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Fire history along environmental gradients in the Sacramento Mountains, New Mexico: Influences of local patterns and regional processes[1]

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Abstract: Patterning in fire regimes occurs at multiple spatiotemporal scales owing to differences in scaling of local and regional influences. Local fire occurrence and behavior may be controlled largely by site factors, while regional climate and changes in human land use can synchronize fire timing across large areas. We examined historical patterns in fires during the past five centuries across gradients in forest types and physiography and in relation to regional climate variability and land use change in the Sacramento Mountains in southern New Mexico. Forest stand-level chronologies of fires were reconstructed for 19 pinyon-juniper, ponderosa pine, and mixed-conifer stands using fire-scar records in crossdated tree-ring series. The fire history documents both local and regional factors effected fire occurrences in stands. Lower-elevation stands recorded more frequent fire than higher-elevation stands, although there were not significant differences between means of fire frequencies from clusters of ponderosa pine and mixed-conifer stands. Mean fire intervals ranged from approximately 3 to 11 years in ponderosa pine sites to 4 to 14 years in mixed-conifer sites. Sites on the steeper west side of the range, where fire spread more readily between forest types, recorded significantly more frequent fire than sites on the more physiographically heterogeneous east side. Fires were also synchronized by regional factors. Fire occurrences and fire-free years are related to variability in both annual Palmer Drought Severity Indices and El Niño-Southern Oscillation events. Fire regimes in the stands were also profoundly effected by changes in human land use patterns, with fire cessation in all sites following intensive Euro-American settlement beginning in the 1880s.
Keywords: dendroecology, crossdating, fire regimes, fire history, fire scars, spatiotemporal scales, ponderosa pine, mixed-conifer, pinyon-juniper, New Mexico.

Résumé : Les patrons résultant des régimes d'incendies s'expriment à de multiples échelles spatiotemporelles en raison des différences entre les influences locales et régionales. L'incidence et le comportement des feux à l'échelle locale peuvent être largement contrôlés par des facteurs stationnels. Par ailleurs, le climat régional et les changements d'utilisation anthropique du territoire peuvent synchroniser l'incidence des feux sur de grandes superficies. Les patrons historiques des feux au cours des cinq derniers siècles le long de gradients de types de forêts et de physiographie ont été mis en relation avec la variabilité climatique régionale et les changements d'utilisation du territoire dans les montagnes Sacramento du sud du Nouveau-Mexique. Des chronologies de feux ont été construites à l'échelle du peuplement chez 19 forêts de pinyon-genévrier, de Pin ponderosa, et de conifères mixtes à l'aide de cicatrices de feux de séries dendrochronologiques interdatées. L'historique des feux montre que les facteurs locaux et régionaux ont influencé l'incidence des incendies. Les peuplements situés à basse altitude ont enregistré des fréquences de feux plus élevées que les peuplements de haute altitude. Cependant, il n'y a pas de différence significative entre les moyennes des fréquences de feu de groupements de peuplements de Pin ponderosa et de peuplements conifériens mixtes. L'intervalle moyen entre deux feux varie entre 3 et 11 ans dans les peuplements de Pin ponderosa et 4 et 14 ans dans les peuplements conifériens mixtes. Les sites localisés sur la pente plus abrupte du versant ouest, où les feux vont plus souvent d'un type de couvert forestier à un autre, ont enregistré des feux significativement plus fréquents par rapport aux sites localisés sur le versant est, où la physiographie est plus hétérogène. Les incendies sont également synchronisés par des facteurs régionaux. L'incidence des feux et l'occurrence d'années sans feu sont toutes deux reliées à la variabilité de l'indice de sévérité de sécheresse de Palmer et aux événements El-Niño. Les régime d'incendies dans les peuplements sont également affectés par les changements du patron d'utilisation anthropique du territoire. Les feux ont cessé dans tous les sites colonisés par les Euro-américains dans les années1880.
Mots-clés : dendroécologie, interdatation, régimes d'incendies, historique des feux, cicatrices de feu, échelles spatiotemporelles, pin ponderosa, pinyon-genévrier, Nouveau-Mexique.

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Introduction

Parameters of fire regimes, including fire frequency, spatial extent of burned areas, fire severity, and season of fire occurrence (Pickett & White, 1985), vary at multiple spatiotemporal scales owing to differences in scaling of environmental forcing factors. At small spatial (0.01 to 10 ha) and short temporal (daily to monthly) scales, local vegetation and physiography largely control the occurrence, spread, and severity of individual fires by influencing fuel type, amount, arrangement, and connectivity. Annual weather patterns and climate regimes which vary along elevation gradients further control fuel moisture and fire ignitions on seasonal time scales. However, at landscape to regional scales (> 10^5 ha), changes in synoptic climate or human land use may override local controls and result in widespread fire synchrony (or fire cessation) on longer time scales (Clark, 1990; Swetnam & Betancourt, 1990; Johnson & Larsen, 1991; Swetnam, 1993; Bessie & Johnson, 1995; Veblen, Kitzberger, & Donnegan, 2000).

Isolated mountain ranges of southern New Mexico and Arizona, often referred to as "sky islands" (DeBano *et al.*, 1995), support extensive forests surrounded by desert or grassland ecosystems. Forests in these ranges occur as recognizable bands of tree species distributed along elevation and topographic gradients. Changes in elevation integrate changes in local climate regimes that effect plant reproduction, establishment, growth, and mortality (Shreve, 1915; Whittaker & Niering, 1975; Peet, 1981). With increases in elevation, local conditions become cooler and wetter and forests generally increase in species composition, density, and productivity. Physiography further influences vegetation patterns, with moister conditions on north-facing than on south-facing aspects in these dry, warm mountains.

Environmental factors controlling plant demography across elevation gradients are also thought to influence the occurrence and spread of fires (Barton, 1993; Peet, 1981). Changes in precipitation and temperature with elevation affect fuel quantity and its ability to burn. Both woody and fine fuels typically increase with elevation because of increases in tree density and understory productivity. However, moister conditions in upper-elevation forests also result in fewer years when fuels are dry enough to permit fire to spread after ignition. Differences in characteristics of needle litter, such as bulk density, surface-to-volume ratios, and heat content (Rothermel, 1972), of different species occurring along elevation gradients also contribute to differences in fire potential (*sensu* Mutch, 1970). Litter from long-needled *Pinus* forests at lower elevations are more flammable than short-needled species in mixed-conifer forests at higher elevation (Mutch, 1970; Wright & Bailey, 1982). Generally, fire frequency decreases with increased elevation while fire severity may increase because of higher fuel loadings and longer periods between fires (Peet, 1981; Wright & Bailey, 1982). Longer periods between fires may also lead to more extensive fires since fuels and forest structure may be more continuous across a landscape.

In this study, we develop fire chronologies that span the past three to five centuries from 19 stands in conifer forests of the Sacramento Mountains in southern New Mexico (Figure 1). Fire events are reconstructed using fire-scar records from dendrochronologically crossdated tree-ring series. Our principal goal with this study is to determine the relative influences of local and regional factors on fire occurrences and how these influences may have varied through time. To assess the effects of site factors that we expect influenced fires in individual stands, we compare fire frequency from stands in different forest types occurring along simple gradients in elevation and physiography from west to east across the mountain range. We chose these gradients to predict how site factors (*sensu* McCune & Allen, 1985) are related to fire occurrence. Our hypotheses are that elevation, forest type, and landscape position would show significant relationships with fire frequency. The Sacramento Mountains rise abruptly from the adjacent desert basin on their western side while to the east there is a more gradual slope (Figures 1 and 2). Forest types on the western escarpment of the main range are restricted to fairly narrow elevational bands but on the east side are more widespread. We expect fire to have been more common in both warmer and drier low-elevation forests and in stands on the west side where fire spread could have occurred more readily.

