United States because of the onset of grazing, logging and fire suppression. In other areas in Mexico, the cessation of frequent fire was coincident with the formation of *ejidos*, which are rural communities living on and managing commonly held land, and with an increase in livestock grazing (Heyerdahl and Alvarado 2003; Yocom *et al.* 2010, Poulos *et al.* 2013). In the region of our study sites, there was a patchwork of ownership, with some areas under *ejido* management and other areas privately owned. *Ejido* formation, which took place in the mid- to late-1930s in this area, would not be expected to align with the dates of last fires across all study sites given that ownership varied across the mountains; and that is indeed what we saw: the dates of last fires spanned several decades. In this case, as elsewhere in Mexico, human influence on fire cessation varied at a fine scale.

The role of ENSO

Despite the lack of fire synchrony among the three mountains, there was a relationship between climate and fire occurrence in our study region. La Niña events were associated with fire occurrence over time. There was a change in the relationship in the 1830s at this study area, but it was nuanced: La Niña events were still strongly associated with fire occurrence after the 1830s although the association was no longer significant at the 95% confidence level (Fig. S3). This contrasted with previous results from north-eastern Mexico, where at Peña Nevada after the 1830s there was no relationship at all between ENSO and fire (Yocom *et al.* 2010). Our results led us to speculate that these study sites, being farther north, are outside the transition zone where ENSO effects change over time. To investigate this point fully, a more extensive network of climate reconstructions and fire-climate sites is needed in this region.

The high frequency of fire in this study region indicated that fires do not burn only in the most extreme climate years. A fire occurred somewhere in the nine sites every 3 years or less in the period common to all nine sites. Climatically, opportunities for fires to burn were fairly common; years with NINO3 values equal to or less than the average NINO3 value for all fires occurred in 140 out of 381 years (36.7%) between 1622 and 2002. This may help explain why fire synchrony was so low among mountains.

Our results highlight the importance of scale in describing fire regimes, and suggest that we can use fire history to understand the controls on complex ecosystem processes. In this region, conditions or fuel continuity were typically not conducive for fire spread from mountain to mountain; the non-contiguous nature of this landscape for fire could indicate a non-contiguous pattern for other processes as well. The asynchronous fire dates but similar fire regimes among the mountains suggest an independent but 'convergent' fire regime on each mountain: before fire exclusion, forests on these mountains burned frequently but not simultaneously. Fires were asynchronous on the three mountains despite their close proximity. This emphasises the importance of limiting inferences about a heterogeneous region based on a small sampled area. Finally, fire exclusion was not synchronous and occurred in this small region over a period of 75 years. Any management activities in this region should take into account the spatial heterogeneity in disturbance history among sites and mountains.

Acknowledgements

We thank local *ejidos* and landowners for permission to work on their land. Armando Becvort, Erica Bigio, Walker Chancellor, Julián Charles, Vicenta Constante García, Osvaldo Turlán Medina and Cameron Fulé provided valuable assistance in the field. Many thanks also to Don Normandin, Charles Machula and other staff and students at the Ecological Restoration Institute. The pilot study in site SA1 in 2001 was done as part of the North American Dendroecological Fieldweek. Two anonymous reviewers and an associate editor made suggestions that greatly improved the manuscript. This research was supported by the National Science Foundation (DEB-0640351) and the Ecological Restoration Institute at Northern Arizona University.

References

Baisan CH, Morino KA (2000) Final report: fire history in Chiricahua National Monument. (University of Arizona: Tucson)

Baisan CH, Swetnam TW (1990) Fire history on a desert mountain range: Rincon Mountain wilderness, Arizona, USA. *Canadian Journal of Forest Research* **20**, 1559–1569. doi:10.1139/X90-208

Brown PM, Kaye MW, Huckaby LS, Baisan CH (2001) Fire history along environmental gradients in the Sacramento Mountains, New Mexico: influences of local patterns and regional processes. *Ecoscience* **8**, 115–126.

