



Climatic influences on fire regimes in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA

A. H. Taylor* and R. M. Beaty

Department of Geography, The Pennsylvania State University, University Park, PA, USA

ABSTRACT

Aim The goal of this study was to understand better the role of interannual and interdecadal climatic variation on local pre-EuroAmerican settlement fire regimes in fire-prone Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) dominated forests in the northern Sierra Nevada Mountains.

Location Our study was conducted in a 6000-ha area of contiguous mixed Jeffrey pine-white fir (*Abies concolor* Gordon & Glend.) forest on the western slope of the Carson Range on the eastern shore of Lake Tahoe, Nevada.

Methods Pre-EuroAmerican settlement fire regimes (i.e. frequency, return interval, extent, season) were reconstructed in eight contiguous watersheds for a 200-year period (1650–1850) from fire scars preserved in the annual growth rings of nineteenth century cut stumps and recently dead pre-settlement Jeffrey pine trees. Superposed epoch analysis (SEA) and correlation analysis were used to examine relationships between tree ring-based reconstructions of the Palmer Drought Severity Index (PDSI), Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO) and pre-EuroAmerican fire regimes in order to assess the influence of drought and equatorial and north Pacific teleconnections on fire occurrence and fire extent.

Results For the entire period of record (1650–1850), wet conditions were characteristic of years without fires. In contrast, fire years were associated with drought. Drought intensity also influenced fire extent and the most widespread fires occurred in the driest years. Years with widespread fires were also preceded by wet conditions 3 years before the fire. Widespread fires were also associated with phase changes of the PDO, with the most widespread burns occurring when the phase changed from warm (positive) to cold (negative) conditions. Annual SOI and fire frequency or extent were not associated in our study. At decadal time scales, burning was more widespread during decades that were dryer and characterized by La Niña and negative PDO conditions. Interannual and interdecadal fire–climate relationships were not stable over time. From 1700 to 1775 there was no interannual relationship between drought, PDO, and fire frequency or extent. However, from 1775 to 1850, widespread fires were associated with dry years preceded by wet years. This period also had the strongest association between fire extent and the PDO. In contrast, fire–climate associations at interdecadal time scales were stronger in the earlier period than in the later period. The change from strong interdecadal to strong interannual climate influence was associated with a breakdown in decadal scale constructive relationships between PDO and SOI.

Main conclusions Climate strongly influenced pre-settlement pine forest fire regimes in northern Sierra Nevada. Both interannual and interdecadal climatic variation regulated conditions conducive to fire activity, and longer term changes in fire frequency and extent correspond with climate-mediated changes observed

*Correspondence: A. H. Taylor, Department of Geography, The Pennsylvania State University, University Park, PA, USA.

E-mail: aht1@psu.edu

Present address: R.M. Beaty, CSIRO Sustainable Ecosystems, GPO Box 284, Canberra, ACT 2601, Australia.

E-mail: matt.beaty@csiro.au

in both the northern and southern hemispheres. The sensitivity of fire regimes to shifts in modes of climatic variability suggests that climate was a key regulator of pine forest ecosystem structure and dynamics before EuroAmerican settlement. An understanding of pre-EuroAmerican fire–climate relationships may provide useful insights into how fire activity in contemporary forests may respond to future climatic variation.

Keywords

Climatic variation, dendrochronology, drought, El Niño/Southern oscillation, fire ecology, fire regimes, forest dynamics, global change, Jeffrey pine, Pacific decadal oscillation.

INTRODUCTION

Recurring fire is a keystone disturbance process that has influenced the structure, dynamics, and diversity of western USA forest ecosystems for millennia (Swetnam, 1993; Whitlock *et al.*, 2003). Although fire regimes (i.e. frequency, return interval, extent, season) are influenced by local controls such as topography (e.g. Taylor & Skinner, 1998, 2003; Taylor, 2000; Heyerdahl *et al.*, 2001), there is increasing evidence that temporal variation in fire regimes is linked to regional climatic variation (e.g. Baisan & Swetnam, 1990; Johnson *et al.*, 1990; Veblen *et al.*, 2000). The interaction between fire and climatic variation is complex (e.g. Swetnam, 1993; Veblen *et al.*, 1999; Grissino-Mayer & Swetnam, 2000; Norman & Taylor, 2003) and determining how climate modulates fire regimes is important for understanding both how forests developed before fire regimes were disrupted by twentieth century fire suppression (e.g. Millar & Woolfenden, 1999; Swetnam *et al.*, 1999), and how fire regimes may respond to future climate change (Price & Rind, 1994; Dettinger & Cayan, 1995; Stocks *et al.*, 1998; Leung & Ghan, 1999).

The relationship between pre-EuroAmerican settlement (hereafter pre-settlement) fire regimes and climatic variation has been studied extensively in ponderosa pine (*Pinus ponderosa* Laws) forests in the American Southwest (SW) (Swetnam & Betancourt, 1990, 1998; Brown *et al.*, 2001) and the southern Rocky Mountains (RM) (Veblen *et al.*, 2000; Donnegan *et al.*, 2001). In these areas, fire regimes are closely linked to interannual climatic variation generated by the El Niño/Southern Oscillation (ENSO). ENSO is a high frequency (i.e. 2–5 years) coupled ocean–atmosphere process in the eastern and central equatorial Pacific Ocean and, through teleconnections with mid-latitude climate systems, is the primary driver of North American interannual climatic variability (Diaz & Markgraf, 2000). During El Niño conditions (warm phase ENSO), the SW is typically wet, and dry conditions prevail during La Niña (cool phase ENSO) events (Kahya & Dracup, 1995). Years of widespread burning tended to occur during dry La Niña years, especially if they were preceded by one to several wet El Niño years (Swetnam & Betancourt, 1998; Veblen *et al.*, 2000). Increased production of

fine grass and needle fuels in wet years, and then drying of these fuels in dry years, may mechanistically link fire hazard with ENSO-related climatic variability in these forests (Swetnam & Betancourt, 1998).

Decadal scale linkages between fire regimes and climate have also been identified in the SW and the Pacific Northwest (PNW). In the SW, decades of weaker and less frequent warm to cool ENSO switching is thought to influence the stability of interannual relationships between the frequency and season of fire and climatic variables such as precipitation (e.g. Grissino-Mayer & Swetnam, 2000; Norman, 2002; Stephens *et al.*, 2003) and fire occurrence is generally lower during these periods (Swetnam & Betancourt, 1998; Grissino-Mayer & Swetnam, 2000; Swetnam & Baisan, 2003). In the PNW and SW, fire activity has also been linked to the Pacific Decadal Oscillation (PDO), an interdecadal ‘ENSO-like’ variation in north Pacific sea surface temperatures (SST) (Dettinger *et al.*, 2000) and associated atmospheric structures. When the PDO is in a warm phase, conditions in the SW are generally wetter than average, and they are dryer and warmer than average in the PNW. The opposite pattern occurs during a cool phase PDO (Gershunov *et al.*, 1999; Hamlet & Lettemeier, 1999; Nigam *et al.*, 1999). Thus, fire activity is high in the PNW when the PDO is warm (Hessl *et al.*, 2004) and in the SW when the PDO is cool (Westerling & Swetnam, 2003).