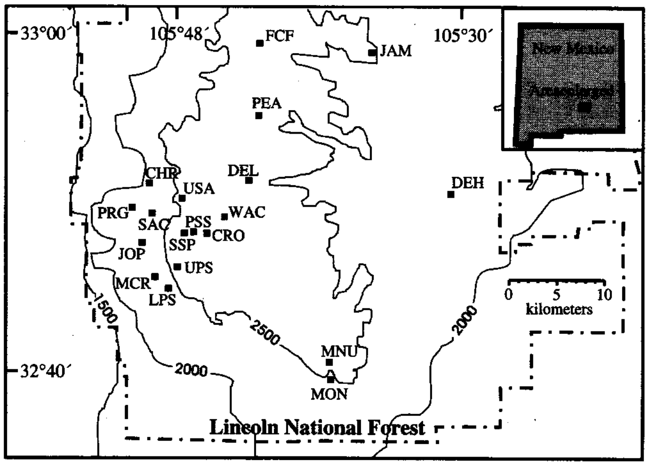

FIGURE 1. Locations of fire history sites in the Sacramento Mountains. Contour lines (solid line) are every 500 m.

To assess regional influences on fire occurrences, we compare variability in fire timing to regional climate and large-scale shifts in land use which occurred with Euro-American settlement of this area in the late nineteenth century. We expect to see relationships between regionally extensive fires and annual variability in moisture regimes (Swetnam & Baisan, 1996), particularly those related to the El Niño-Southern Oscillation (ENSO; Swetnam & Betancourt, 1990). We also expect to see a general cessation of fires corresponding to widespread Euro-American settlement beginning in the late 1800s. Recent cessation of historical patterns of fires is a common pattern in forests of the western U.S.A. and can be related to changes in land use and fire suppression (Swetnam, 1993; Swetnam & Baisan, 1996; Brown & Sieg, 1999; Covington *et al.*, 1997; Fulé, Covington & Moore, 1997). Data from this study provide information on the historical range of variability (Morgan *et al.*, 1994) in fire regimes of this area, critical information for use in forest management in the sky islands of the Southwest (Kaufmann *et al.*, 1998).

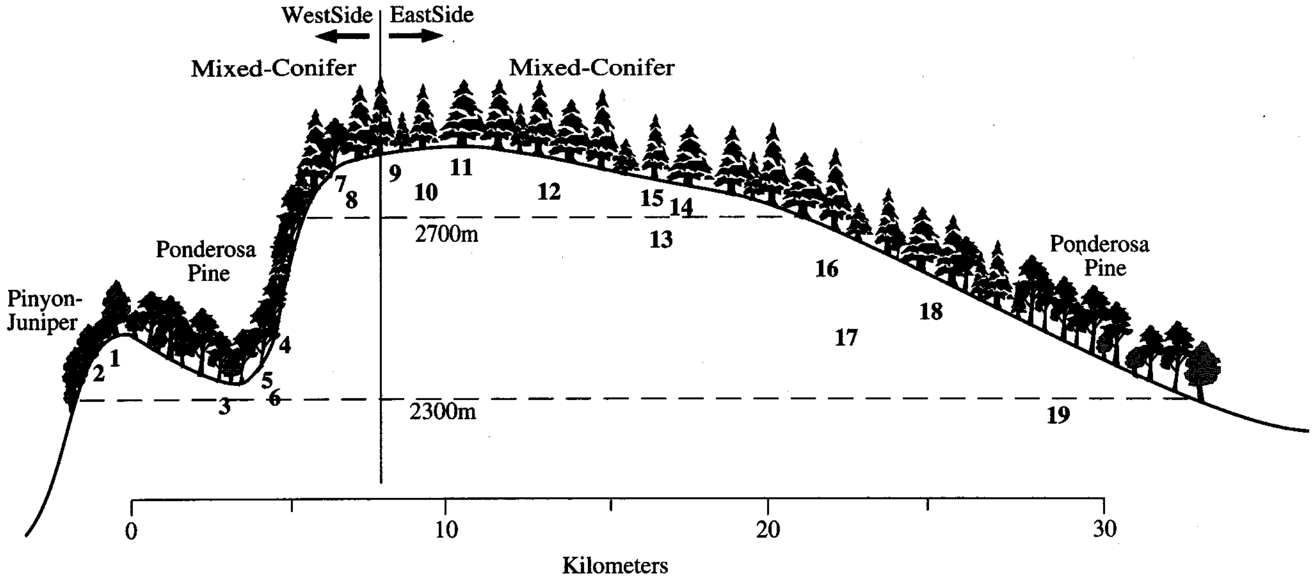

FIGURE 2. Schematic locations of fire history sites across forest types. Vertical exaggeration is 15×. Numbers correspond to sites in Table I.

Material and methods

STUDY AREA

The Sacramento Mountains are located at the southeastern edge of the Basin and Range physiographic province. The range includes Sierra Blanca peak to the north and a more massive central range in the south (area shown in Figure 1). Sierra Blanca is the highest point in the range at 3050 m; the highest elevations to the south are around 2900 m. The main range is bordered by a steep, stepped escarpment on the west side rising abruptly over 1600 m above the Tularosa Basin, and a gradual slope to the east descending to the Pecos River over a distance of approximately 150 km (Figure 2). The main range is characterized by steep and rugged topography, with several deep canyons draining to the east.

Forest types in the Sacramento Mountains are similar to those of adjacent sky islands to the west and north (Alexander *et al.*, 1984; Dick-Peddie, 1993; Figure 2). Lowest forest borders are defined by pinyon-juniper woodlands dominated by alligator juniper (*Juniperus deppeana* Stend.) and pinyon (*Pinus edulis* Engelm.). Ponderosa pine (*P. ponderosa* var. *scopulorum* Engelm.) forests occur above the pinyon-juniper woodlands and at lower elevations in mesic canyons. Gambel oak (*Quercus gambelii* Nutt.) is a common understory component with ponderosa pine. As elevation increases, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), southwestern white pine (*P. strobiformis* Engelm.), and white fir (*Abies concolor* [Gord. and Glend.] Lindl. ex Hildebr. var. *concolor*), become more common and form the major components of mixed-conifer forests. Mixed-conifer stands include to a lesser extent ponderosa pine and occasionally aspen (*Populus tremuloides* Michx.). Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) - subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) forests occur above 3000 m on Sierra Blanca. Engelmann spruce without subalpine fir occurs occasionally in mixed-conifer stands in the main range.

Climate regimes in the Sacramento Mountains vary considerably as a function of elevation (Figure 3). Mean annual precipitation ranges from 500 mm to 750 mm over the forested area (Karl *et al.,* 1983), with 60% to 70% of total precipitation received as rain from convective monsoonal storms from July to September (Alexander *et al.,* 1984). Remaining annual precipitation falls in the period from October to March as rain or snow. Snowpack is usually low except at the highest elevations. After spring snowmelt, May and June are often hot and very dry. "Dry" lightning storms can be common before the onset of the summer monsoons and often lead to widespread fire ignitions (Barrows, 1978).

