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Tropical and north Pacific teleconnections influence fire regimes in pine-dominated forests of north-eastern California, USA

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Abstract

Aim To assess the importance of drought and teleconnections from the tropical and north Pacific Ocean on historical fire regimes and vegetation dynamics in north-eastern California.

Location The 700 km^2 study area was on the leeward slope of the southern Cascade Mountains in north-eastern California. Open forests of ponderosa pine (*Pinus ponderosa* var. *ponderosa* Laws.) and Jeffrey pine (*P. jeffreyi* Grev. & Balf) surround a network of grass and shrub-dominated meadows that range in elevation from 1650 to 1750 m.

Methods Fire regime characteristics (return interval, season and extent) were determined from crossdated fire scars and were compared with tree-ring based reconstructions of precipitation and temperature and teleconnections for the period 1700–1849. The effect of drought on fire regimes was determined using a tree-ring based proxy of climate from five published chronologies. The number of forest-meadow units that burned was compared with published reconstructions of the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

Results Landscape scale fires burned every 7–49 years in meadow-edge forests and were influenced by variation in drought, the PDO and ENSO. These widespread fires burned during years that were dryer and warmer than normal that followed wetter and cooler years. Less widespread fires were not associated with this wet, then dry climate pattern. Widespread fires occurred during El Niño years, but fire extent was mediated by the phase of the PDO. Fires were most widespread when the PDO was in a warm or normal phase. Fire return intervals, season and extent varied at decadal to multi-decadal time scales. In particular, an anomalously cool, wet period during the early 1800s resulted in widespread fires that occurred earlier in the year than fires before or after.

Main conclusions Fire regimes in north-eastern California were strongly influenced by regional and hemispheric-scale climate variation. Fire regimes responded to variation that occurred in both the north and tropical Pacific. Near normal modes of the PDO may influence fire regimes more than extreme conditions. The prevalence of widespread teleconnection-driven fires in the historic record suggests that variation in the Pacific Ocean was a key regulator of fire regimes through its influence on local fuel production and successional dynamics in north-eastern California.

Keywords
Fire, climate variability, ponderosa pine, Pacific Decadal Oscillation, El Niño/Southern Oscillation.

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INTRODUCTION

Temporal variations in fire regimes are thought to contribute to the structural and compositional diversity of ecosystems (Swetnam, 1993; Bond & van Wilgen, 1996). Fire regimes are known to vary in response to interannual, interdecadal and century-scale climate variation (Clark, 1988; Swetnam, 1990). Along the western Cordillera of the Americas, much of this variation in fire climate has been linked to changes in the sea surface temperature of the Pacific Ocean and the associated atmospheric structures (i.e. teleconnections) that influence climate over extended areas. In particular, variation of the tropical El Niño/Southern Oscillation (ENSO) is known to affect fire regimes in both the Northern and Southern Hemispheres (Simard *et al.*, 1985; Swetnam & Betancourt, 1990; Kitzberger *et al.*, 2001). Fire climate in an area may reflect the influence of complex synoptic processes, however, and temperate latitude sea surface temperatures may be more important than are tropical sea surface temperatures. Interdecadal variability of north Pacific sea surface temperatures is known to influence winter precipitation and streamflow along the western coast of North America (Bitz & Battisti, 1999; Hamlet & Lettenmeier, 1999; Nigam *et al.*, 1999; Barlow *et al.*, 2001). The importance of this interdecadal influence of the north Pacific on fire regimes, and hence vegetation dynamics, is poorly known, but it may influence successional pathways of vegetation and prevent any equilibrium from developing (Swetnam, 1993).

Equatorial and temperate Pacific sea surface temperatures have far-reaching impacts on hemispheric and global climate by affecting atmospheric circulation (Latif & Barnett, 1994; Trenberth & Hurrell, 1994; Diaz & Markgraf, 2000). Given the eastward progression of weather systems at temperate latitudes, variability in sea surface temperature has a particularly strong influence on North America's climate. Tropical climate forcing related to ENSO affects the position and strength of the Aleutian Low and the position of the subtropical jet stream that influences weather systems across North America (Wallace & Gutzler, 1981; Yarnal & Diaz, 1986; Leathers *et al.*, 1991). During the warm phase of ENSO (El Niño), a mid-tropospheric ridge typically extends northward into the Canadian Rockies strengthening moisture-bearing westerly flow from the subtropical Pacific into California (Schonher & Nicholson, 1989; Mo & Higgins, 1998). This pattern diverts moisture from the Pacific Northwest (PNW) and southwestern Canada, which are characteristically dry during El Niño events (Earle, 1993; Dettinger *et al.*, 1998). In contrast, strong La Niña conditions typically bring drought and decreased stream flow to southern California and the southwest USA (Swetnam & Betancourt, 1990; Kahya & Dracup, 1994) and high snowfall anomalies and increased stream flow to the PNW (Earle, 1993; Cayan, 1995; Bitz & Battisti, 1999; Hamlet & Lettenmeier, 1999; Nigam *et al.*, 1999).

Variability in the strength and spatio-temporal stability of ENSO is partly explained by decadal-scale climate variation in the north Pacific Ocean. The most widely used index of North Pacific climate variability is the Pacific Decadal Oscillation (PDO), and the PDO is correlated with annual and winter temperature ($P < 0.01$), and annual and winter precipitation ($P < 0.05$) in northern California (Norman, 2002). When the PDO is in a warm phase, north-eastern Pacific sea surface temperatures are warm, and the Aleutian Low moves southeastward, consistent with strong El Niño winters (Gershunov *et al.*, 1999). When the PDO enters a cool phase, the Aleutian Low weakens, El Niño events are less intense and La Niña events are strengthened (Gershunov *et al.*, 1999). Because of these interacting ENSO–PDO effects on the Aleutian Low, a given El Niño may or may not cause high precipitation anomalies in southern California, and La Niña events are only sometimes associated with severe drought. It is likely, therefore, that an improved understanding of fire–climate interactions will be provided by the integration of tropical and north Pacific teleconnections.