Pine-dominated forests in the Sierra Nevada Mountains of California historically burned every 2–20 years before fire regimes were disrupted by fire suppression and perhaps grazing in the late nineteenth and early twentieth centuries (e.g. Kilgore & Taylor, 1979; Parsons & DeBenedetti, 1979; Caprio & Swetnam, 1995; Skinner & Chang, 1996). The relationship between climate and fire regimes in Sierra Nevada pine forests is not well established, although ENSO and the PDO are recognized as important influences on California climate (e.g. Schoner & Nicholson, 1989; Mo & Higgins, 1998a; Cayan *et al.*, 1999; Nigam *et al.*, 1999). Fire activity in the southern Sierra Nevada forests has been linked to interannual drought and centennial scale variation in temperature (Swetnam, 1993), but fire–climate relationships at intermediate time scales have not been explored. Similarly, in pine forests in the southern Cascade Mountains in

north-eastern California, interannual fire activity has been linked to drought, and to ENSO and the PDO (Norman & Taylor, 2003). However, fire–climate relationships were not explored at intermediate time-scales or for different time periods. Given the temporal instability of relationships between teleconnections and precipitation in the western USA on decadal time scales (McCabe & Dettinger, 1999), explicit analyses of fire–climate relationships at both interannual and interdecadal time scales are needed for different time periods to elucidate the role of climate in regulating pine forest fire regimes.

The goal of this study was to understand better the role of interannual and interdecadal climatic variation on fire regimes in fire-prone Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) dominated forest ecosystems in the northern Sierra Nevada Mountains. Jeffrey pine forests in California historically burned every 3–15 years (Taylor, 2000; Stephens, 2001; Norman & Taylor, 2003). In this study, particular emphasis is placed on identifying variation in the influence of climate on fire regimes at interannual and interdecadal time-scales during different time periods prior to EuroAmerican settlement (c. 1850) (Strong, 1984) to minimize any confounding effects of land use change on fire–climate relationships. By examining temporal variation in fire–climate relationships over a range of time-scales it is possible to distinguish the effects of different climatic influences on fire regimes (Swetnam & Betancourt, 1998; Grissino-Mayer & Swetnam, 2000; Heyerdahl *et al.*, 2002; Hessl *et al.*, 2004). Given their importance in the SW and PNW, we expect ENSO and the PDO to be important regulators of fire regimes in the northern Sierra Nevada. However, the northern Sierra Nevada region is located in the pivot zone of the ENSO-PDO precipitation dipole (Dettinger *et al.*, 1998). In this intermediary zone, fire–climate relationships may be similar to the SW or PNW. Alternatively, fire occurrence and extent may be unaffected by climate or the relationships may be different than in pine forests in the SW or PNW. We specifically address the following questions: (1) How have fire frequency and fire extent varied over time? (2) Were fires more widespread during dry years and less extensive during wet ones? (3) Did fire frequency and fire extent vary in response to ENSO and PDO teleconnections? (4) Did fire–climate relationships vary over time or were they constant? To help answer these questions, we first developed a pre-settlement record of fire frequency and fire extent in a pine forest in the northern Sierra Nevada using fire scar dendrochronology. We then related the fire record to proxy climatic records at interannual and interdecadal time-scales.

STUDY AREA

Our study was conducted in a 6000-ha area of contiguous mixed Jeffrey pine-white fir (*Abies concolor* Gordon & Glend.) forest on the western slope of the Carson Range, on the east shore of Lake Tahoe (Fig. 1). At the time of EuroAmerican settlement, Jeffrey pine-white fir forests in the Carson Range were open (i.e. mean density = 68 trees ha⁻¹; mean basal

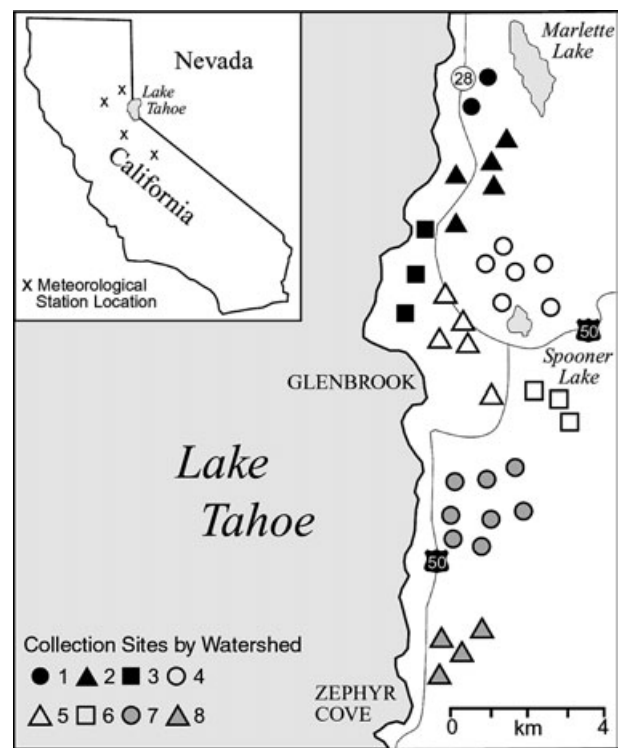


Figure 1 Location of fire scar collection sites by watershed unit, northern Sierra Nevada, Lake Tahoe, NV, USA.

area = 25.5 m² ha⁻¹) and had fourfold more Jeffrey pine than white fir, and trees were large (mean diameter = 67.5 cm) and presumably old (i.e. > 250 years) (Taylor, 2004). Sites in the study area ranged in elevation from 1910 to 2300 m. The climate in the Carson Range is characterized by cold-wet winters and warm-dry summers. Mean monthly temperatures range from -1 °C in January to 18 °C in July, and mean annual precipitation at South Lake Tahoe, CA (1820 m) is 78.4 cm, with most (86%) falling as snow between November and April. April snowpack depths above 2300 m frequently exceed 2 m. Thunderstorms occur in the dry season and lightning is a common source of ignition for fires (Manley *et al.*, 2000). The terrain in the study area is steep and complex, and several perennial streams and areas with rock outcrops are present and may have acted to inhibit the spread of fire. Soils are shallow (< 1 m), excessively drained, medium in acidity and derived from Mesozoic aged granite (Rogers, 1974; Hill, 1975).

People have been present in the Lake Tahoe Basin for a long time, at least since the early archaic period (c. 7000 BP) (Lindstrom, 2000). At the time of EuroAmerican contact (1844), Native Americans (Washoe) used the area seasonally and their use of fire may have influenced local fire regimes and patterns of vegetation. Washoe are known to have set fires to drive game and to increase production of certain plants for food and fiber (e.g. Lindstrom, 2000). Forests in the Carson Range were virtually clear-cut between 1873 and 1900 to supply wood to the Comstock silver mines in Virginia City, Nevada (Leiberg, 1902; Strong, 1984; Lindstrom, 2000).

Contemporary forests in the Carson Range are young and they established after nineteenth century logging (Taylor, 2004). Local grazing, especially of montane meadows, began in the mid 1850s and grazing peaked between 1920 and 1930. Land use changed again when lands in the Carson Range became part of the Toiyabe National Forest in 1907; early management emphasized fire suppression and the regulation of grazing (Strong, 1984; Lindstrom, 2000).