Euro-American settlement of the Sacramento Mountains intensified after subjugation of native Apache tribes in the 1880s. Prior to this time, the Mescalero Apache used the southern and western portions of the range as a strong-

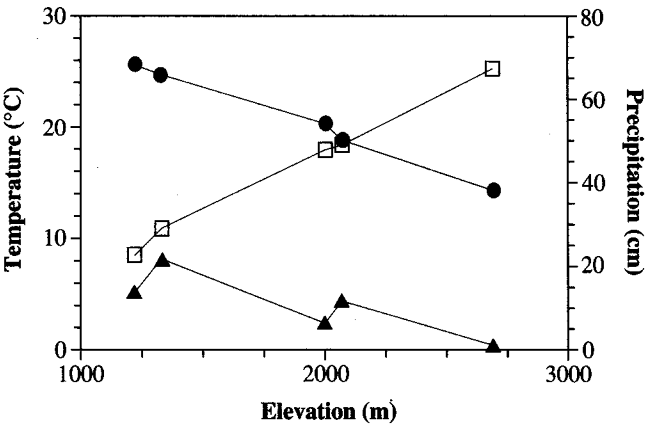

FIGURE 3. Average maximum July temperatures (●), minimum January temperatures (▲), and average annual precipitation (□) from five climate stations in and near the Sacramento Mountains. Stations, locations, and elevations are: White Sands National Monument in the Tularosa Basin 50 km west of the range at 1220 m; Alamogordo at the base of the west side at 1330 m; Mountain Park on the western escarpment at 2070 m; Cloudcroft, located on the crest at 2690 m; and Mayhill at the eastern edge at 2000 m. Mountain Park, Cloudcroft, and Mayhill are in forested areas.

hold where they could take refuge from attacks or flee from surrounding Spanish, Mexican, and later American settlements (Thomas, 1969; Betancourt, 1981; Kaye & Swetnam, 1999). Land use during the twentieth century has profoundly changed the forest structure (Regan, 1997; Kaufmann *et al.*, 1998). Intensive logging accompanied construction of a railroad network from 1898 to the 1920s (Glover, 1984; Kaufmann *et al.*, 1998). Heavy livestock grazing in the late 1800s and early 1900s (Cox, 1959) reduced grass and herbaceous cover. Present-day forests are generally dense with many young, small-diameter trees (Regan, 1997; Kaufmann *et al.*, 1998), as in most areas of low-elevation forest in the southwest and western U.S.A. which have experienced intensive logging and fire suppression over the past century (Arno *et al.*, 1995; Covington *et al.*, 1997; Brown *et al.*, 2001).

SELECTION OF SITES FOR FIRE CHRONOLOGIES

We collected fire-scarred trees from 19 sites in the main range of the Sacramento Mountains (Figures 1 and 2; Table I). Selection of sites was based primarily on stands that fit gradients in forest types from west to east across the mountain range (Figure 2). Our strategy during collection at each site was to obtain stand-level, long-term inventories of past fires using fire-scar records found on individual trees (Brown & Sieg, 1996; Swetnam & Baisan, 1996). A fire scar results when surface fire kills a portion of a tree's cambium, forming a characteristic lesion visible in its tree-ring series. Sites from which trees were collected varied from 10 to 30 ha in size, *i.e.*, the scale of forest stands. Stand-level inventories of fire events were reconstructed because fire-scar records from individual trees may be incomplete. Not all fires that burn at the base of a tree may be recorded as scars, and scars may be burned off or eroded. We attempted to maximize both the completeness and length of the fire inventory from each site by collecting multiple trees and compiling all fire-scar dates into a single fire chronology (Dieterich, 1980). Sites were selected in pinyon-juniper, ponderosa pine, and mixed-conifer stands on the west side of the main range and in ponderosa pine and mixed-conifer stands on the east side (Table I, Figure 2). Fire-scar records were difficult to locate in pinyon-juniper woodlands. Several of the sites were transitional between forest types and were classified based on habitat types (Alexander *et al.*, 1984; W. Moir, pers. comm.).

DEVELOPMENT OF FIRE CHRONOLOGIES

At each site selected for fire history reconstruction, we cut partial or full cross-sections from fire-scarred trees using chain-saws. We relied heavily on dead material to minimize cutting on living old-growth trees and to extend fire chronologies as far into the past as possible. Cross sections were surfaced using combinations of power planers, belt sanders, and hand sanding until cell structure was visible in tree rings. Tree-ring series and fire scars recorded within them were crossdated using standard dendrochronological methods (Stokes & Smiley, 1968). Positions of fire scars within annual rings were assigned when possible to assess seasonality of past fires. Time spans of individual trees and dates of fire scars were compiled into a fire chronology for each site using program FHX2 (Grissino-Mayer, 1995).

MEASURES OF FIRE FREQUENCY

To compare fire frequencies across elevations, forest types, and physiographic gradients, we used three measures to describe surface fire frequency for periods of analysis within fire chronologies. We determined periods of analysis

TABLE I. Sites collected for Sacramento Mountains fire history. Numbers correspond to site locations in Figure 2.

Site name	Site code	aspect(s)	Elevation range (m)	Dominant tree species [1]
West side pinyon-juniper stands:				
1. Long Ridge	PRG	SE, NE	2400 - 2440	PIED, JUDE, PIPO
2. Joplin Ridge	JOP	NE, SE	2400 - 2430	PIED, JUDE
West side ponderosa pine stands:				
3. Cherry Canyon	CHR	N, NW	2190 - 2260	PIPO, QUGA
4. Lower San Andreas Canyon	SAC	SW, S	2300 - 2490	PIPO, QUGA
5. Lower Pine Spring Canyon	LPS	S, W	2230 - 2320	PIPO, PIED, JUDE
6. Lower Escondido Canyon	MCR	W, NW	2200 - 2250	PIPO, PIED, JUDE
West side mixed-conifer stands:				
7. Upper San Andreas Canyon	U.S.A.	S, SW	2710 - 2790	PSME, ABCO, PIPO, PIST
8. Upper Pine Spring Canyon	UPS	S, SW	2710 - 2740	PSME, PIST, PIPO
East side mixed-conifer stands:				
9. Sunspot	SSP	W	2800 - 2870	ABCO,PSME, PIST
10. Pines at Sunspot	PSS	S	2790 - 2820	PIPO, PSME, ABCO
11. Cosmic Ray Observatory	CRO	W, SW	2860 - 2880	ABCO, PSME, POTR
12. Water Canyon	WAC	SE	2700 - 2750	ABCO, PSME
13. Delworth	DEL	S	2570 - 2590	ABCO, PSME, PIST
14. Peake Canyon	PEA	S, W	2630 - 2710	PSME, PIST, ABCO
15. Fir Campground	FCF	S, W	2640 - 2740	PSME, ABCO, PIST, PIPO
16. Monument Canyon Upper	MNU	N,E	2520 - 2590	PSME, ABCO, PIST, POTR
East side ponderosa pine stands:				
17. Monument Canyon	MON	SW	2420 - 2430	PIPO, PSME
18. James Ridge	JAM	S, SE	2500 - 2580	PIPO, JUDE, QUGA, PSME
19. Denny Hill	DEH	N, NE	2270 - 2320	PIPO, QUGA, JUDE

[1] Codes for dominant tree species are: ABCO: *Abies concolor*, JUDE: *Juniperus deppeana*, PIED: *Pinus edulis*, PIPO: *Pinus ponderosa*, PIST: *Pinus strobiformis*, POTR: *Populus tremuloides*, PSME: *Pseudotsuga mensiezii*, QUGA: *Quercus gambellii*.