Tree-ring based reconstructions of fire–climate interactions have documented the existence of a latitudinal gradient in fire-teleconnection effects. Fires are common during La Niña droughts in the south-western and southern United States (Swetnam, 1990; Brenner, 1991; Swetnam & Betancourt, 1998; Grissino-Mayer & Swetnam, 2000; Donnegan *et al.*, 2001). In contrast, fire extent increased during droughts linked to El Niño in Alaska (Hess *et al.*, 2001) and in some, but not all areas studied in north-eastern Oregon (Heyerdahl *et al.*, 2002). Our intent in this paper is to improve understanding of the effects of historic climate variability on fire regimes within this intermediary zone in north-eastern California, USA. At this latitudinal location, fire regimes may especially be sensitive to changes in the structure and strength of teleconnections over time.

Climate is not the only regulator of fire regimes, however, in that local-scale factors are also known to be important. Patterns of fire ignition and spread may be influenced by topography (Heinselman, 1973) and fire spread, and behaviour may reflect successional changes in fuel and vegetation since the last fire (Taylor, 2000). Within a watershed, upper or south-facing slopes may experience more drying and more frequent fire than lower or north-facing slopes because of their greater exposure to sun and wind (Rothermel, 1983; Beaty & Taylor, 2001). Conversely, elevational differences in vegetation, fuel type and fuel moisture may act as barriers to the upslope spread of fire (Taylor, 2000). In many forests, succession may increase fuel accumulation and continuity that may enhance fire spread (Miller & Urban, 2000). When fire return intervals are artificially lengthened through fire suppression, the high level of fuel may increase fire severity over historic levels in some coniferous forests (Parsons & DeBenedetti, 1979). The importance of a cyclical pattern of fire and successional feedbacks that lead to the next fire may be spatially variable, however. Fuel accumulation may be less important than climate in open pine forests, where grass understories are thought to have carried fire (Swetnam & Betancourt, 1990). Understanding the spatial and temporal interaction of these endogenous (local) and exogenous (external) factors is critical for understanding the patterns and dynamics of vegetation.

In this paper, we examine fire–climate relationships in pine-dominated forests of north-eastern California prior to the arrival of Euro-Americans (i.e. 1700–1849). Our study addresses five questions. First, did fire season and intervals vary over time? Secondly, was fire most widespread during years of drought and least during wetter years? Thirdly, were fires more widespread following years with wetter climate? Fourthly, did fire extent vary in response to equatorial and/or north Pacific teleconnections? Fifthly, is an improved understanding of the fire climate achieved by considering tropical and north Pacific teleconnections together?

STUDY AREA

Our study area was on the leeward slope of the southern Cascade Mountains in north-eastern California, USA (Fig. 1). The topography in the 700 km^2 study area consists of extinct, Middle to Late Quaternary-Age shield volcanoes, cinder cones and basalt flows that range in elevation from 1650 to nearly 2300 m (MacDonald, 1966). Broad 2–4 km-wide alluvial valleys support treeless meadows that are fringed by mixed forests of ponderosa pine (*Pinus ponderosa* var. *ponderosa* Laws.), Jeffrey pine (*Pinus jeffreyi* Grev. & Balf) and scattered lodgepole pine [*Pinus contorta* var. *murrayana* Loudon (Grev & Balf.)] and western juniper (*Juniperus occidentalis* Hook.). Meadows are dominated by grasses [*Poa secunda* J.S. Presl, *Festuca idahoensis* Elmer, *Elymus elymoides* (Raf) Swezey (J.G.Smith)], sedges (*Carex rossii*, *C. filifolia* var. *erostrata* Nutt. Kuk), sagebrush (*Artemesia cana* Pursh, *A. arbuscula* Nutt., *A. tridentata* Nutt.) and antelope bitterbrush [*Purshia tridentata* (Pursh) DC] (Grinnell *et al.*, 1930; Ratliff *et al.*, 1972). Above the pine forest and meadows, slopes support mixed-conifer stands of ponderosa pine, Jeffrey pine, white fir [*Abies concolor* (Gordon & Glend.) Lindley], incense cedar [*Calocedrus decurrens* (Torrey) Florin] and sugar pine (*P. lambertiana* Douglas). Nearly all forests in the area have been clearcut or selectively logged since the 1920s.

The climate is characterized by cold-wet winters and warm-dry summers. Average annual precipitation is 78 cm and four-fifths of this typically falls between 1 November and 30 April, primarily as snow. An important manifestation of the climate on fire regimes is that the seasonal separation of high moisture and warm temperatures limits organic decomposition (Hart *et al.*, 1992). Historically, fuel accumulation in these forests was checked by high fire frequency more than decomposition. The low humidity that characterizes the summer and autumn season allows accumulated fuel to readily burn after ignition (Show & Kotok, 1925). Historically, both lightning and Native Americans were sources of ignition in the study area (Schulz, 1954; McMillin, 1963; Rorig & Ferguson, 1999).