METHODS

Fire regimes

The pre-settlement fire regime [i.e. fire frequency, fire return interval (FRI), fire extent, fire season] was reconstructed from fire scars preserved in the annual growth rings of nineteenth century cut stumps ($n = 91$) and recently dead pre-settlement ($n = 2$) Jeffrey pine trees. Thirty-six c. 10 ha sites were sampled and an average of 2.8 (range, 1–5) wood samples were collected at each site. Wood cross-sections were removed with a chainsaw (e.g. Arno & Sneek, 1977) and their locations were identified with a GPS and recorded on a topographic map.

Fire years in each sample were determined by first sanding each wood sample to a high polish and then cross-dating the sample's annual growth rings using standard techniques (e.g. Stokes & Smiley, 1968). The calendar year of each tree ring with a fire scar lesion in it was then recorded as the fire date.

The season of burn for each fire was identified from the position of the fire scar lesion within the annual growth ring (cf. Baisan & Swetnam, 1990). Intra-ring fire scar positions were classified as: early (first one-third of earlywood); middle (second one-third of earlywood); late (last one-third of earlywood); latewood (in latewood); and dormant (at ring boundary). In this area of strongly seasonal precipitation (winter-wet, summer-dry), dormant season fires represent fires that burned in late summer or fall after radial growth ceased for the year, and not winter or early spring burns (e.g. Caprio & Swetnam, 1995). In the Carson Range, late-lying spring snowpack and high fuel moisture in spring reduce the likelihood of early season burns.

Fire regimes were characterized at the scale of watersheds. Site fire chronologies were grouped from north to south based

on their location in eight contiguous watersheds that drain into Lake Tahoe (Fig. 1). Each watershed, on average, included four site fire chronologies (range, 2–8) (Table 1). The site fire chronologies in each watershed were then combined to develop a composite fire chronology for each watershed. We then computed fire regime statistics (fire frequency, FRI, fire extent) for the common period of fire occurrence among all watersheds (i.e. 1650–1850). The year and number of fires that burned in ≥ 1 , ≥ 2 , and up to ≥ 8 watersheds were used to calculate the fire extent statistics. Although, the number of watersheds that recorded a fire in a given year is not a direct measure of burn area (cf. Taylor, 2000), it is a robust index of relative fire extent regardless of whether the scars are from a single fire or multiple fires (Swetnam & Baisan, 2003; Taylor & Skinner, 2003).

Instrumental and proxy climate data

We used three tree ring-based reconstructions of climate variables in our analysis. First, as a measure of drought, we used reconstructed Palmer Drought Severity Index (PDSI). PDSI is a composite climate index that integrates immediate (same month) and lagged (previous months) precipitation and temperature values to estimate drought severity (Palmer, 1965; Alley, 1984). Negative PDSI conditions represent drought, while the opposite conditions prevail when PDSI is positive. We used the reconstruction of summer PDSI (grid point 13) developed by Cook *et al.*, 1999 for North America. This reconstruction captures 50–70% of the variation in instrumental PDSI (Cook *et al.*, 1999). Second, as an index of ENSO activity, we used reconstructed values of the winter (December to February) Southern Oscillation Index (SOI) based on tree rings in the SW, Mexico, and Indonesia (Stahle *et al.*, 1998). When SOI is positive, La Niña conditions prevail and when it is negative El Niño conditions dominate. The SOI reconstruction captures 53% of the variation in instrumental SOI. Finally, as a PDO index, we used reconstructed values for the PDO based on tree rings from Mexico and southern California (Biondi *et al.*, 2001). The Biondi *et al.* (2001) index was chosen because it was developed from sites (i.e. northern Mexico, southern California) closer to the study area that may better capture the local expression of PDO than

Watershed number	Number of sites (number of samples)	Number of fire intervals	Mean FRI	Median FRI	WMPI	FRI Range	SD	Skew.
1	2 (4)	26	9.4	9	8.0	1–36	7.2	1.9
2	5 (11)	46	4.9	5	4.4	1–12	3.2	0.5
3	3 (10)	69	3.8	3	3.4	1–15	2.7	1.5
4	6 (11)	52	4.9	4.5	4.4	1–16	3.4	1.4
5	5 (12)	70	3.4	3	3.1	1–9	2.0	0.5
6	3 (9)	50	4.8	4.5	4.4	1–12	2.9	0.5
7	8 (26)	70	3.9	3	3.2	1–16	3.2	1.6
8	4 (10)	46	5.0	5	4.4	1–16	3.3	1.1

WMPI is the Weibull median probability interval, SD is the standard deviation of the mean fire return interval, and skewness is of the frequency distribution of fire return intervals.

Table 1 Sample characteristics and fire return interval (FRI) statistics (years) for the period 1650–1850 in each watershed in the Carson Range. Site and watershed locations are given in Fig. 1

reconstructions based on geographically remote sites (i.e. D'Arrigo *et al.*, 2001). Index values are positive when the PDO is warm and they are negative during a cool PDO. The PDO reconstruction captures 41% of the variance in the instrumental PDO (Biondi *et al.*, 2001).

The PDSI, PDO, and SOI reconstructions are indices of climate variation over large spatial scales and variation in these indices may or may not be reflected in local climate variation. We identified how the PDSI, PDO, and SOI reconstructions are related to climate in our study area by calculating Pearson product moment correlations between each climate index and local instrumental climate data at annual and decadal time-scales. Our local climate data consisted of mean monthly temperature and mean monthly total precipitation from four Sierra Nevada meteorological stations (Nevada City, Placerville, Tahoe City, Yosemite) with long records. Decadal scale time series were developed by fitting 10 years smoothing splines (with 50% of the variance retained) to the climate data and index values.

Variation in local climate was associated with variation in the climate indices. Current year PDSI was significantly correlated ($P < 0.05$) with wet season (fall, winter, spring) precipitation (+) and spring growing season temperature (–) at annual time scales, and current year and lagged relationships were significant ($P < 0.05$) at decadal time scales (Fig. 2). Local climate variation was not correlated with PDO at annual time-scales. However, at decadal time scales, PDO is well correlated ($P < 0.05$) with current year and lagged winter (+), late summer (–), and fall (–) temperature, and summer (–), late fall (+), winter (+) and spring (+) precipitation.

Local climate variation and SOI was only weakly correlated ($P < 0.05$) with lagged wet season temperatures (–) at annual time scales. However, at decadal time scales, SOI was well correlated ($P < 0.05$) with current year and lagged local wet season temperatures (–), and it was moderately correlated ($P < 0.05$) with winter (–), summer (+), and late fall (+) precipitation.