for each fire chronology based on a minimum of four trees in the chronology. Periods of analyses were pre-Euro-American settlement because of the general lack of fire scars recorded during the twentieth century. We calculated mean fire intervals (MFI) as the average number of years between fire dates during each period of analysis. MFI has been widely used to describe fire frequency in fire history studies (Romme, 1980; see also summary of studies in Heyerdahl, Berry & Agee, 1995). Variability in fire intervals is described by the standard deviation and range of intervals. We also calculated Weibull median probability intervals (WMPI; Grissino-Mayer, 1999) as the fire interval associated with the 50% exceedance probability of a modeled Weibull distribution of fire intervals. WMPI is considered to be a better estimator of central tendency in fire interval data because of potential skew in interval distributions (Grissino-Mayer, 1999). If fire intervals are distributed normally, MFI and WMPI will be the same. Variability with the Weibull model is described by the 5% and 95% exceedance intervals. Program FHX2 (Grissino-Mayer, 1995) was used to calculate MFI and WMPI for each site. The third measure of fire frequency was a regression-derived statistic that permits both statistical and graphical assessments of changes in fire frequency through time (Brown, Kaufmann & Shepperd 1999; Brown & Sieg, 2000). This descriptor is the number of fires per year estimated from the slope of a linear regression fit through a cumulative sequence of fire dates. Piecewise linear regression procedures (Neter, Wasserman & Kutner, 1989) were used to estimate significant changes in slopes of cumulative fire dates.

Possible differences in fire frequency between sites in ponderosa pine and mixed-conifer stands, and from the west side to the east side of the range, were assessed using a one-way analysis of variance. The statistical null hypotheses of no significant differences in WMPIs between sites ($p < 0.01$) based on forest type or physiographic position was tested. Means of WMPIs were used to compare groups of sites. We also assessed influence of elevation on WMPIs using simple linear regression.

CHARACTERIZING FIRE-CLIMATE RELATIONSHIPS

We evaluated the influence of regional climate on fire occurrences using superposed epoch analyses (SEA; Swetnam, 1993). SEA was conducted using both fire and non-fire event years against independent tree-ring based reconstructions of Palmer Drought Severity Index (PDSI; Cook *et al.*, 1996) and the Southern Oscillation Index (SOI; Stahle & Cleaveland, 1993). Years between 1700 to 1900 when fire scars were recorded at an arbitrary minimum of 25% of the sites were designated fire event years, while years when no fires were recorded at any site were designated non-fire event years. SEA tests a statistical null hypothesis that no short-term (< 10 years) relationship existed between fire or non-fire years and annual climate. We used the program EVENT (Holmes & Swetnam, 1994) to identify patterns between event years and an eight-year window of climate values: five years prior to the event year, the event year, and two years following. Confidence intervals were determined using mean climate values and variances calculated from 1000 randomly selected event data sets with the same number of event dates as the tested fire or non-fire event data. Reconstructed PDSI values from 33° N, 104.5° W (Cook *et al.*, 1996) were selected based on the grid point's proximity to the study area. A tree-ring reconstruction of winter Southern Oscillation Index (SOI) from 1699 to 1971 (Stahle & Cleaveland, 1993) was used to compare historical SOI patterns with event years. Positive values of SOI indicate La Niña (cold) events while negative values indicate El Niño (warm) events.

Results

We crossdated 265 trees which had recorded 1501 fire scars from 19 sites in the Sacramento Mountains. Fire chronologies from 17 ponderosa pine and mixed-conifer stands are shown in Figure 4. The number of trees per year

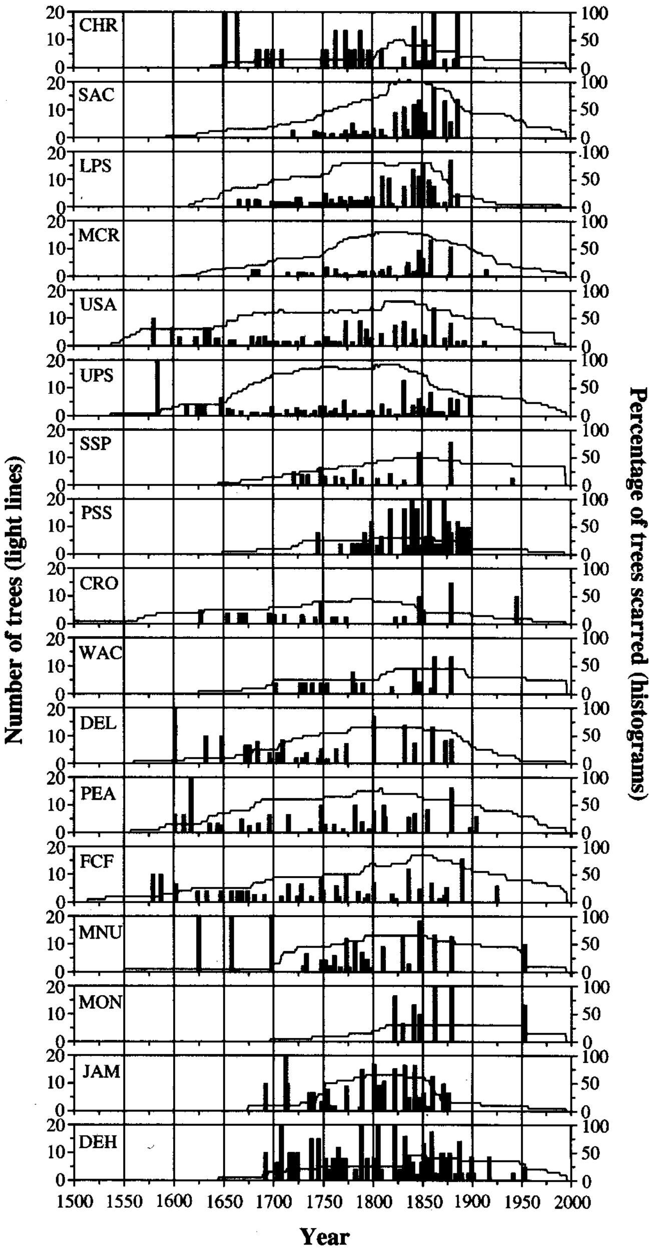

FIGURE 4. Fire chronologies from 17 ponderosa pine and mixed-conifer stands. Irregular light lines are numbers of trees per year of chronologies. Histograms are percentages of fire scars recorded by trees for each year relative to the number of trees.

is lowest in the earliest part of each chronology and reflects the difficulty in finding older fire-scarred material. The number of trees is also lower in the latter part of the chronologies and reflects the lack of living fire-scarred trees as a result, in part, of past logging. Only 43 trees from the 17 sites were living, comprising 16% of trees collected. A summary of fire chronologies with landscape-scale fire years (recorded at ≥ 25% of the sites) is shown in Figure 5. A prominent gap in landscape fires is evident between 1801 and 1832.

In the first two sections below, we describe results from 17 sites in east and west side ponderosa pine and mixed-conifer stands in the main part of the range. Fire chronologies from two pinyon-juniper sites on the west side, sites JOP and PRG (Table I), were not included in these analyses because of low numbers of crossdated trees and potential under-representation of stand-level fire dates. Fire history from these sites will be described in a separate section below.

LOCAL PATTERNS IN FIRE CHRONOLOGIES

Variability in fire frequency among stands did not differ by forest type but was related to elevation and physiographic position on the mountain range. There was only a weak relationship between elevation and Weibull median probability intervals (WMPIs; Figure 6). Fire was generally less frequent in higher elevation sites but there was large variability in fire frequency along the elevational gradient. WMPIs did not differ significantly for ponderosa pine and mixed-conifer stands but were significantly lower for sites on the west side than on the east side (Table II). Although mixed-conifer stands tended to record longer intervals between fires, higher fire frequency was recorded at sites PSS and MNU (at least before 1810; Table II) than at other mixed-conifer sites on the east side. Sites CHR and MON also recorded lower fire frequency than other ponderosa pine sites (Table II).