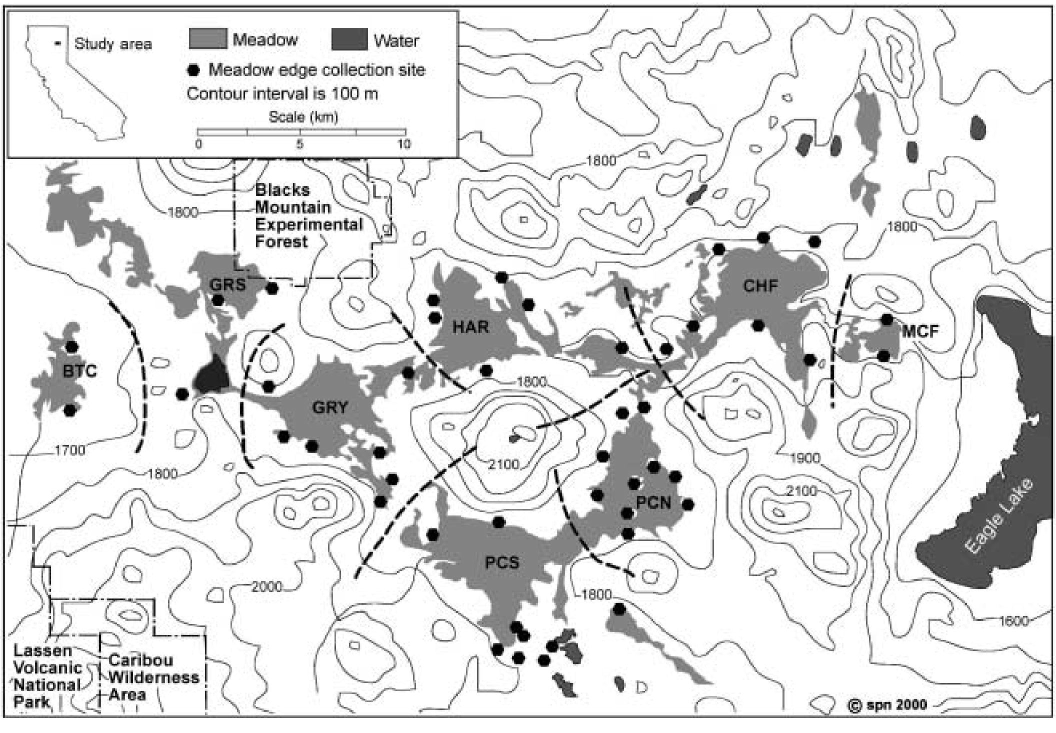

Figure 1 The location of fire scar collection sites and meadow-edge forest units, Lassen National Forest, California, USA. Dashed lines separate meadow sample units. BTC is Butte Creek, GRS is Grass Valley, GRY is Grays Valley, HAR is Harvey Valley, PCS is Pine Creek South, PCN is Pine Creek North, CHF is Champs Flat and MCF is McCoy Flat.

METHODS

Climate reconstruction

To compare fire history with climate before instrumental records were kept, climate variation for the period 1700–1849 was reconstructed using variation in annual tree ring widths. Standardized tree ring chronologies were selected from the International Tree-Ring Data Bank (ITRDB) that met the following criteria: (1) they included the period 1630–1979, (2) were located on the eastside of the Sierra–Cascades divide, (3) were within 250 miles of the study area and (4) were below 2250 m elevation so growth was sensitive to climate at the elevation of the pine forests. Eight chronologies met these criteria, however, three of the chronologies were excluded from further consideration because they exhibited high serial correlation and/or were insensitive to climate variables important for fire or annual fuel production during the instrumental period (1892–1979). The five selected chronologies were correlated ($P < 0.05$) with at least a 1-month record of precipitation during the 10 months prior to August of the year of growth or at least a 1-month record of temperature from May to August of the year of growth. The five chronologies used as the basis for the reconstruction were Lemon Canyon (*P. jeffreyi*, CA06401), Bryant Creek (*P. monophylla* Torr. and Frem., CA09102), Dalton Reservoir (*P. ponderosa*, CA06501), Black Cone (*P. ponderosa*, CA526), and Hager Basin Reservoir (*J. occidentalis*, CA07301).

A climate proxy was then developed by extracting the common variance in the tree ring chronologies using principal component analysis (PCA) (Cook & Kairiukstis, 1990). The proxy was related to climate by correlating PCA scores with monthly temperature and precipitation values. The climate variables used for the correlation were for August of the year of growth and for the fourteen preceding months. The instrumental climate record spanned the period 1892–1979 and was based on the averages for Redding (elevation 150 m, 125 km west) and Chico, California (elevation 56 m, 115 km southwest).

Reconstruction of pre-1850 fire regimes

Fire regimes were reconstructed for the period 1700–1849 for pine forests using fire-scars preserved in the tree rings of stumps, logs, snags and live trees (Arno & Sneck, 1977). We chose trees from meadow-edge sites because open canopy structures are thought to have supported grass fuel that was conducive to fire spread. Eight meadow-edge forest units in the study area were surveyed, and one to five wood samples were collected with a chainsaw from a minimum of two 0.25–3.0-ha sites around each meadow (Fig. 1). The criteria for fire scar sample selection included the number of visible fire scars, the degree of stump decay, and tree species. A total of 112 samples were collected from forty-five meadow-edge sites.

Fire dates were identified in the samples after sanding the wood surfaces until the cellular structure was visible under 7–15× magnification. Individual tree rings were assigned their calendar date of formation by crossdating (Stokes & Smiley, 1968) the sample rings with nearby tree ring chronologies (ITRDB). Tree rings with fire scars were then identified and assigned their calendar date of formation (McBride, 1983). The season when the fire occurred was inferred from the relative position of the scar within the annual growth ring (Baisan & Swetnam, 1990). Fire scars were classified as having formed during dormancy, the growing season (in earlywood and latewood) or as unknown. Fire season was summarized by decade for the period 1680–1899 by comparing the percentage of fire scars occurring in different seasons. Temporal variation in fire frequency in forest units were identified by comparing the fire frequency of the 1700–1774 and 1775–1849 periods using a Student's *t*-test (Grissino-Mayer, 1995).