Fire-climate analysis

We used a combination of superposed epoch analysis (SEA) and correlation analysis to examine relationships between PDSI, ENSO, PDO and fire occurrence and extent (Haurwitz & Brier, 1981; Baisan & Swetnam, 1990). First, however, we plotted the number of watersheds burned during a given year and calculated moving 49-year sums of fire frequency (i.e. fire years) and fire extent (i.e. number of watersheds burned) to graphically evaluate if there was evidence of a temporal shift in fire regime parameters in our fire record (Fig. 3) (e.g. Kitzberger & Veblen, 1997). Late eighteenth century shifts in fire frequency, fire extent, and fire seasonality that are thought to be climate related have been identified in pine forests in the SW (e.g. Grissino-Mayer & Swetnam, 2000; Swetnam & Baisan, 2003), the PNW (Heyerdahl *et al.*, 2002; Hessler *et al.*, 2004), and in north-eastern California (Norman & Taylor, 2003). The 49-year sums graphic suggests a fire regime shift

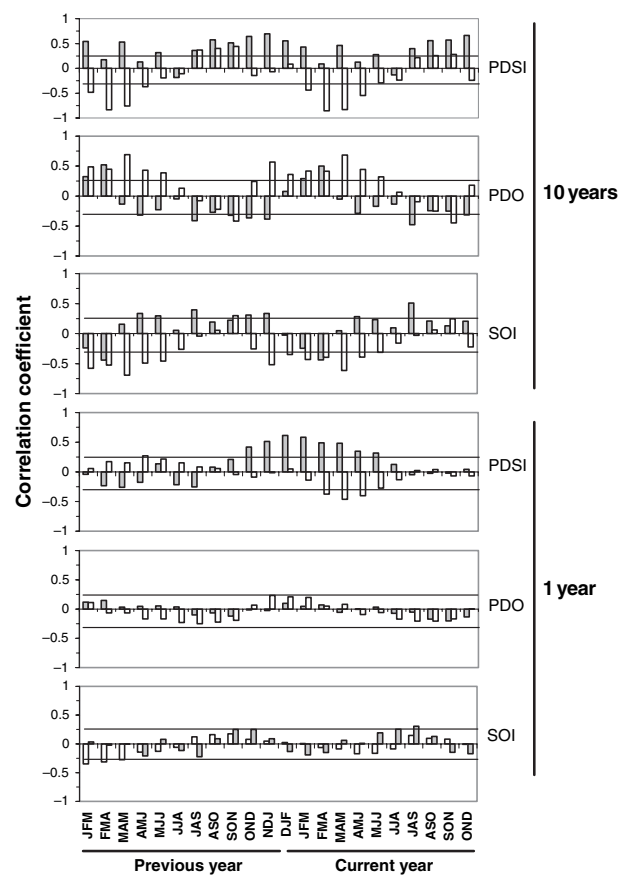


Figure 2 Pearson product moment correlations of local temperature (open bars) and precipitation (solid bars) (1921–78, $n = 58$ year) with the reconstructed Palmer Drought Severity Index (PDSI) (Cook *et al.*, 1999), reconstructed Southern Oscillation Index (SOI) (Stahle *et al.*, 1998), and reconstructed Pacific Decadal Oscillation Index (PDO) (Biondi *et al.*, 2001) for the current year and previous year. Correlations were computed for both annual and decadal (10 years moving average) time-scales. Significance ($P < 0.05$) is indicated by the horizontal lines.

from more frequent to less frequent fire in *c.* 1775 (Fig. 3). To determine if the two periods on either side of 1775 were characterized by different fire–climate relationships, we examined fire–climate relationships for each half (i.e. divided at 1775) and the full period spanned by the fire and climate records.

The relationship between proxy climate and fire occurrence and extent at interannual time scales was identified using SEA. SEA determines relationships between events (i.e. fire years) and climate (i.e. PDSI, ENSO, PDO) by superposing a window of contemporaneous and lagged climatic conditions over each event year. Monte Carlo simulations (1000 runs) are then used to compare average climatic conditions preceding, during, and following event years to conditions present over the complete record using bootstrapped confidence interval estimates (Mooney & Duval, 1993). SEA analysis was performed separately for fire years of different extent (i.e. ≥ 1 , ≥ 2 , and up to ≥ 8

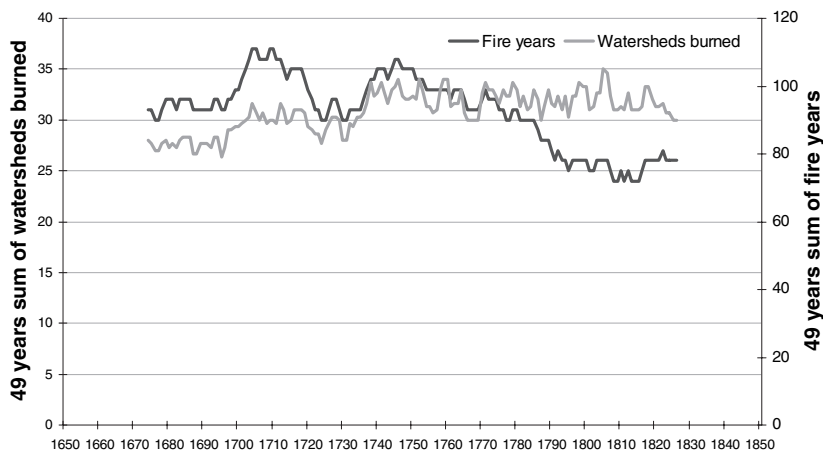


Figure 3 Moving 49-year sums of fire years and fire extent (i.e. watersheds burned in a fire year) for the period 1650–1850 in the northern Sierra Nevada, Lake Tahoe, NV, USA.

watersheds), and non-fire years, and to identify climatic conditions conducive to and unfavourable for fire. An 8-year window (5 years preceding, 2 years following) was chosen for the SEA analysis to identify multi-year relationships between climatic conditions and fire frequency and extent. The climate proxies overlap after the year 1700 (except for SOI which begins in 1706) so fire–climate relationships were investigated for the period 1700–1850.

Correlation analysis was used to examine decadal-scale variation in fire–climate relationships. Pearson product moment correlation coefficients were calculated between climate and fire extent time series that were smoothed with a cubic spline that retained 50% of the variance in the original series over periods of 10 years (Diggle, 1990).

RESULTS

Pre-settlement fire regimes

Fire record

A long history of frequent fire was identified in Jeffrey pine forests in the Carson Range. In total, 190 fires were recorded between AD 1160 and 1871. However, only one watershed had a record of fires prior to 1400. For the period analysed for the fire disturbance analysis (1650–1850), 121 fires were recorded. The average period between fires detected in the eight watersheds in the study area was 1.5 years (Table 1).

Fire season

The position of fire scars within annual growth rings indicates that fires mainly burned (90%) in the dormant season after trees had stopped radial growth for the year. North of Lake Tahoe (120 km), Jeffrey pine radial growth is complete by late August (Taylor, 2000) suggesting that dormant season fires represent burns in late summer or early fall. The late summer–fall period is coincident with contemporary seasonal peaks in lightning ignitions and low fuel moisture in the Sierra Nevada that favour fire spread (Skinner & Chang, 1996).

Fire return intervals

Statistical description of the fire return intervals for the eight watersheds include the mean fire interval, the median fire interval, and the Weibull median probability interval (WMPI) as measures of central tendency (Table 1). Fire interval distributions are asymmetrical and the WMPI is a measure used to describe central tendency in asymmetrical distributions (Grissino-Mayer, 2001). The fire interval distribution in each watershed was positively skewed with more short than long intervals (Table 1). Median and mean FRI, and WMPI, did vary among watersheds ($P < 0.001$, Kruskal–Wallis H -test), but paired comparisons indicate that only WS1 had longer average FRIs ($P < 0.001$, Mann–Whitney test). Similarly, only WS1 had a different FRI distribution ($P < 0.01$, Kolmogorov–Smirnov test) than the other watersheds. Lower fire occurrence in WS1 is probably caused by lower fuel bed continuity. In WS1, rock outcrops are more extensive than in the other watersheds. Rock outcrops reduce fuel bed connectivity and the probability of fire spread from a point of ignition, or import of fire from adjacent watersheds (Agee, 1993; Taylor, 2000).