Standard deviations and ranges of fire intervals often document large variability between fires in individual sites (Table II). Linear regressions fit through cumulative fire dates emphasize synchronous and asynchronous patterns in fire occurrences within and between stands (Figure 7). Many sites recorded long intervals between fires in the early 1800s, and two sites, LPS and MNU, recorded pro-

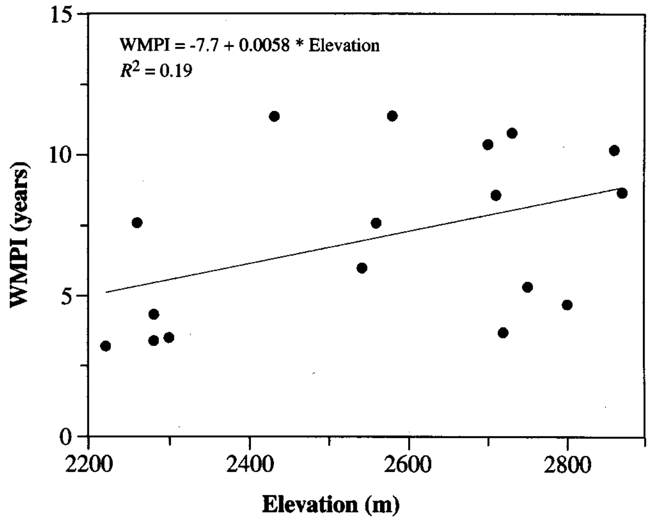

FIGURE 6. Weibull median probability intervals (WMPI) for 17 ponderosa pine and mixed-conifer sites by elevation. Regression is significant at $p = 0.08$.

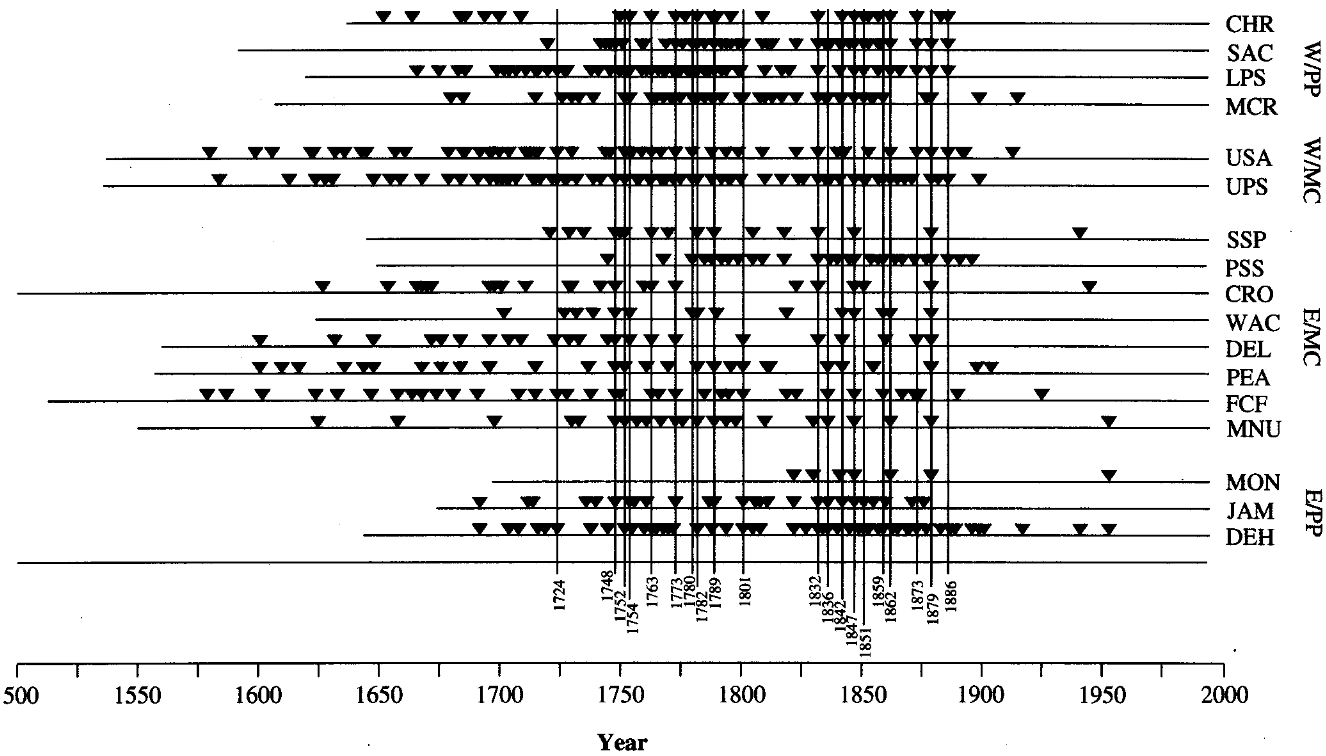

FIGURE 5. Landscape fire years (vertical lines) recorded by trees in ≥ 25% of the 17 ponderosa pine (PP) and mixed-conifer (MC) sites on the west (W) and east (E) sides. Time spans of fire chronologies are represented by horizontal lines with fire dates represented by inverted triangles.

TABLE II. Measures of historical fire frequency for fire history sites. Fire intervals used in calculations are for all fire dates recorded at each site during the period of analysis.

Site	Period of analysis	Number of intervals	MFI ± SD [1]	Range of intervals [2]	WMPI [3]	5% to 95% probability interval [4]	Fire frequency (from Figure 7) [5]
West side ponderosa pine stands:							
CHR	1652 to 1886	26	9.0 ± 8.3	2 to 41	7.6	1.7 to 18.0	0.109
SAC	1742 to 1886	37	3.9 ± 2.7	1 to 11	3.5	1.0 to 7.3	0.264
LPS 1	1699 to 1800	39	2.6 ± 1.8	1 to 10	2.4	1.0 to 4.9	0.380
LPS 2	1800 to 1886	13	6.6 ± 2.5	3 to 12	6.6	3.0 to 10.3	0.155
MCR	1730 to 1859	35	3.7 ± 2.8	1 to 13	3.2	1.0 to 7.6	0.283
West side mixed-conifer stands:							
U.S.A.	1580 to 1913	52	6.4 ± 4.9	1 to 20	5.3	1.0 to 14.9	0.176
UPS	1648 to 1899	61	4.1 ± 2.6	1 to 13	3.7	1.0 to 8.1	0.266
East side mixed-conifer stands:							
SSP	1721 to 1879	14	11.3 ± 7.5	2 to 32	10.2	2.2 to 24.4	0.094
PSS	1780 to 1896	24	4.8 ± 2.5	2 to 14	4.7	1.9 to 7.8	0.200
CRO	1627 to 1879	21	12.0 ± 12.1	1 to 50	8.7	1.0 to 30.1	0.089
WAC	1702 to 1879	14	12.6 ± 9.4	2 to 29	10.8	1.9 to 28.2	0.078
DEL	1601 to 1879	22	12.6 ± 8.7	3 to 31	11.4	2.9 to 24.7	0.086
PEA	1601 to 1904	27	11.2 ± 6.5	1 to 24	10.4	2.6 to 22.8	0.091
FCF	1579 to 1890	34	9.1 ± 4.9	2 to 22	8.6	2.5 to 17.3	0.115
MNU 1	1730 to 1810	13	6.2 ± 3.5	3 to 15	5.9	2.2 to 10.2	0.173
MNU 2	1810 to 1879	5	13.8 ± 5.5	6 to 20	13.8	5.3 to 23.7	0.076
East side ponderosa pine stands:							
MON	1822 to 1879	5	11.4 ± 4.6	6 to 17	11.4	4.7 to 18.7	0.088
JAM	1736 to 1876	22	6.4 ± 3.7	2 to 14	6.0	1.8 to 11.8	0.153
DEH	1692 to 1901	45	4.6 ± 3.1	1 to 14	4.3	1.3 to 8.4	0.220