Fire–climate interactions

The relationship between climate and fire extent was evaluated by counting the number of forest-meadow units with fire between 1700 and 1849. Fires occurring in multiple meadows may have been large, continuous fires or smaller, separate fires that resulted from multiple ignitions. In this paper, we refer to either possibility as a widespread fire. Superposed epoch analyses (Haurwitz & Brier, 1981) were performed separately on fires that burned 1–2, 3–4, 5–6 and 7–8 forest-meadow units. A superposed epoch analyses was also performed on non-fire years to identify climate conditions that were unfavourable to fire. PCA scores were used as the climate proxy and mean PCA scores were calculated for the fire year and for the 5 years before and 2 years after each fire year. In the superposed epoch analyses, each epoch surrounding a fire is compared with randomly selected epochs in the time series to determine statistical significance. For this, a Monte Carlo simulation of 1000 runs determined bootstrapped confidence intervals.

Teleconnection–climate relationships were analysed for past centuries by comparing the local climate proxy with two tree-ring derived reconstructions of the PDO (Biondi *et al.*, 2001; D'Arrigo *et al.*, 2001), and the Southern Oscillation Index (SOI) (Stahle *et al.*, 1998) for the period 1706–1849. Two PDO reconstructions were used because they were derived from tree ring records from different locations and no comprehensive PDO reconstruction has been developed using hemispheric proxy records comparable with the SOI. Tree ring chronologies from different locations may be sensitive to different signals and variability of the teleconnection (D'Arrigo *et al.*, 2001). The period of teleconnection-fire analysis is limited by the Southern Oscillation reconstruction that covers the period 1706–1977. Reconstructions were normalized (using z-scores) to the period, 1878–1977, and then the normalized teleconnection indices were used as a climate proxy in the superposed epoch analyses. To assess the interactive effects of the PDO and ENSO on fire regimes, reconstructed teleconnection indices were divided into thirds based on z-score values of ±0.43 and categorized as above normal, normal and below normal.

The mean number of forest units burned was then calculated for each phase category of the two PDO reconstructions and the SOI. To identify how teleconnections and local climate interacted over time, we calculated 31-year running correlations between PC1 and the PDO Index (D'Arrigo *et al.*, 2001) and the SOI (Stahle *et al.*, 1998).

RESULTS

Climate reconstruction

The first eigenvector of the PCA (PC1) explained 55% of the variation in the five tree ring chronologies. For the 87-year calibration period, PC1 is negatively correlated with October, November and January precipitation before the growing season and positively correlated with the previous years' November temperature and June temperature during the growing season (Table 1). High PC1 axis scores represent warm summers and/or warm, dry winters. Low scores represent cool summers and/or cool, wet winters. Subsequent PCA axes had eigenvalues <1.0 and axes with such low values are not normally useful because the variance is dominated by single variables (Jackson, 1993). Correlations between the individual chronologies and PCA scores on the second and third axes confirmed this, and so only PCA axis 1 scores were used for the fire–climate analysis.

Our annual climate proxy provides information that is relevant to summer burning conditions (June temperature) and winter drought (precipitation). In that summers are always dry, given the Mediterranean climate, our proxy is a poor indicator of summer precipitation. Our proxy is a better indication of annual or multi-season climate than summer drought. Given the limits of our resolution, we are limited in our ability to interpret how the production of fine fuel varied during the growing season and how fire climate varied during the late summer and early autumn.

Historic fire regimes

The pine forest experienced both small and widespread fires between 1700 and 1849 (Fig. 2). On six occasions, fire burned seven or more meadow units, and the interval between these widespread fires ranged from 7 to 49 years (Table 2). Moderately widespread fires burned in four or more units on nineteen occasions, and intervals between these fires ranged from 2 to 22 years. Fire burned in at least one unit in 93 of 150 years. There were more years with no recorded fire during the early portion of the study period than the latter, but 2–6-year periods without fire occurred on three occasions between 1785 and 1835 (Fig. 2).

Fire return intervals were longer during the period 1700–1774 than the period 1775–1849. Limited intervals for widespread fires restricted this analysis to two components: fires that burned one or more forest-meadow units, and two or more units. The period between fires that burned at least two units was significantly shorter after 1775 than before ($P = 0.046$), and intervals for single-unit fire events were also shorter ($P = 0.057$).

The season of burning was determined for 75% of fire scars. For the period 1700–1849, over half of these fires

Table 1 Pearson's correlation coefficients for PCA axis 1 (PC1) scores and mean monthly and seasonal climate variables from August of the year of growth through June of the preceding year for the period 1882–1979. Annual values were calculated from December of the prior winter through November of the year of growth. Winter is December, January and February and summer is June, July and August

	Prior October	Prior November	January	June	Winter	Summer	Annual
Temperature							
PC1	–	0.21*	–	0.32**	–	0.22*	–
Precipitation							
PC1	−0.21*	−0.23*	−0.28**	–	−0.28**	–	−0.32**

Only months or seasons with significant correlations are shown: *($P < 0.05$) or **($P < 0.01$).

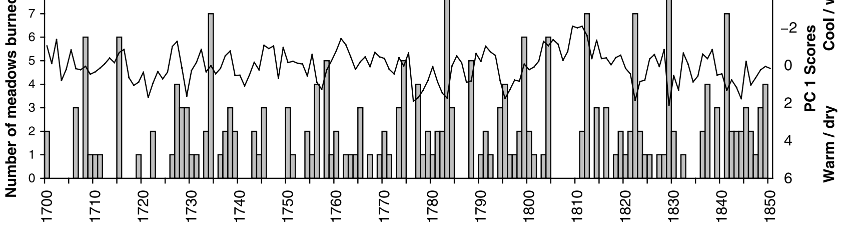

Figure 2 The number of units burned compared with PC1 axis scores for five tree ring chronologies. PC1 values were normalized to the 1878–1977 period. Positive PC1 values represent warm/dry winters and/or warm summers. Negative values indicate cool/wet winters and or cool summers. Note that the PC1 axis is reversed.