Fire extent

The number of watersheds burned varied by fire year (Table 2). The mean and median number of watersheds burned by a fire was three and two watersheds, respectively. Small fires were more frequent than large ones and fires recorded in at least two watersheds occurred in 79 of 200 years. Large burns recorded in ≥ 6 watersheds occurred 21 times, and the FRI for these more widespread fires ranged from 3 to 31 years. Fires recorded in the same year in all eight watersheds occurred only five times over the 200-year period.

Temporal patterns

Fire frequency was different before and after 1775. The mean FRI for fires that burned in at least one watershed (i.e. ≥ 1 watershed) was shorter before (1.4 ± 0.9 years) than after (1.9 ± 1.1 years) 1775 ($P < 0.003$, Mann–Whitney U -test).

Table 2 Fire return interval (FRI) statistics (years) for fires of different extent for the period 1650–1850

Number of watersheds recording a fire	Fire frequency	Mean FRI	Median FRI	WMPI	FRI		
					Range	SD	Skew.
≥ 1	121	1.5	1	1.5	1–6	1.1	2.2
≥ 2	79	2.5	2	1.8	1–7	1.6	1.1
≥ 3	56	3.5	3	3.3	1–9	2.0	0.7
≥ 4	47	4.1	4	3.9	1–9	2.2	0.3
≥ 5	30	6.2	6	5.8	1–21	3.6	2.3
≥ 6	18	10.3	8.5	9.5	3–31	7.4	1.6
≥ 7	9	19.3	12	15.4	4–36	13.1	0.4
≥ 8	5	34.8	35	43.8	21–58	14.6	1.2

WMPI is the Weibull median probability interval, SD is the standard deviation of the mean fire return interval, and skewness is of the frequency distribution of fire return intervals.

However, the mean FRI for more extensive burns (i.e. ≥ 2 , and up to ≥ 6 watersheds) was similar in the two periods ($P > 0.05$). Two periods of lower fire occurrence, 1735–1755 and 1775–1800, were also evident (Fig. 4a) and no fires were recorded in the study area after 1871. The > 130 -year fire-free period after 1871 is unprecedented in length compared with fire-free intervals in the pre-settlement period.

Fire and climate

Interannual relationships

The SEA of PDSI indicated that fire years are associated with low moisture conditions and the opposite is true for non-fire years. PDSI was positive (wet, cool) in non-fire years and negative (dry, warm) in fire years, and burns recorded in larger numbers of watersheds occurred during the driest years ($P < 0.01$) (Fig. 5a). Antecedent PDSI was also important. Fires that burned from ≥ 2 to ≥ 6 watersheds were preceded by

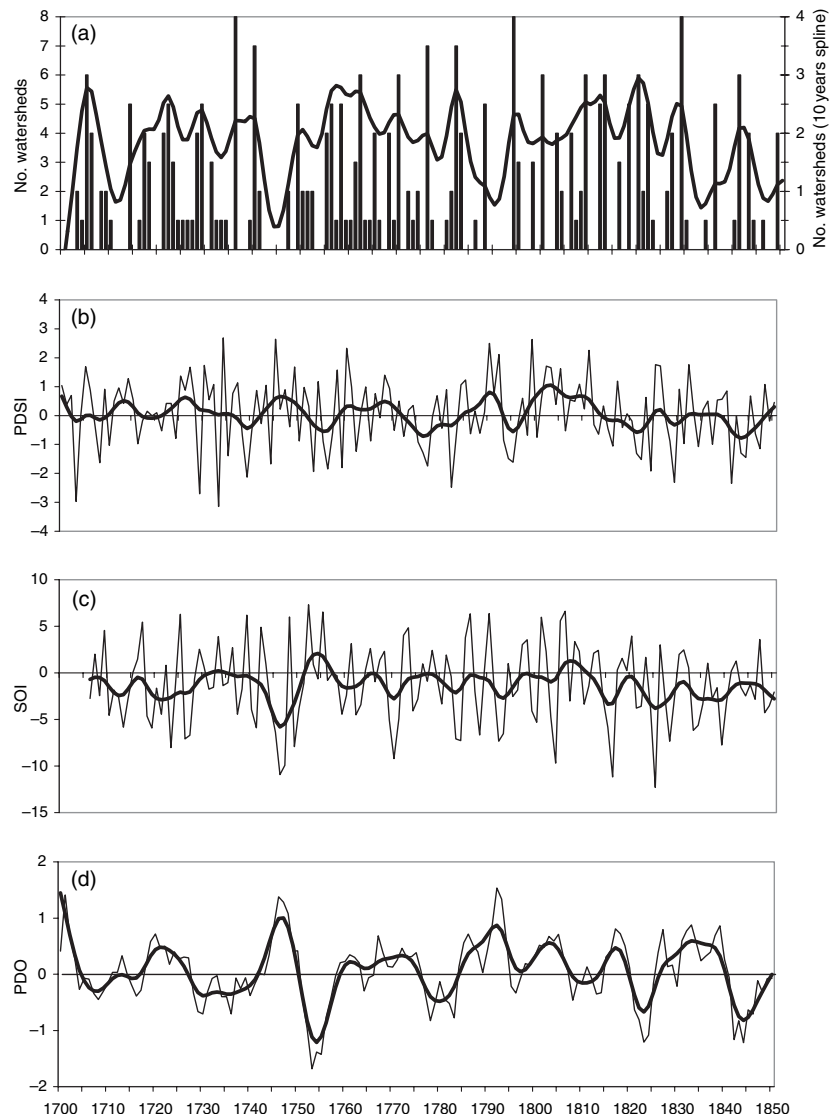


Figure 4 (a) Number of watersheds burned in each fire year between 1650 and 1850 in the northern Sierra Nevada, Lake Tahoe, NV, USA, (b) reconstructed PDSI (Cook *et al.*, 1999), (c) reconstructed Southern Oscillation Index (SOI) (Stahle *et al.*, 1998), and (d) reconstructed Pacific Decadal Oscillation (PDO) (Biondi *et al.*, 1999). The annual series were smoothed with a cubic spline (heavy lines) that retained 50% of the variance in the original series over periods of 10 years.