Brown PM, Heyerdahl EK, Kitchen SG, Weber MH (2008*a*) Climate effects on historical fires (1630–1900) in Utah. *International Journal of Wildland Fire* **17**, 28–39. doi:10.1071/WF07023

Brown PM, Wienk CL, Symstad AJ (2008*b*) Fire and forest history at Mount Rushmore. *Ecological Applications* **18**, 1984–1999. doi:10.1890/07-1337.1

Caso M, Gonzalez-Abraham C, Ezcurra E (2007) Divergent ecological effects of oceanographic anomalies on terrestrial ecosystems of the Mexican Pacific coast. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 10 530–10 535. doi:10.1073/PNAS.0701862104

Contreras-Medina R, Luna-Vega I (2007) Species richness, endemism and conservation of Mexican gymnosperms. *Biodiversity and Conservation* **16**, 1803–1821. doi:10.1007/S10531-006-9072-3

Cook ER (2000) Nino 3 Index Reconstruction. International Tree-Ring Data Bank. IGBP PAGES/World Data Center-A for Paleoclimatology Data Contribution Series #2000–052. NOAA/NGDC Paleoclimatology Program. (Boulder, CO)

Donnegan JA, Veblen TT, Sibold JS (2001) Climatic and human influences on fire history in Pike National Forest, central Colorado. *Canadian Journal of Forest Research* **31**, 1526–1539. doi:10.1139/X01-093

Falk DA, Miller C, McKenzie D, Black AE (2007) Cross-scale analysis of fire regimes. *Ecosystems* **10**, 809–823. doi:10.1007/S10021-007-9070-7

Farjon A (1990) 'Pinaceae – Drawings and Descriptions of the Genera *Abies*, *Cedrus*, Keteleeria, *Nothotsuga*, *Tsuga*, *Cathaya*, *Pseudotsuga*, *Larix* and *Picea*.' (Koeltz Scientific Books: Königstein)

Farjon A, Styles BT (1997) '*Pinus* (Pinaceae). Flora Neotropica Monograph 75.' (The New York Botanical Garden: Bronx, NY)

Farris CA, Baisan CH, Falk DA, Van Horne ML, Fulé PZ, Swetnam TW (2013) A comparison of targeted and systematic fire-scar sampling for estimating historical fire frequency in south-western ponderosa pine forests. *International Journal of Wildland Fire* **22**, 1021–1033. doi:10.1071/WF13026

Ferrusquía-Villafranca I (1993) Geology of Mexico: a synopsis. In 'Biological Diversity of Mexico: Origins and Distribution'. (Eds TP Ramamoorthy, R Bye, A Lot, J Fa) pp. 3–108. (Oxford University Press: New York)

Flatley WT, Lafon CW, Grissino-Mayer HD (2011) Climatic and topographic controls on patterns of fire in the southern and central Appalachian Mountains, USA. *Landscape Ecology* **26**, 195–209. doi:10.1007/S10980-010-9553-3

Fulé PZ, Covington WW (1999) Fire regime changes in La Michilía Biosphere Reserve, Durango, Mexico. *Conservation Biology* **13**, 640–652. doi:10.1046/J.1523-1739.1999.97512.X

Fulé PZ, Crouse JE, Heinlein TA, Moore MM, Covington WW, Verkamp G (2003) Mixed-severity fire regime in a high-elevation forest of Grand Canyon, Arizona, USA. *Landscape Ecology* **18**, 465–486. doi:10.1023/A:1026012118011

Gavin DG, Brubaker LB, Lertzman KP (2003) Holocene fire history of a coastal temperate rain forest based on soil charcoal radiocarbon dates. *Ecology* **84**, 186–201. doi:10.1890/0012-9658(2003)084[0186:HFHOAC]2.0.CO;2

Grissino-Mayer HD (1995) Tree-ring reconstructions of climate and fire history at El Malpais National Monument, New Mexico. PhD thesis, University of Arizona, Tucson.

Grissino-Mayer HD (2001) FHX2 – Software for analyzing temporal and spatial patterns in fire regimes from tree rings. *Tree-Ring Research* **57**, 115–124.

Grissino-Mayer HD, Swetnam TW (1997) Multi-century history of wildfire in the ponderosa pine forests of El Malpais National Monument. *New Mexico Bureau of Mines & Mineral Resources* **156**, 163–171.