Table 2 Fire return intervals (FRI, in years) for fire events of different extent for the period 1700–1849

Number of units	Fire frequency	Mean FRI	Median FRI	FRI range
7+	6	21.4	12.0	7–49
6+	10	14.8	10.0	5–49
5+	13	11.1	9.5	5–24
4+	19	7.8	7.0	2–22
3+	34	4.3	4.0	1–12
2+	59	2.6	2.0	1–7
1+	93	1.6	1.0	1–7

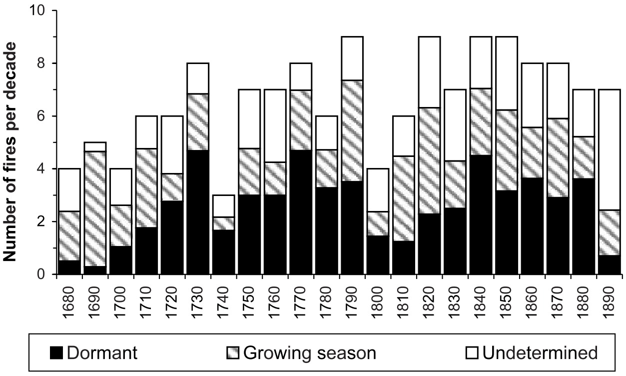

Figure 3 Seasonal variation in fire by decade, 1680–1899.

(57%) burned during the dormant period and nearly a one-third (32%) of fires scarred in earlywood. In this area, earlywood fires probably burned in early- to mid-summer (Taylor, 2000). The remaining fires (11%) occurred in latewood and probably burned during mid- to late-summer shortly before trees became dormant. Over a longer period of time, the prevailing season during which fires occurred varied considerably (Fig. 3). Growing season fires (including both earlywood and latewood scars) prevailed between 1680 and 1720, during the 1790s, and between 1810 and 1830. In other decades, fires burned mainly during the dormant season.

Fire–climate interactions

Climatic conditions influenced the occurrence of widespread, but not small fires between 1700 and 1849. Fires that burned seven or eight units occurred when winters were dry and/or June temperatures were high ($n = 6$, $P < 0.05$) (Fig. 4a). Years with less widespread fire were not associated with dryer or warmer than average conditions. However, conditions prior to widespread fires were important. Wetter/cooler than average conditions occurred 3 years prior to the most widespread fires ($n = 6$, $P < 0.05$), but the 1–3 years prior to fires that burned one or two units were dryer/warmer than normal ($n = 59$, $P < 0.05$ and/or $P < 0.01$). Although non-fire years were not wetter/cooler than average ($n = 57$, $P > 0.05$), the prior 1 year was typically wetter/cooler than average ($P < 0.05$).

Fire–teleconnection interactions

We found no relationship between ENSO variation and the number of units burned ($P > 0.05$) (Fig. 4b). Fires of all sizes occurred during El Niño conditions. Fires that burned five or six units occurred 4 years after an El Niño and 2 years before La Niña ($n = 7$), but this pattern was not found for the most widespread fires ($n = 6$, $P > 0.05$) and non-fire years were not associated with either phase of ENSO ($n = 52$).

A relationship between the PDO and fire extent is suggested by one of the two PDO reconstructions. For one reconstruction (Biondi *et al.*, 2001), widespread fires occurred the year before a negative (cool) phase of the PDO ($n = 6$, $P < 0.05$) (Fig. 4c). This suggests that widespread fires may be associated with the transitional phase of the PDO. Fires that burned one or two units occurred 1–2 years after a positive PDO ($n = 58$, $P < 0.05$). Non-fire years are associated with multi-year positive phases of the PDO ($n = 52$, $P < 0.01$). Analysis using the second PDO reconstruction (D'Arrigo *et al.*, 2001) showed no relationship to fire extent (Fig. 4d). Extreme phases of either ENSO or the PDO provide only a partial explanation for when fires of variable extent occur.

Consideration of ENSO and the PDO together suggests that variations in both ENSO and the PDO affect fire extent. Fire extent was greatest during normal or El Niño conditions ($P < 0.05$), but fire extent was strongly mediated by the phase of the PDO. The response of fire differs according to the PDO reconstruction used, however. El Niño fires were more widespread ($P < 0.05$) during warm PDO conditions (Table 3A) or when the PDO was normal (Table 3B). The most widespread fires occurred when an El Niño occurred while the PDO was normal (Table 3B). These results demonstrate that interactions of both tropical and temperate teleconnections were important components of the fire climate of north-eastern California.

Interactions between ENSO and the PDO were unstable over time, however. Correlations between PC1 and the PDO Index and the SOI indicate that the influence of teleconnections on local climate varied (Fig. 5). During most of the period, correlations with PC1 and both teleconnection indices were not significant ($P > 0.05$). Wet/cool conditions were associated with the cool phase of the PDO from 1790 through the 1820s, but with the warm phase of the PDO during the 1750s and 1770s ($P < 0.05$). ENSO was poorly correlated with PC1 during most of the period before 1850, but wet/cool conditions were associated with El Niño from 1730 through 1760.