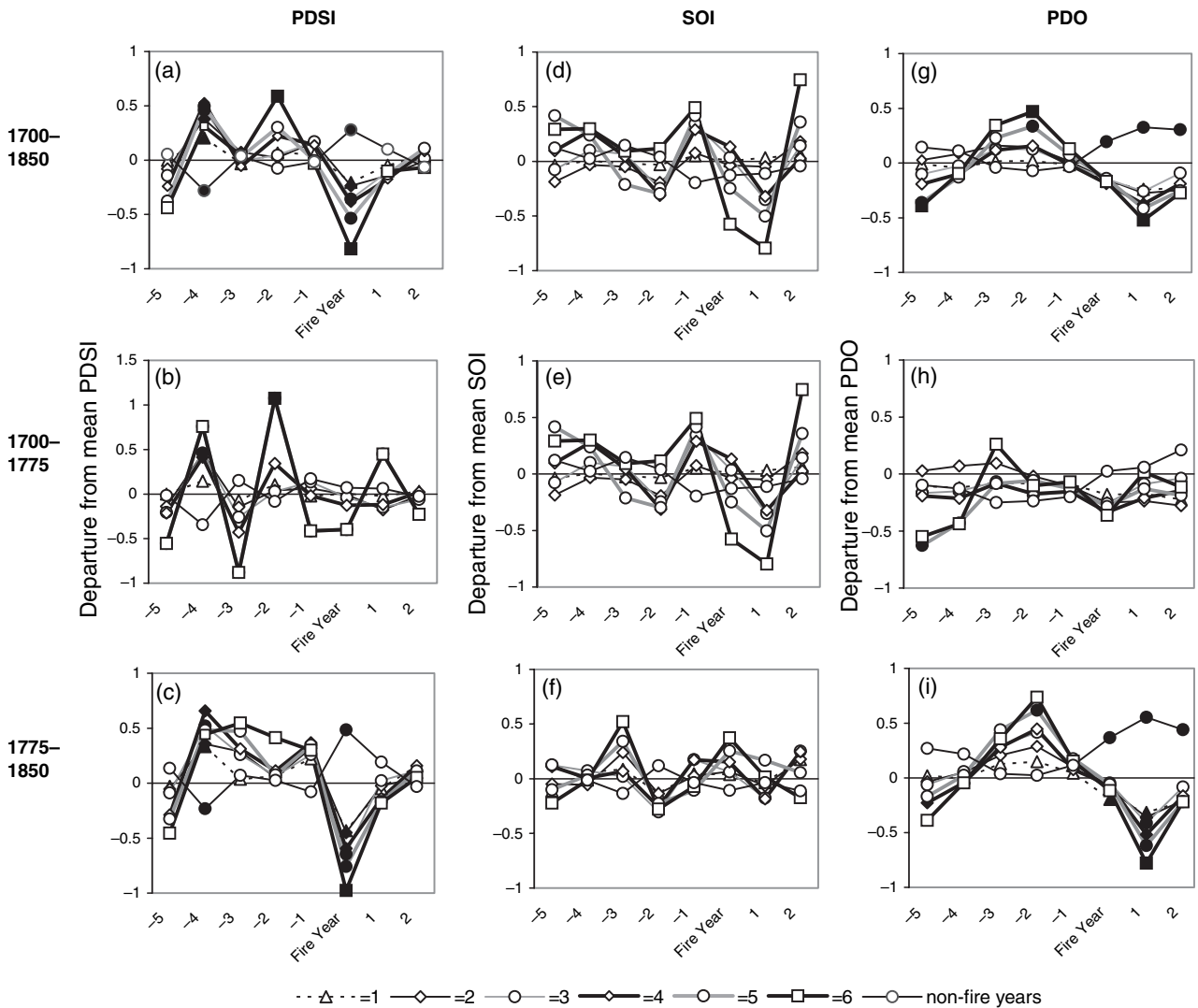


Figure 5 Superposed epoch analysis (SEA) of reconstructed PDSI (Cook *et al.*, 1999) (a–c), SOI (Stahle *et al.*, 1998) (d–f), and PDO (Biondi *et al.*, 2001) (g–i) with non-fire years and fire years of different extent (i.e. ≥ 1 watershed, ≥ 2 watershed, and up to ≥ 6 watersheds) in the northern Sierra Nevada, Lake Tahoe, NV, USA for the periods 1700–1850; 1700–1775 and 1775–1850. The analysis window includes the period 5 years before and 2 years after each fire or non-fire year. Values with filled symbols indicate statistical significance ($P < 0.05$) determined from bootstrapped confidence interval estimates (95%) based on 1000 Monte Carlo simulations of the same number of years as fire or non-fire years (Mooney & Duval, 1993).

wet years 2–4 years before the fire ($P < 0.01$). Too few fires burned 7 or 8 watersheds to analyse climatic influences on the most widespread fires.

The relationship between PDSI and fire was not the same in the first and second half of the fire record (Fig. 5b,c). The interannual relationship between fire extent and PDSI was weak in the first half (1700–1775) of the record and only wet antecedent conditions preceded years of widespread burns ($P < 0.01$). But in the second half (1775–1850) of the record, both wet antecedent conditions and drought were associated ($P < 0.01$) with years of fires of different extent, and non-fire years were wet ($P < 0.01$) (Fig. 5c).

The SEA of SOI found no association ($P > 0.05$) between ENSO and years with fires of any extent, or non-fire

years, for the full, first, or second half of the fire record (Fig. 5d–f).

The PDO–fire relationship indicates that fire years and non-fire years are associated with phase switches of the PDO. Years with widespread fires were associated with a negative (cool phase) PDO 1 year after ($P < 0.01$) and a positive PDO 2 years before ($P < 0.01$) the fire year (Fig. 5g). The PDO was a positive (warm phase) in non-fire years ($P < 0.05$) and in the trailing 2 years ($P < 0.01$) (Fig. 5g). The relationship between PDO and fire, however, was different in the first and second half of the fire record (Fig. 5h,i). In the first half of the record, variation in the PDO was not related to fire or non-fire years (Fig. 5h). But in the second half, years with fires of any extent were associated with a negative (cool-phase) PDO 1 year after ($P < 0.01$), and a

positive (warm-phase) PDO 2 years before ($P < 0.01$) the fire year. Moreover, years with the most widespread fires were associated with the largest swings in the PDO. The relationship between the PDO and non-fire years for the second half of the record was identical to that for the full record.

Interdecadal relationships

The smoothed PDSI and fire extent time series were correlated for the full ($r = -0.24$, $P < 0.01$) and first half ($r = -0.39$, $P < 0.001$) of the fire record, but not for the second half ($r = -0.16$, $P > 0.05$) (Fig. 6). These correlations indicate that burning was more widespread during dry than wet decades, but mainly in the early part of the fire record.

The smoothed time series of ENSO and fire extent were also correlated (Fig. 6). Fire extent was positively correlated ($r = 0.32$, $P < 0.0001$), with SOI indicating that burning was more widespread during La Niña than El Niño decades. The strength of the SOI-fire extent correlation varied by time period and was stronger in the first half ($r = 0.41$, $P < 0.001$) than in the second half ($r = 0.23$, $P < 0.05$) of the record.

The PDO and fire extent smoothed time series for the full record were also correlated ($r = -0.37$, $P < 0.0001$) indicating that more widespread burning was associated with cool (negative) rather than warm (positive) PDO decades (Fig. 6). The strength of the PDO-fire extent correlation varied by time period. PDO and fire extent were well correlated in the first half ($r = -0.45$, $P < 0.0001$), but weakly correlated ($r = -0.27$, $P < 0.05$) in the second half of the fire record.

The PDO, SOI, and PDSI smoothed time series were also intercorrelated, but the strength of the relationships varied by time period (Fig. 6). PDO and SOI were well correlated ($r = -0.53$, $P < 0.0001$) over the full record and highly correlated in the first ($r = -0.90$, $P < 0.0001$), but not correlated at all in the second half ($r = -0.09$, $P > 0.05$) of the record. The PDO and PDSI time series were well correlated in each time period (full, $r = 0.54$, $P < 0.0001$; first half, $r = 0.63$, $P < 0.0001$; second half, $r = 0.54$, $P < 0.0001$) but the PDSI and SOI correlation varied by time period. PDSI and SOI were strongly ($r = -0.70$, $P < 0.0001$) and weakly ($r = 0.27$, $P < 0.05$) correlated in

the first and second half of the record, respectively. Over the entire record, there was no association ($r = -0.14$, $P > 0.05$) between PDSI and SOI.