[1] Mean fire interval and standard deviation of all intervals in composite fire chronology in years
[2] In years
[3] Weibull median (50% exceedance) probability interval in years
[4] Weibull 5% and 95% exceedance probability intervals in years
[5] Slope of line calculated from cumulative fire dates (number of fires $year^{-1}$)

nounced shifts in fire occurrence after the beginning of the 19th century (see also Figures 4 and 5; Table II). Several stands recorded more patchy fires (*i.e.*, fewer trees scarred) before 1800 and more widespread fires (*i.e.*, most trees scarred) after 1800, notably at sites SAC, LPS, MCR, U.S.A., UPS, DEL, PEA, and MNU (Figure 4).

Positions of fire scars within annual rings generally did not differ between groups of sites, although middle early-wood (M) fire scars occurred less often in mixed-conifer than ponderosa pine sites (Figure 8). Many fire scars were recorded as dormant season (occurring between two rings) and were assigned to the latter year (*i.e.*, to have been spring fires occurring before a growing season began) because of the greater number of early-earlywood and middle-earlywood scars recorded for other years and on other trees for the same year. We found very few late-earlywood or latewood scars (Figure 8).

REGIONAL PATTERNS IN FIRE CHRONOLOGIES

We found relationships between landscape fire and non-fire years and synoptic climate patterns. General patterns were of dry landscape fire years preceded by at least two relatively wet years (Figure 9). This pattern did not vary significantly with elevation (data not shown). We also found that years with no record of fire in any stand were strong or very strong El Niño years (the wet phase of SOI; Figure 10). We found no patterns between SOI and the landscape fire years, although many individual fire years were La Niña years (dry phase of SOI).

In addition to regional climate, we found only a few fire scars at any site during the twentieth century (Figures 4 and 5), coincident with Euro-American settlement and later management of the Sacramento Mountains. Fire-scars recorded during 1953 in several stands were the result of extensive fires over much of the range in that year.

FIRE PATTERNS IN PINYON-JUNIPER STANDS

Values of central tendency for fire frequency from pinyon-juniper sites (Table I) were not calculated because numbers of fire-scarred trees were not sufficient to characterize stand-level fire interval distributions. Instead, point fire intervals (Romme, 1980) for each pinyon tree recording multiple fire scars were calculated as the average interval between fire scars. Such data are likely conservative estimates of fire frequency since not every fire that burned at the base of a tree was necessarily recorded as a fire scar, and fire scars may be eroded or burned off a tree's surface. No fire-scarred juniper trees were successfully crossdated from the Sacramento Mountains owing to anomalous growth patterns (false and missing rings).

Of ten fire-scarred pinyon collected from sites PRG, JOP, and LPS, seven recorded multiple fire scars. The mean point fire interval for all trees was 27.5 years, with a range of intervals from 10 to 49 years. Nineteen fire dates were recorded by pinyon trees, five of which coincided with regional fire years from ponderosa pine and mixed-conifer sites (1724, 1847, 1851, 1859, and 1879; Figure 5). Age and stand structures of pinyon-juniper woodlands at the sites also suggest that a stand-replacing fire or other disturbance event occurred sometime within the past century. The majority of overstory trees appeared to be young with a marked absence of older living trees. Numerous dead and downed trees partially consumed by fire were present in many pinyon-juniper stands.

Discussion

FIRE HISTORY IN RELATION TO SITE FACTORS

Environmental gradients can provide insight into factors influencing disturbance regimes by accentuating changes in physical components which occur along the gradient (Shreve, 1915; Daubenmire, 1943; Whittaker & Niering, 1975; Barton, 1993). However, environmental factors unaccounted for by gradient and site histories can have a major influence in disturbance occurrence, with the result that predictability in patterns can be difficult to achieve (McCune & Allen, 1985). In this study, even relatively simple predictions about fire behavior in relation to elevation and forest type were only partially supported by the fire history. We expected to find less frequent fire in higher-elevation mixed-conifer forests where seasonal fuel moisture conducive to fire spread likely would have occurred less often than in lower-elevation ponderosa pine stands. However, we found no differences in fire frequency between ponderosa pine and mixed-conifer stands and only a weak relationship between fire frequency and elevation (Figure 6). Although ponderosa pine forests generally recorded more frequent fires than the mixed conifer stands, there was large variability within forest types (Table II). Swetnam and Baisan (1996) found similar weak relationships between fire frequency and both forest type and elevation in 63 ponderosa pine and mixed-conifer stands elsewhere in Arizona and New Mexico. Stands used in their study are from throughout the Southwest and regional variability in climate regimes was likely responsible for at least some of the variability in fire frequency. In our study, all stands are from the same mountain range and responding to the same meso-scale climate patterns, yet our results are similar to those found by Swetnam and Baisan (1996). Pre-settlement MFIs and WMPIs reported in Table II are comparable to those found by Swetnam and Baisan (1996) for other forests of the Southwest.

Higher fire frequency in stands on the steeper west side of the Sacramento Mountains than those on the more gradually sloping east side supports a role for local physiography in fire occurrence and spread (Figure 2, Table II). We expected that fire frequency was higher in forests of the western escarpment where fires have the potential to spread more readily because of shorter distances and fewer topographic breaks between stands. Topographically or vegetatively diverse landscapes result in smaller potential