DISCUSSION

Variation in climate influenced fire extent in north-eastern California in two important ways. First, fire extent was affected by interannual variability in moisture during the

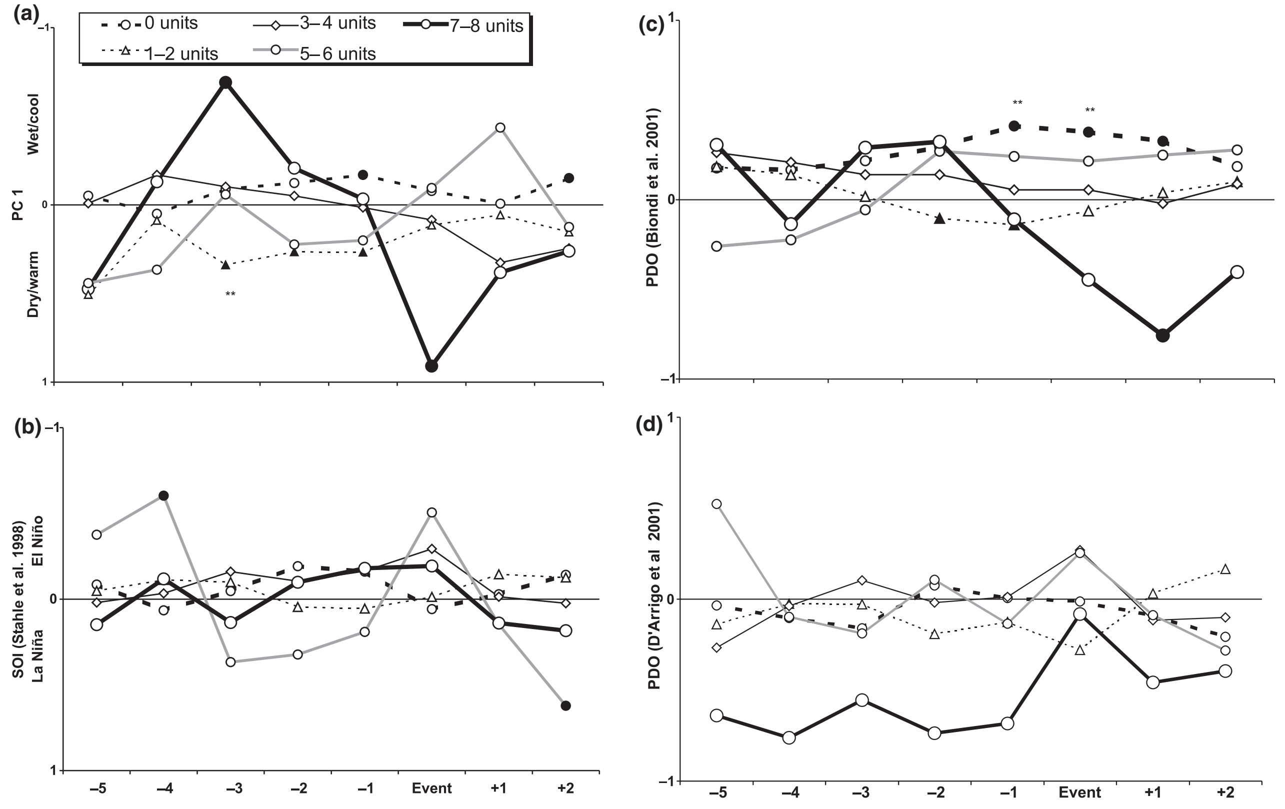

Figure 4 Superposed epoch analyses (SEA) of the scores of the first principle component (PC1) and three teleconnection indices with fires of different extent (1706–1849). PC1 and teleconnection values were normalized to the 1878–1977 period. Significant values are indicated by a filled circle ($P < 0.05$) or a filled circle and **($P < 0.01$) and were determined by a Monte Carlo simulation of 1000 runs. (a) *Z*-scores for the proxy of north-eastern California's climate based on the first principal component of the five chronologies; (b) the normalized Southern Oscillation Index (Stahle *et al.*, 1998); (c) the normalized Pacific Decadal Oscillation (PDO) of Biondi *et al.* (2001) and (d) D'Arrigo *et al.* (2001). The number of events used in the SEA for PC1 are: 0 meadow units, $n = 57$; 1–2 units, $n = 59$; 3–4 units, $n = 21$; 5–6 units, $n = 7$; 7–8 units, $n = 6$. SEAs using the PDO and Southern Oscillation Indices had no fire occur in 52 years and 1–2 units burned in 58 years.

year of burn and secondly, wet/cool conditions in the years prior to fire may have increased the production of fine fuel that was conducive to fire spread. This climate variation was influenced by teleconnections between the tropical and North Pacific. Interdecadal changes in fire season and fire return intervals provide further evidence that long-term climate variation provides an additional exogenous control on both fuel production and vegetation dynamics.

Climate and fuel dynamics

Climate conditions in the years prior to fires may have preconditioned the landscape to burn by increasing the production of fine fuel. Fuel accumulation in grass-dominated systems is thought to be particularly sensitive to short-term climate variability because grass responds quickly to seasonal and annual variation in climate (Cable, 1975; Bond & van Wilgen, 1996). A pattern of wetter than normal climate preceding widespread fire years has been documented in the Southwest (Baisan & Swetnam, 1990; Swetnam & Betancourt, 1998; Grissino-Mayer & Swetnam, 2000), Colorado (Veblen *et al.*, 2000; Donnegan *et al.*, 2001) and Argentina (Kitzberger *et al.*, 1997; Veblen *et al.*, 1999). In our study, a similar pattern of wet/cool conditions before widespread fires may suggest that an increase in fine fuel was necessary for fires to become widespread. Such short-term variation in fuel dynamics may help explain why only 7 years separate two of the most widespread fires (1822 and 1829). In our pine forests, fire hazard may have changed in response to short-term climate variation, rather than as a function of longer-term fuel accumulation related to time since last fire. By affecting short-term fuel accumulation and fire spread, variation in climate was a key regulator of fire frequency and hence, on forest structure and composition.