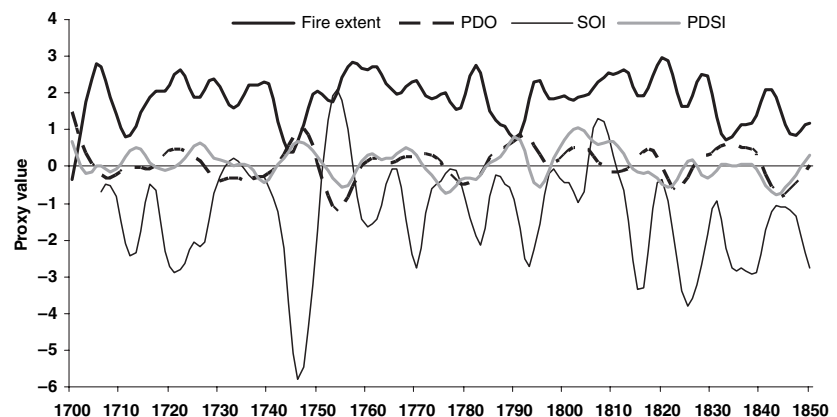
Consideration of ENSO and PDO together suggest that their interactions affect fire extent (Fig. 6). Decades with less extensive burning are associated with constructive relationships between positive PDO (warm phase)-negative SOI (El Niño). Similarly, some decades with extensive burning correspond with constructive relationships between negative PDO (cool)-positive SOI (La Niña).

DISCUSSION

Fire occurrence and extent in the northern Sierra Nevada were strongly influenced by climatic variability in several important ways. First, non-fire years, years with localized fires, and years with widespread fires were all affected by climatic conditions that influence fuel moisture and flammability at both interannual and interdecadal time scales. Second, fires were affected by interannual variability in prior years climate, presumably via climate-caused variation in rates of fine fuel production needed for fire spread. Third, the timing and extent of fires were affected by interannual and decadal scale variation in tropical and North Pacific teleconnection, and their interactions. Fourth, fire regime characteristics and their relationship with climate were not stable over time and they varied during periods dominated by different climatic regimes.

The association of drought with widespread burning during the pre-fire suppression period is a hallmark of pine dominated forest ecosystems in the western USA that were once characterized by a regime of frequent low to moderate severity surface fires (e.g. Swetnam, 1993; Swetnam & Betancourt, 1998; Veblen *et al.*, 2000; Heyerdahl *et al.*, 2002; Norman & Taylor, 2003; Hessl *et al.*, 2004). The overall effect of drought on patterns of burning in the northern Sierra Nevada is similar to drought effects on fire extent in these other forests. Yet, years of widespread burning were not related simply to interannual variability in drought. Climatic conditions in the years preceding fires apparently pre-conditioned the landscape for burning.

Figure 6 Decadal variation in fire extent (number of watersheds burned) in the northern Sierra Nevada, Lake Tahoe, NV, USA, reconstructed PDSI (Cook *et al.*, 1999), reconstructed Southern Oscillation Index (SOI) (Stahle *et al.*, 1998), and reconstructed Pacific Decadal Oscillation (PDO) (Biondi *et al.*, 2001). The annual series were smoothed with a cubic spline that retained 50% of the variance in the original series over periods of 10 years.



In northern Sierra Nevada pine forests, wetter and cooler than normal climatic conditions preceded fire years. Fine fuel production in open forests is thought to be particularly sensitive to climatic variability because of the strong grass and forb growth response to variation in seasonal and annual moisture (Cable, 1975; Bond & van Wilgen, 1996). An increase in fine fuel production during wet/cool years probably increased fuel connectivity in the landscape promoting fire spread during subsequent dry years. The importance of wetter than normal conditions before years of widespread fire has been documented in other pine-dominated forests in the SW (Baisan & Swetnam, 1990; Swetnam & Betancourt, 1998; Grissino-Mayer & Swetnam, 2000; Brown *et al.*, 2001), RM (Veblen *et al.*, 2000; Donnegan *et al.*, 2001), northern Mexico (Stephens *et al.*, 2003), the southern Cascades (Norman & Taylor, 2003), and in xeric woodlands in Argentina (Kitzberger & Veblen, 1997; Veblen *et al.*, 1999). In contrast, years of widespread burning in pine forests in the PNW are associated only with drought (Heyerdahl *et al.*, 2002; Hessl *et al.*, 2004). The response of grass and forb production to wet years in these more northern forests is apparently insufficient to cause significant variation in annual fuel production that affected fire.

Interannual variability in ENSO has been shown to be a strong driver of historical variation in fire extent in pine forests in the SW (Swetnam & Betancourt, 1990; Grissino-Mayer & Swetnam, 2000) and PNW (Heyerdahl *et al.*, 2002). Widespread burning in both regions occurs during the ENSO phase which corresponds to regionally dryer and warmer conditions. Yet, in the northern Sierra Nevada, annual burning is not associated with ENSO variation; nor is it in the nearby southern Cascades (Norman & Taylor, 2003). Interannual variation in the north–south position of zonal precipitation in the geographic region near the ENSO pivot may mask any ENSO climatic effect on fire regimes. Annual precipitation variation in the central and northern high Sierra Nevada of California tends to be independent of ENSO (Schoner & Nicholson, 1989), and there was no correlation between annual instrumental precipitation and SOI in our study area. Annual variability in the fire–climate of the northern Sierra Nevada, however, was linked to North Pacific climatic variation as expressed in the PDO.

Fire occurrence and extent in the northern Sierra Nevada were strongly associated with phase changes in the PDO. Widespread burning occurred in years preceded by significantly positive PDO conditions (warm phase) followed by strongly negative ones (cold phase). The fire-PDO pattern in the northern Sierra Nevada is similar to the fire-ENSO switching pattern documented in SW and RM pine forests, but phase switching of the PDO is less frequent because it varies over longer (decadal) time scales. During positive PDO conditions, warm SST in the north-eastern Pacific, and cold SST in the western and central north Pacific, promote a stronger sub-tropical jet-stream similar to El Niño winters (Gershunov *et al.*, 1999) while the opposite climatic pattern characterizes negative PDO conditions (Gershunov *et al.*,

1999). The fire–PDO relationship suggests that a strong change in burning conditions in the northern Sierra Nevada accompanies the positive to negative PDO switch and this shift is probably related to moisture conditions. Local instrumental fall, winter, and spring precipitation are all positively correlated with PDO at decadal time scales. A similar, fire–PDO relationship has been documented in PNW pine forests, but years with extensive fires are associated with a switch from negative to positive PDO conditions (Hessl *et al.*, 2004).