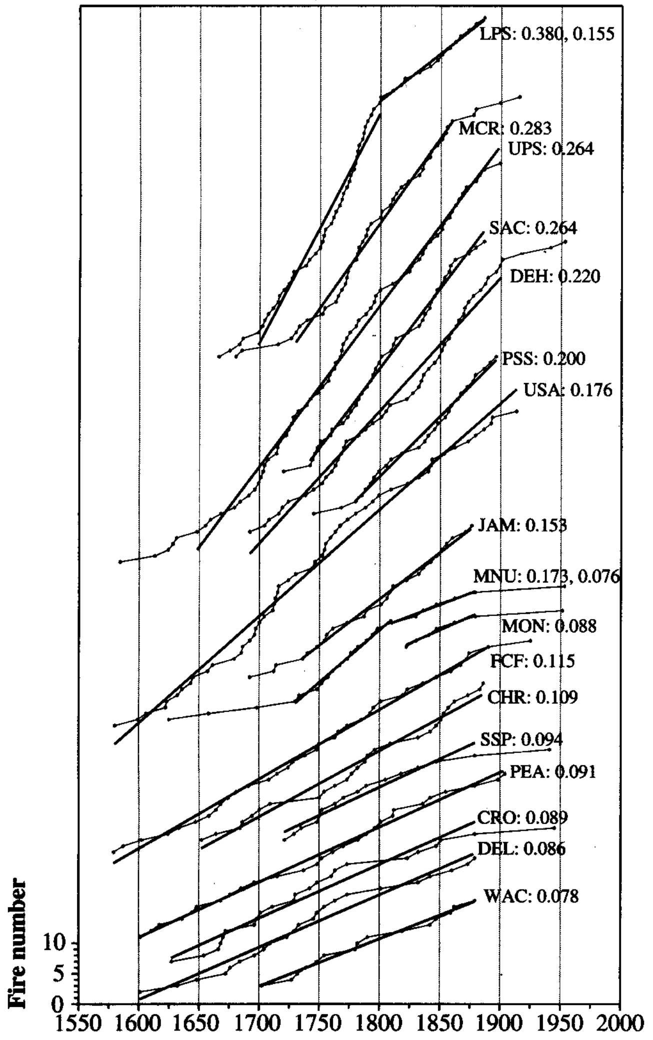

FIGURE 7. Fire frequency determined from linear regressions fit through cumulative fire dates for period of analysis in each fire chronology. Numbers for each site are regression slope, or numbers of fires per year. Heavy lines represent periods of analysis for chronologies. All fire dates are shown for each site but note that dates in the earliest portions of chronologies at LPS, MCR, UPS, SAC, PSS, JAM, and MNU do not fit longer trends in fire frequency, likely as a result of poor sample replication in these periods. Fire dates during the twentieth century in chronologies from MCR, DEH, MNU, MON, FCF, and SSP also do not fit longer trends seen during the pre-settlement period, likely as a result of post-settlement changes in land use (see discussion).

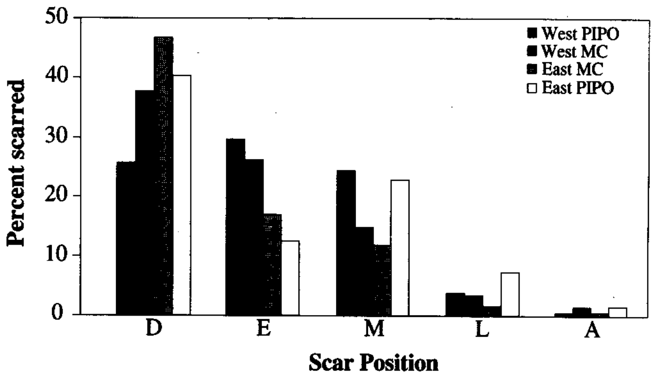

FIGURE 8. Fire-scar positions in annual growth rings from ponderosa pine (PIPO) and mixed-conifer (MC) sites on west and east sides. Fire-scar positions assigned were: D, dormant season between adjacent rings; E, early-earlywood, within the first third of the earlywood band; M, within the second third of earlywood; L, within the last third of earlywood; A, within the latewood band; or U (not shown), unknown position because of poor visibility of scar boundaries within rings. Dormant season scars were assigned to either the earlier or later year (*i.e.*, early spring fires that occurred before a growing season began, and late summer or early fall fires that occurred after a growing season ended) depending on the presence of early or late season fire scars on other trees for the same time period. Years in which only dormant season scars were recorded were assigned to the later year (*i.e.*, spring fires) because of the predominance of early season fire scars seen in the fire chronologies from the Sacramento Mountains, other mountain ranges in the southwestern U.S.A. (Swetnam & Baisan, 1996), and early season fires recorded in modern fire records (Swetnam & Betancourt, 1990).

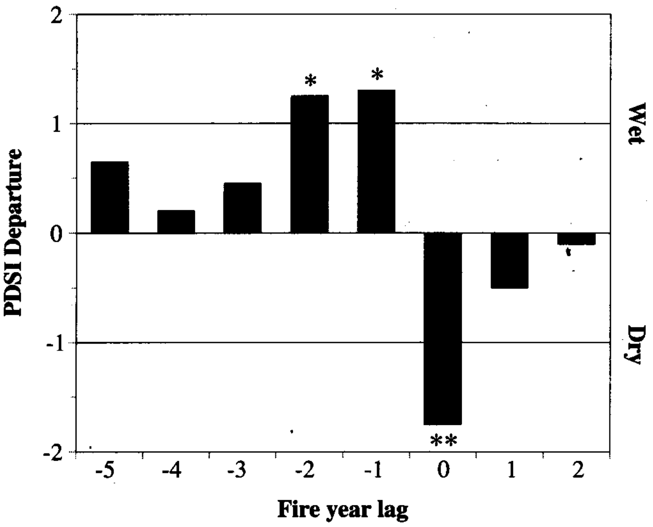

FIGURE 9. SEA of departures of PDSI values over an eight-year window around landscape-scale fire years (recorded at ≥ 25% of the sites) from 1700 to 1900 (n = 20; dates given in Figure 5). Fire year lags are: -5 to -1 = five years prior to fire years; 0 = fire year; 1 to 2 = two years following fire years. * = years in which departure of actual PDSI from simulated PDSI in SEA were significant at $p < 0.01$; ** = years where departure was significant at $p < 0.001$.

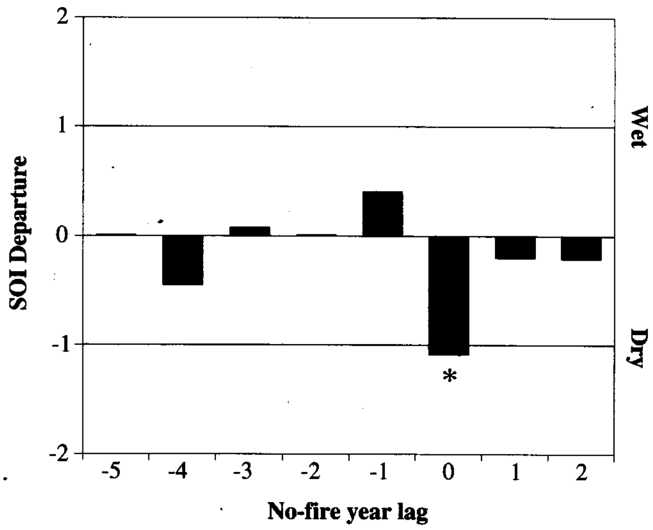

FIGURE 10. SEA of departures of reconstructed winter Southern Oscillation Index (SOI; Stahle & Cleaveland, 1993) values over an eight-year window around years when no fires were recorded in the Sacramento Mountains from 1700 to 1900 (n = 47). * = years in which departure of actual SOI from simulated SOI values in SEA were significant at $P = 0.01$.

"fire-sheds" across which fires may spread before encountering possible barriers (Brown & Sieg, 1996). Prevailing winds in the area are also from the west and may have contributed to increased fire spread between stands.

Variability in general trends along the elevational gradient (Figure 6, Table II) can be related in part to differences in physical environments, vegetation characteristics, or site histories. Site MON recorded less frequent fire than the other two ponderosa pine sites on the east side of the main range (Table II). Fire-scarred trees at MON were collected near the bottom of a canyon where locally mesic conditions likely resulted in fewer opportunities for fire spread. Site CHS had lower fire frequency than other ponderosa pine stands on the west side (Table II). CHS is located near the bottom of a sloped bench above a steep escarpment (Figure 2). The location of this site suggests that fires may have been limited by the reduced area available for lightning strikes or otherwise restricted fire spread from adjacent areas. Differences in fuel characteristics of tree species may also result in differences in potential for fire occurrences. Site PSS was one of the highest elevation mixed-conifer stands (Table I, Figure 2), but trees there recorded the highest fire frequency of any mixed-conifer site on the east side (Table II). This stand was never logged and the present-day forest is dominated by ponderosa pine, although small-diameter Douglas-fir and white fir have established over the past century as a dense, sub-canopy layer. Relatively more frequent fire at this site compared to adjacent mixed-conifer stands may have been the result of fuel dynamics established by ponderosa pine litter (*sensu* Mutch, 1970). Frequent surface fires likely resulted in positive feedback which maintained ponderosa pine dominance in this stand. In the absence of frequent fires since settlement, less fire-tolerant Douglas-fir and white fir are now becoming dominant in this high elevation site.