Grissino-Mayer HD, Romme WH, Floyd ML, Hanna DD (2004) Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. *Ecology* **85**, 1708–1724. doi:10.1890/02-0425

Hessl AE, McKenzie D, Schellhaas R (2004) Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. *Ecological Applications* **14**, 425–442. doi:10.1890/03-5019

Heyerdahl EK, Alvarado E (2003) Influence of climate and land use on historical surface fires in pine-oak forests, Sierra Madre Occidental, Mexico. In 'Fire and Climatic Change in Temperate Ecosystems of the Western Americas'. (Eds TT Veblen, WL Baker, G Montenegro, TW Swetnam) pp. 196–217. (Springer-Verlag: New York)

Heyerdahl EK, Brubaker LB, Agee JK (2001) Spatial controls of historical fire regimes: a multiscale example from the Interior West, USA. *Ecology* **82**, 660–678. doi:10.1890/0012-9658(2001)082[0660:SCOHFR]2.0.CO;2

Heyerdahl EK, Morgan P, Riser JP, III (2008) Multi-season climate synchronized historical fires in dry forests (1650–1900), northern Rockies, USA. *Ecology* **89**, 705–716. doi:10.1890/06-2047.1

Holmes RL (1983) Computer-assisted quality control in tree-ring dating and measurements. *Tree-Ring Bulletin* **43**, 69–78.

IMTA (2006) Extractor Rápido de Información Climatológica (ERIC III). (CD-ROM) (Instituto Mexicano de Tecnología del Agua: Jiutepec, Morelos, Mexico)

Iniguez JM, Swetnam TW, Yool SR (2008) Topography affected landscape fire history patterns in southern Arizona, USA. *Forest Ecology and Management* **256**, 295–303. doi:10.1016/J.FORECO.2008.04.023

Iniguez JM, Swetnam TW, Baisan CH (2009) Spatially and temporally variable fire regime on Rincon Peak, Arizona, USA. *Fire Ecology* **5**, 3–21. doi:10.4996/FIREECOLOGY.0501003

Ireland KB, Stan AB, Fulé PZ (2012) Bottom-up control of a northern Arizona ponderosa pine forest fire regime in a fragmented landscape. *Landscape Ecology* **27**, 983–997. doi:10.1007/S10980-012-9753-0

Jain A, Narasimha Murty M, Flynn P (1999) Data clustering: a review. *ACM Computing Surveys* **31**, 264–323. doi:10.1145/331499.331504

Kellogg LK, McKenzie D, Peterson D, Hessl A (2008) Spatial models for inferring topographic controls on historical low-severity fire in the eastern Cascade Range of Washington, USA. *Landscape Ecology* **23**, 227–240. doi:10.1007/S10980-007-9188-1

Kennedy MC, McKenzie D (2010) Using a stochastic model and cross-scale analysis to evaluate controls on historical low-severity fire regimes. *Landscape Ecology* **25**, 1561–1573. doi:10.1007/S10980-010-9527-5

Kitzberger T, Brown PM, Heyerdahl EK, Swetnam TW, Veblen TT (2007) Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 543–548. doi:10.1073/PNAS.0606078104

Margolis EQ, Balmat J (2009) Fire history and fire-climate relationships along a fire regime gradient in the Santa Fe Municipal Watershed, NM, USA. *Forest Ecology and Management* **258**, 2416–2430. doi:10.1016/J.FORECO.2009.08.019

Ortega-Jiménez S (2008) Reconstrucción histórica del uso del bosque de San Antonio de las Alazanas, Arteaga, Coahuila. MSc Thesis, Universidad Autónoma Agraria Antonio Narro, Saltillo, Mexico.