The response of fire regimes to interannual climatic patterns that affect moisture conditions varied over time. Between 1700 and 1775, fires were much more frequent, and fire frequency and extent were not associated with interannual variation in moisture except that wet/cool conditions preceded (2–4 years) the most widespread fires; smaller fires burned independently of moisture conditions at annual time-scales. On the other hand, both wet antecedent conditions and drought in the fire year characterized the relationship between moisture and fire extent between 1775 and 1850. Wet antecedent conditions, probably by increasing fuel production, were an important and consistent climatic influence on fire regimes, but annual drought was a significant influence only after 1775. A similar, but opposite, late eighteenth century shift in the importance of drought on fire occurrence and extent has been documented in pine forests in the SW (Grissino-Mayer & Swetnam, 2000). In the SW, drought was associated with widespread burning before but not after 1775. The temporal variability in the importance of annual drought on pine forest fire regimes in the northern Sierra Nevada, the SW (e.g. Swetnam & Betancourt, 1998; Grissino-Mayer & Swetnam, 2000), and northern Mexico (Stephens *et al.*, 2003) suggests that fire–climate relationships may not be stable over time.

The timing of the change in the importance of annual drought on fire occurrence and extent in the northern Sierra Nevada is coincident with temporal changes in fire regimes identified in PNW (Heyerdahl *et al.*, 2002), RM (Veblen *et al.*, 2000; Donnegan *et al.*, 2001), northern Mexico (Stephens *et al.*, 2003), SW (Swetnam & Betancourt, 1998; Grissino-Mayer & Swetnam, 2000; Swetnam & Baisan, 2003), and southern Cascade (Norman & Taylor, 2003) pine forests. For several decades, beginning in the late eighteenth century, pine forests variously experienced: (1) a reduction in fire frequency; (2) a shift to more synchronous widespread fire; (3) a shift in the season of fire; and (4) a weakening of relationships between fire events and climate indices (Stephens *et al.*, 2003; Swetnam & Baisan, 2003). The onset and duration of the fire regime shift corresponds with a documented period of lower ENSO variability (Anderson *et al.*, 1992; Cleaveland *et al.*, 1992). The frequency and strength of ENSO switching is thought to have weakened from *c.* 1790 to 1840 (Anderson *et al.*, 1992; Cleaveland *et al.*, 1992), leading to a fairly stable climate and to weaker fire–climate linkages. Evidence for the change in the amplitude of the ENSO signal during this period has been identified in both the northern and southern hemisphere,

suggesting a global scale climatic effect (Diaz & Markgraf, 2000; Kitzberger *et al.*, 2001). In North America, temperature reconstructed from δO^{18} in tropical corals (Dunbar *et al.*, 1994) and tree rings (Jacoby & D'Arrigo, 1989; Luckman *et al.*, 1997) indicate a rapid temperature change c. 1790. An unusually cool phase of the PDO also characterized this period (D'Arrigo *et al.*, 2001), with cooler than average conditions in the Canadian Rockies (Case & MacDonald, 1995; Luckman *et al.*, 1997), the PNW (Wiles *et al.*, 1996), and Sierra Nevada (Graumlich, 1993), and increased stream-flow in the Sacramento River (Earle, 1993).

Fire regimes in the northern Sierra Nevada experienced some, but not all, of the changes observed in other regions beginning in the late eighteenth century. There was a reduction in fire frequency and a shift to more synchronous and widespread fires in the northern Sierra Nevada, but pine forests did not experience a shift in the seasonality of fires or a weakening of interannual fire–climate relationships. In fact, the influence of interannual climatic variation on fire occurrence and extent strengthened after 1775. Before 1775, fire occurrence and extent were not associated with interannual variation in drought, SOI, or the PDO. Instead, fire activity was associated with climatic variation at decadal time scales. For example, fires were more frequent before 1775 and variation in fire extent was associated with decadal but not interannual variation in moisture. Overall climatic conditions (i.e. fire season length, fuel moisture, relative humidity, ignitions) before 1775 were apparently more conducive to fire; fires were significantly more frequent before than after 1775. During this high fire frequency period, the relationship between fire extent and moisture were consistent over decades but annual drought was not a necessary condition for fire as it was after 1775. After 1775, fire frequency was lower and burning was confined mainly to dry years preceded by wet years that appears to be driven by phase changes from a warm to a cool PDO, but the relationship between fire extent and moisture was not consistent over decades. The strengthening, rather than weakening, of interannual fire–climate relationships is probably caused by the weak influence of interannual ENSO variability on fire in the northern Sierra Nevada, and a shift from strong interdecadal to interannual climate influence related to the breakdown of decadal scale constructive relationships between the PDO and ENSO.

Before 1775, periods of both less and more extensive fire at interdecadal time scales were strongly associated with constructive relationships between ENSO and the PDO. The combined influence of these climate teleconnections appears to be the dominant influence on fire activity during this period. The strength of interdecadal climatic variation on factors that control ignitions, fuel production and moisture, and/or the length of the fire season were sufficiently strong to dampen the interannual climate signal. Yet after 1775, as the influence of ENSO weakens, fires become more strongly related to interannual rather than interdecadal climatic variation. For example, wet conditions followed by drought

and phase shifts of the PDO become strong drivers of fire activity. These patterns demonstrate the sensitivity of fire regimes, and hence fire effects on forest structure and dynamics in fire-prone ecosystems, to shifting modes of climatic variability.

Climate strongly influenced pre-settlement pine forest fire regimes in northern Sierra Nevada. Both interannual and decadal variation in climate effectively regulated conditions conducive to fire, and longer term changes in fire frequency and extent correspond with climate-mediated changes observed in both the northern and southern hemispheres (e.g. Kitzberger *et al.*, 2001). Given that past climate influenced fire regimes in the northern Sierra Nevada, future climate change may also influence fire regimes. However, it is uncertain if an understanding of historical climate–fire relationships could serve as a basis for anticipating or predicting future fire regimes under changing climatic conditions (i.e. $2 \times CO_2$) (e.g. Leung & Ghan, 1999). Land use changes since EuroAmerican settlement have altered the relationships between climate, fire, and fuels at least on annual time scales. Fire exclusion since the early 1900s, in particular, has reduced the frequency and extent of annual burning and this has strongly contributed to an increase in the quantity and continuity of fuels in Sierra Nevada pine forests compared with conditions in pre-fire suppression forests (Skinner & Chang, 1996). Yet there is evidence that even contemporary fire activity in the western USA is related to the geographic variation in wet/dry cycles (Westerling *et al.*, 2003) that are known to be influenced by tropical ocean (i.e. ENSO) and north Pacific (i.e. PDO) climatic variability. Thus, an understanding of pre-settlement fire–climate relationships may provide useful insights into how fire activity in local contemporary forests may respond to future climatic variation.

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BIOSKETCHES

Alan H. Taylor is Professor of Geography at the Pennsylvania State University, and he is interested in plant ecology, biogeography and conservation. His current research is focused on the role of natural and human disturbance, and climate, on vegetation dynamics at time scales of weeks to centuries and at plot and landscape scales. He has worked extensively in the montane conifer forests of western North America and southwestern China. He serves as an Associate Editor for the *Canadian Journal of Forest Research* and is on the editorial board of *Physical Geography*.

R. Matthew Beaty is a postdoctoral fellow with CSIRO Sustainable Ecosystems, with interests in vegetation dynamics, palaeoecology, landscape ecology, urban ecology and human dimensions of environmental change. He has recently worked on understanding relationships between wildfire, climate and vegetation change in the central Sierra Nevada Mountains by integrating image analysis, dendrochronology and fossil charcoal analysis. His current work focuses on urban and peri-urban landscape ecology and biodiversity in Australia.

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