Our understanding of the relative importance of fire spread vs. multiple ignitions is limited by the distance that separates our fire scar collection sites. Trees are rare or absent from the expansive meadows that we believe provided fuel continuity. Our best record of mid-meadow fires is from samples collected from isolated tree groves in the centre of Pine Creek North (PCN) (Fig. 1). The similarity of fire

Table 3 Mean number of meadow-edge forest units burned during positive, normal and negative phase combinations of the Southern Oscillation Index (SOI) and two separate reconstructions (A and B) of the Pacific Decadal Oscillation (PDO) (1706–1849). All teleconnection values were normalized to the 1878–1977 period and were divided into three categories using *z*-scores of −0.43 and 0.43

	PDO (Biondi *et al.*, 2001)			
(A)	Warm (+) $P = 0.033^*$	Normal $P = 0.974$	Cool (−) $P = 0.097$	SOI alone $P = 0.040^*$
SOI (Stahle *et al.*, 1998)				
La Niña (+) $P = 0.015^*$	0.4 ($n = 16$)	1.7 ($n = 13$)	1.0 ($n = 10$)	1.0 ($n = 39$)
Normal $P = 0.158$	1.1 ($n = 16$)	2.0 ($n = 24$)	2.2 ($n = 21$)	1.8 ($n = 61$)
El Niño (−) $P = 0.339$	1.7 ($n = 24$)	1.6 ($n = 14$)	3.5 ($n = 6$)	1.9 ($n = 44$)
PDO alone $P = 0.018^*$	1.1 ($n = 56$)	1.8 ($n = 51$)	2.1 ($n = 37$)	1.6 ($n = 144$)

	PDO (D'Arrigo *et al.*, 2001)			
(B)	Warm (+) $P = 0.350$	Normal $P = 0.029^*$	Cool (−) $P = 0.369$	SOI alone $P = 0.040^*$
SOI (Stahle *et al.*, 1998)				
La Niña (+) $P = 0.910$	1.0 ($n = 8$)	0.8 ($n = 9$)	1.1 ($n = 22$)	1.0 ($n = 39$)
Normal $P = 0.702$	2.1 ($n = 21$)	2.0 ($n = 15$)	1.5 ($n = 25$)	1.8 ($n = 61$)
El Niño (−) $P = 0.031^*$	1.3 ($n = 22$)	3.4 ($n = 12$)	1.5 ($n = 10$)	1.9 ($n = 44$)
PDO alone $P = 0.292$	1.6 ($n = 51$)	2.2 ($n = 36$)	1.3 ($n = 57$)	1.6 ($n = 144$)

Significance was determined by a Kruskal–Wallis test of medians. $^*P < 0.05$. n is the number of years.

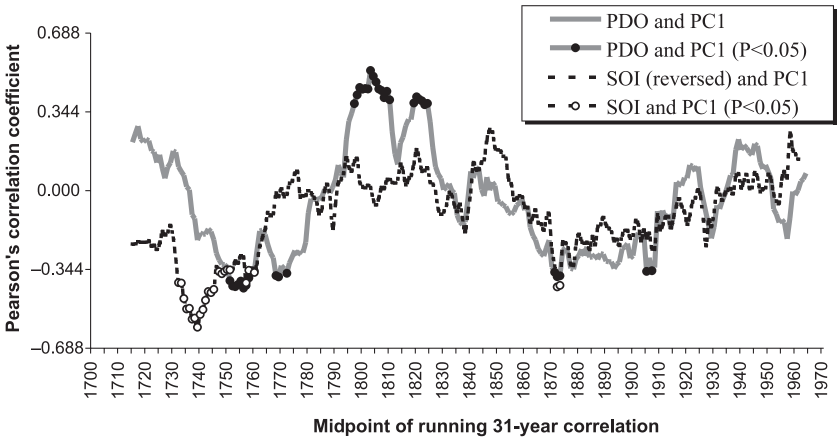

Figure 5 Temporal variation in the importance of teleconnections on north-eastern California climate shown by running 31-year correlations. Positive correlations of the Pacific Decadal Oscillation PDO (D'Arrigo *et al.*, 2001) and PC1 mean that a positive PDO is associated with warm/dry conditions in north-eastern California when fire extent was high. Negative correlations mean that a negative PDO is associated with warm/dry conditions. Negative correlations of the reversed Southern Oscillation Index (SOI) with PC1 suggest that occasionally warm/dry conditions were associated with La Niña, as they are today in the southwestern United States. Note that the correlation of PC1 with either phase of the SOI or PDO is low during most of the period of record. Significant correlations ($P < 0.05$) are indicated with open circles (SOI) or closed circles (PDO).

dates from these groves and meadow edge sites is consistent with our interpretation that fuels were continuous in meadows and in the forest understory and that widespread fires resulted from a climate-driven increase in fine fuel cover.

The importance of antecedent climate suggests that before 1850, widespread fires were the result of climate forcing rather than Native American ignitions. Ethnographic evidence gathered during the 20th century indicates that the Native Americans in the study area routinely burned for hunting and to harvest insects (Schulz, 1954; McMillin, 1963). Like ignitions from lightning, however, human ignitions may have only resulted in widespread fires during drought years that followed wetter than average climate conditions. Lightning ignitions are common in the study area (Rorig & Ferguson, 1999), unlike coastal California (Keeley, 2002), and so the ability of Native Americans to alter vegetation at the landscape scale using fire may have been limited by variation in climate and fuel production.

Climate and vegetation dynamics

The composition and structure of fire prone forests may be affected by changes in fire frequency, season, severity and extent (Agee, 1993; Bond & van Wilgen, 1996). Vegetation responses to changes in fire intervals are difficult to reconstruct, but evidence from the 20th century period of fire exclusion indicates that long fire-free periods in pine forests can lead to an increased density of less fire tolerant species, such as white fir (McNeil & Zobel, 1980; Taylor, 2000). In this study, fire intervals were longer between 1700 and 1774 than the subsequent 75-year period. This difference may have affected pine establishment, but it is unlikely to have had a substantial and lasting effect on forest composition. Fire intervals were much shorter between 1700 and 1774 than during the 20th century, and white fir trees or stumps are rare in meadow-edge forests (Norman, 2002).