Parisien MA, Miller C, Ager AA, Finney MA (2010) Use of artificial landscapes to isolate controls on burn probability. *Landscape Ecology* **25**, 79–93. doi:10.1007/S10980-009-9398-9

Poulos HM, Villanueva Díaz J, Cerano Paredes J, Camp AE, Gatewood RG (2013) Human influences on fire regimes and forest structure in the Chihuahuan Desert Borderlands. *Forest Ecology and Management* **298**, 1–11. doi:10.1016/J.FORECO.2013.02.014

Rodríguez Trejo DA (2008) Fire regimes, fire ecology, and fire management in Mexico. *Ambio* **37**, 548–556. doi:10.1579/0044-7447-37.7.548

Seklecki MT, Grissino-Mayer HD, Swetnam TW (1996) Fire history and the possible role of Apache-set fires in the Chiricahua Mountains of southeastern Arizona. In 'Effects of Fire on Madrean Province Ecosystems: A Symposium Proceedings', 11–15 March 1996, Tuscon, AZ. (Eds PF Ffolliott, LF DeBano, MB Maker Jr, GJ Gottfried, G Solis-Garza, CB Edminster, DG Neary, LS Allen, RH Hamre) USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-289, pp. 238–246. (Fort Collins, CO)

Speer JH, Brown PM, Krusic PJ, Grissino-Mayer HD (2006) Professional fieldweeks as an educational experience and a venue for explorative research: case study of the North American Dendroecological Fieldweek. Indiana State University, Department of Geography, Geology, and Anthropology, Professional Paper Series #23. (Terre Haute, IN)

Stephens SL, Skinner CN, Gill SJ (2003) Dendrochronology-based fire history of Jeffrey pine – mixed conifer forests in the Sierra San Pedro Martir, Mexico. *Canadian Journal of Forest Research* **33**, 1090–1101. doi:10.1139/X03-031

Swetnam TW (2005) Fire histories from pine-dominant forest in the Madrean Archipelago. In 'Connecting Mountain Islands and Desert Seas: Biodiversity and Management of the Madrean Archipelago II. 5th Conference on Research and Resource Management in the Southwestern Deserts'. 11–15 May 2004, Tucson, AZ. (Eds GJ Gottfried, BS Gebow, LG Eskew, CB Edminster) USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-36, pp. 35–43. (Fort Collins, CO)

Swetnam TW, Baisan CH (2003) Tree-ring reconstructions of fire and climate history in the Sierra Nevada and Southwestern United States. In 'Fire and Climatic Change in Temperate Ecosystems of the Western Americas'. (Eds TT Veblen, WL Baker, G Montenegro, TW Swetnam) pp. 158–195 (Springer-Verlag: New York)

Swetnam TW, Betancourt JL (1990) Fire–Southern Oscillation relations in the southwestern United States. *Science* **249**, 1017–1020. doi:10.1126/SCIENCE.249.4972.1017

Taylor AH, Beaty RM (2005) Climatic influences on fire regimes in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA. *Journal of Biogeography* **32**, 425–438. doi:10.1111/J.1365-2699.2004.01208.X

Taylor AH, Skinner CN (2003) Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. *Ecological Applications* **13**, 704–719. doi:10.1890/1051-0761(2003)013[0704:SPACOH]2.0.CO;2

Van Horne ML, Fulé PZ (2006) Comparing methods of reconstructing fire history using fire scars in a southwestern United States ponderosa pine forest. *Canadian Journal of Forest Research* **36**, 855–867. doi:10.1139/X05-289

Veblen TT, Hadley KS, Nel EM, Kitzberger T, Reid MS, Villalba R (1994) Disturbance regime and disturbance interactions in a Rocky Mountain subalpine forest. *Journal of Ecology* **82**, 125–135. doi:10.2307/2261392

Villanueva-Diaz J, Stahle DW, Luckman BH, Cerano-Paredes J, Therrell MD, Cleaveland MK, Cornejo-Oviedo E (2007) Winter–spring precipitation reconstructions from tree rings for northeast Mexico. *Climatic Change* **83**, 117–131. doi:10.1007/S10584-006-9144-0

Yocom LL, Fulé PZ (2012) Human and climate influences on frequent fire in a high-elevation tropical forest. *Journal of Applied Ecology* **49**, 1356–1364. doi:10.1111/J.1365-2664.2012.02216.X

Yocom LL, Fulé PZ, Brown PM, Cerano-Paredes J, Villanueva J, Cornejo-Oviedo E, Falk DA (2010) El Niño–Southern Oscillation effect on a fire regime in northeastern Mexico has changed over time. *Ecology* **91**, 1660–1671. doi:10.1890/09-0845.1