Higher fire frequencies in some sites may also have been related to increased ignitions as a result of use of this area by Mescalero Apache (Betancourt, 1981; Kaye & Swetnam, 1999). Comparisons between periods of known land-use by the Apache and variations in fire frequency suggest that the Apache may have increased fire occurrence in the second half of the eighteenth century in sites LPS, MCR, and CSU (Table II; Kaye & Swetnam, 1999)

Few studies have documented historical fires in pinyon-juniper woodlands. Fire-scarred alligator juniper trees are occasionally observed in the Southwest (Leopold, 1924), but because of irregular annual growth patterns (*i.e.*, false and missing rings), their rings usually cannot be crossdated. Fire-scarred pinyon pine are rare since fire often directly kills trees or indirectly causes tree mortality by increasing susceptibility to heart-rot fungi (Gottfried *et al.*, 1995). Although data found by this study are incomplete, they offer some insight into historical patterns. Fire intervals of approximately 25 to 30 years as we found on individual pinyon trees most likely would have maintained a savanna-like structure by thinning young trees that were not yet tall enough to survive (Leopold, 1924; Despain & Mosely, 1990; Gottfried *et al.*, 1995). Stand age structure and composition at pinyon-juniper sites also suggest that stand-replacing fires may have occurred, although an extensive outbreak of *Ips* beetles in pinyon-juniper woodlands during the 1920s (Kaufmann *et al.*, 1998) also may have contributed to widespread stand-opening with subsequent establishment. Evidence of infrequent stand-replacing fires in conjunction with patchy surface fires has been documented in pinyon-juniper woodlands of northern Arizona (Despain & Mosely, 1990). More extensive study of living tree age structure and death dates of dead trees are needed to determine the relative influences of stand-replacing and surface fires and other disturbances in pinyon-juniper woodlands in the Sacramento Mountains. Also, with the exception of the pinyon-juniper stands, we found no evidence of crown fires (based on the presence of even-aged forest structure) in any other site in the Sacramento Mountains. This result supports patterns found in all other studies of pre-settlement ponderosa pine and mixed-conifer forests in the Southwest that extensive crown fires were rare to non-existent.

Seasonal positions of fire scars in all stands suggest that the majority of fires occurred early in the growing season or before growth began for a year (Figure 8). Based on radial growth phenological data from nearby mountains (Fritts, 1976; Swetnam & Baisan, unpubl. data), ponderosa pine trees in the Southwest likely break growth dormancy in late April or early May during most years. Comparison of fire-scar positions with these phenological data suggest that a majority of past fires occurred between April and June. Fire records from the Lincoln National Forest from 1969 to 1994 also document that a majority (64%) of recent lightning fire ignitions occurred in the months of April, May, or June (Kaufmann *et al.*, 1998).

FIRE HISTORY IN RELATION TO REGIONAL CLIMATE AND LAND USE CHANGE

At a landscape scale and over longer periods, fire occurrence in the Sacramento Mountains was related to both climate variability and shifts in patterns of land use. These regional driving factors resulted in synchrony of fire and non-fire years across the mountain range. At an annual scale, years when landscape-scale fires were recorded were dry and these years were often preceded by at least two wet years (Figure 9). Wet conditions, especially those resulting from very strong or strong El Niño events (negative SOI in Figure 10), often resulted in lack of fires but also helped create a buildup of grasses and forbs which were the primary fuels for surface fires occurring in subsequent dry years (Swetnam & Betancourt, 1990). Many of the landscape fire years recorded in the Sacramento Mountains (Figure 5) were regional fire years over the Southwest as found by Swetnam and Baisan (1996).

Synchrony of shifts in decadal-scale patterns of fires at multiple sites further documents the influence of longer-term variability in synoptic climate and relations between fire occurrences over large areas. No landscape fires were recorded in the Sacramento Mountains between 1801 and 1832 (Figure 5) and shifts in both fire frequency and spatial patterns were recorded at several sites in the early nineteenth century (Figures 4 and 5). Fire chronologies from many areas of the Southwest recorded gaps in fire timing and changes in fire frequency in the early to mid-1800s, often followed by further changes in timing, spatial patterning, and/or seasonality of fires after this period (Allen, 1989; Touchan, Swetnam & Grissino-Mayer, 1995; Morino, 1996; Swetnam & Baisan, 1996; Swetnam & Betancourt, 1998; Grissino-Mayer & Swetnam, 2000). Grissino-Mayer and Swetnam (2000) propose that climate over the southwestern U.S.A. was transitional *ca.* 1790, switching from below normal to above normal rainfall, which can be related to mesoscale changes in atmospheric circulation patterns associated with summer monsoons and the Southern Oscillation (see also Swetnam & Betancourt, 1998).

The general and widespread cessation of fires at the end of the nineteenth century (Figures 4 and 8) corresponds to regional patterns seen in forests throughout the western U.S.A. (Savage, 1991; Swetnam, 1993; Swetnam & Baisan, 1996; Brown & Sieg, 1996; 1999; Brown, Kaufmann & Shepperd, 1999; Fulé, Covington & Moore, 1997; Grissino-Mayer & Swetnam, 2000). Cessation of surface fires usually coincided with the beginning of intensive livestock grazing and usually preceded, often by several decades (Savage, 1991; Touchan, Swetnam & Grissino-Mayer, 1995), the beginning of active fire suppression by land management agencies. Herbivory by livestock removes grasses and other fine fuels necessary for fire spread. In the Sacramento Mountains, intensive grazing began after settlement in the 1880s (Cox, 1959; Kaufmann *et al.*, 1998) and was usually concurrent with the last surface fires recorded at most of the sites. Changes in climate regimes may also have been a factor in fire cessation during the early twentieth century, as the period between 1905 and 1925 was very wet in the Southwest (Meko, Stockton & Boggess, 1995).

Conclusion

Understanding the relative influences of local and regional processes in structuring communities and ecosystems is an important goal in ecology (Ricklefs, 1987; Huston, 1999). Results from this study document large variability in fires related to differences in spatial and temporal scales of forcing factors. At stand scales, fire patterns are related to differences in elevation and landscape position, with fire occurring more commonly in lower-elevation forests and in forests where fire spreads more readily between stands. At a regional scale, fire patterns are related to longer-term shifts in synoptic climate and to changes in human land use. However, large variability in reconstructed fire frequencies both within and among stands also highlight heterogeneity in ecological processes which are not easily predicted by easily observable environmental variables (*sensu* McCune & Allen, 1985).

Following Euro-American settlement of the Sacramento Mountains beginning about 1880, changes in land-use became the dominant factor influencing fire occurrence, overriding virtually all other physical and climatological influences. Loss of surface fires, coupled with logging and grazing, has had profound effects throughout ecosystem structure and function in this area (Regan, 1997; Kaufmann *et al.*, 1998). Forest closure, shifts in species composition, and widespread crown fires in recent years point to changes in ecosystem function that may be unsustainable in the long-term (Kaufmann *et al.*, 1998). A historical perspective on ecosystems, as provided by this study, is therefore crucial for providing information on longer-term patterns of sustainable behavior which will prove useful for management and restoration of ecosystem processes (Committee of Scientists, 1999).

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