Variation in season of burning may have had more important consequences for pine forest dynamics because pine species responses to fire are strongly influenced by the season of burn. For example, ponderosa pine mortality may be higher when fire occurs during the growing season than during the dormant season (Swezy & Agee, 1991). Small trees may be particularly vulnerable to these early season fires (Harrington, 1993). In our study, the periods 1680–1720, the 1790s, 1810s and 1820s experienced more early season fires than other periods, and these periods may have been particularly unfavourable for young tree survival. Ongoing variation in the seasonal pattern of ignition are also suggested by instrumental climate records for the last 31 years. Lassen National Forest fire records show that 47% of lightning ignitions occurred in August, 19% occurred in July and only 11% occurred in June. This seasonal pattern is inconsistent with the early season of burning that often occurred before 1850. Ignitions by Native Americans may account for the importance of early season fires (Martin & Sapsis, 1992), but when early season fires were widespread, it was because of a combination of drought and a wet/cool pre-fire climate that probably increased fuel production and hence the ability of fire to spread.

A climatic influence on fire extent is most apparent during severe drought years that are infrequent ($n = 6$). Less widespread fires show no consistent relationship with climate variability. This may reflect the limitations of our climate proxy or it may suggest that vegetation dynamics reflect the combined influence of episodic climate-driven fires and site-specific factors including time since fire and topography. Such complex multiscale interactions have been described elsewhere in the region where fire regimes varied according to slope aspect, elevation and the configuration of fuel breaks (Taylor, 2000; Beaty & Taylor, 2001; Heyerdahl *et al.*, 2001; Taylor and Skinner, 2003).

Climate dynamics

Variation in the extent of fire can be partially explained by climate and teleconnections. El Niño fires are more widespread than La Niña fires, but this distinction is most apparent when the PDO is in a normal or warm phase (Table 3). The typical strengthening of El Niño during the warm phase of the PDO may explain this pattern (Gershunov *et al.*, 1999). Discrepancies between the two PDO reconstructions may reflect differences in how the proxies were developed. One reconstruction relies on tree rings from southern California and Baja California, Mexico (Biondi *et al.*, 2001), while the other incorporates tree rings from north-western Mexico and the north Pacific (D'Arrigo *et al.*, 2001). Reconstructions developed from tree-ring chronologies from different areas may provide different signals. In particular, North Pacific chronologies may provide a stronger and more consistent record of changes in the PDO than reconstructions from lower latitudes (D'Arrigo *et al.*, 2001). The strength of El Niño fires during the normal phase of the PDO (D'Arrigo *et al.*, 2001) (Table 3B) suggests that fire regimes may be more sensitive to intermediate phases of the PDO than to the extremes.

The multi-decadal period of strong PDO influence on local climate that occurred between the 1790s and the 1820s (Fig. 5) is of particular interest because ENSO is thought to have weakened during this period (Anderson, 1992; Dunbar *et al.*, 1994; Kitzberger *et al.*, 2001). The PDO was in an unusually cool phase (D'Arrigo *et al.*, 2001) and temperatures were below normal in the Canadian Rockies (Case & MacDonald, 1995; Luckman *et al.*, 1997). The PNW experienced its coolest growing season temperatures since 1750, in many years 0.5–1.0 °C cooler than normal (Wiles *et al.*, 1996), and between 1805 and 1820, precipitation was above normal in western Washington (Graumlich, 1987). In the Sierra Nevada of California, the 50-year 1780–1829 period was −0.3 °C cooler than the instrumental period (1928–1988) normal (Graumlich, 1993), and it was also a time of increased stream flow in the Sacramento River (Earle, 1993).

The fire climate of northern California appears to have also changed during this period. Widespread fires were more common between 1783 and 1841 than earlier. Early season fires prevailed from 1790–1799 and 1810–1829. These changes in fire climate coincide with those in the Southwestern United States (Swetnam & Betancourt, 1998; Grissino-Mayer & Swetnam, 2000) and Argentina (Kitzberger *et al.*, 2001). Our results from the Southern Cascades differ from other areas, however, in that fires were widespread during this period in north-eastern California, while in New Mexico (Brown *et al.*, 2001) and north-eastern Oregon (Heyerdahl *et al.*, 2002) fires were less extensive.

Variation in the magnitude and direction of the correlations between reconstructed teleconnections and our climate proxy (Fig. 5) emphasizes that the climate processes that affect fire–climate relationships are complex. In that fire–climate relationships changed over decades, a better understanding of climate dynamics will enhance our understanding of how future changes in ENSO and the PDO may affect fire regimes.

Changes in the historic fire climate of north-eastern California provide some insight into how the latitudinal effects of teleconnections vary over time. Widespread fires were usually associated with El Niño, as was reported in portions of north-eastern Oregon (Heyerdahl *et al.*, 2002) rather than La Niña, as is typical of the southwest (Swetnam & Betancourt, 1990). We have provided evidence that ENSO's effect on northern California fire climate was influenced by the climate of the north Pacific. This is consistent with the way that ENSO and the PDO are thought to interact (Gershunov *et al.*, 1999). Further fire climate studies conducted along this latitudinal gradient may improve our understanding of how the influence of teleconnections on ecological processes may vary regionally and over time.

Climate-mediated fire regimes provided the pine forests of north-eastern California with an ever-changing history of disturbance. Interannual variation in climate effectively regulated conditions conducive to fire, and longer-term change in fire intervals, season and extent correspond with climate-mediated changes observed across the hemisphere. In this paper, we show that the source of this variability of fire regimes is short and long-term changes in the North Pacific (PDO) and the tropics (ENSO). Over time, the dynamic disturbance regime that these teleconnections fostered probably contributed to variable pathways of forest development. The structure and composition of the area's pine forests upon Euro-American arrival in 1849 would have reflected this unique history.

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