Climatic influences on fire regimes in montane forests of the southern Cascades, California USA

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Abstract

The relationship between climate variability and fire extent was examined in montane and upper montane forests in the southern Cascades. Fire occurrence and extent were reconstructed for seven sites and related to measures of reconstructed climate for the period 1700 to 1900. The climate variables included the Palmer Drought Severity Index (PDSI), summer temperature (TEMP), NINO3, a measure of the El Niño-Southern Oscillation, and the Pacific Decadal Oscillation PDO. Fire extent at the site and regional scale was associated with dry and warm conditions in the year of the fire and regional fire extent was not associated with ENSO or PDO for the full period of analysis. The relationship between regional fire extent and climate was not stable over time. The associations of fire extent with PDSI and TEMP were only significant from c. 1775 onward and the associations are strongest between 1805-1855. PDO and fire extent were also associated during 1805-1855 period and ENSO was associated with fire extent before 1800, but not after. The interannual and interdecadal variability of the fire response to temperature and drought, suggests that increased periods of regional fire activity may occur when high interannual PDSI variation coincides with warm decades.

Key words: Climatic variation, fire regimes, Pacific Decadal Oscillation, El Niño/Southern Oscillation, fire ecology, American Pacific Coast, montane forests

Running Head: Fire climate interactions in the southern Cascades

Introduction

Fire regimes in the forested landscapes of the southern Cascades are controlled by environmental processes and interactions that vary across a range of spatio-temporal scales (Skinner and Taylor 2006). For example, at local scales spatial and temporal variation in fire frequency, extent, and severity prior to widespread Euro-American settlement are related to elevation, slope aspect, species composition, and time since the last fire (Taylor 2000; Beaty and Taylor 2001; Bekker and Taylor 2001; Taylor and Solem 2001; Taylor and Skinner 2003). On the other hand, at regional scales spatial and temporal variation in fire regimes are linked to changes in land use practices such as fire suppression and to climatic variability (Beaty and Taylor 2001; Taylor and Solem 2001; Norman and Taylor 2003; Skinner and Taylor 2006). Years of widespread burning in forests of Pacific Coast states before 20th century fire exclusion were broadly synchronous and usually associated with drought conditions (e.g. Swetnam and Baisan 2003; Hessl et al. 2004; Taylor and Beaty 2005), but drought may not be a precondition for widespread burning during some periods (Taylor and Beaty 2005). Thus, fire-climate interactions can be complex (e.g. Swetnam 1993; Grissino-Mayer and Swetnam 2000) and analyses of how climate modulates fire regimes over long periods are needed to understand fire-climate relationships and how fire regimes may respond to projected temperature increases associated with global climate change (Hayhoe et al. 2004). In the southern Cascades, where this study was conducted, fire regimes are thought to be particularly sensitive to temperature increases because of their effect on snowpack duration and fire season length (Dettinger and Cayan 1995; Lenihan et al. 2003; Hayhoe et al. 2004).

Interannual climatic variation along the Pacific Coast is strongly influenced by variation in sea surface temperatures (SST) in the eastern and central tropical Pacific Ocean associated with the El Niño-Southern Oscillation (ENSO). ENSO is a coupled ocean-atmospheric process that generates regionally distinct high frequency (3-7 year) variations in temperature and precipitation (Diaz and Markgraf 2000). Conditions in the American Southwest (SW) during a warm phase ENSO (El Niño) are typically wet and warm, while during a cool phase ENSO (La Niña) conditions are cooler and drier. The pattern of climatic variation associated with ENSO is the opposite in the American Pacific Northwest (PNW). SST variation associated with the Pacific Decadal Oscillation (PDO) in the north Pacific generates "ENSO-like" climatic variation at inter-decadal time scales (Dettinger et al. 2000). When the PDO is in a warm phase, conditions in the SW are wetter than average and they are dry and warmer in the PNW; the opposite pattern prevails during a cool phase PDO (Nigam et al. 1999). Moreover, the PDO interacts with ENSO modulating the amplitude and geographic expression of climatic variation associated with ENSO (Gershunov et al. 1999). The southern Cascades are located in the pivot zone of the ENSO-PDO precipitation dipole that is located at c. 40-45° N and which shifts north or south on interannual and decadal time-scales (Dettinger et al. 1998). Thus, interannual and interdecadal fire-climate associations in this location may be similar to those in the PNW in some periods and to the SW in others (Westerling and Swetnam 2003; Taylor and Beaty 2005).

The goal of this study is to identify the relationships between climate variability (ENSO, PDO, drought) and fire occurrence and extent during the pre fire suppression period in the southern Cascades at interannual to multi-decadal time scales. In our analysis, we place particular emphasis on identifying fire-climate relationships: 1) across the range of of dominant forest types in the montane and upper montane zones in the southern Cascades; and 2) during different time periods prior the establishment of organized fire suppression in 1905 (Strong 1973). Specifically, we address the following questions: 1) How have fire extent and frequency varied over time? 2) Were widespread fires synchronous, did they burn primarily in dry year,s and were years with less burning wet ones? 3) Has fire frequency and extent varied with ENSO, PDO and their interactions? 4) Have fire-climate relationships varied over time or have they remained constant?

Materials and Methods

Study Area

Montane and upper montane forests in the southern Cascades are segregated primarily by elevation and secondarily by topographic position (Barbour 1988; Parker 1991). Low elevation (< 600m) xeric sites on the westside of the range are usually dominated by ponderosa pine (Pinus ponderosa) with black oak (Quercus kelloggii) as an important associate. On the eastside of the range, low elevation (<1700m) xeric uplands are dominated either by Jeffrey pine (Pinus jeffreyi) or ponderosa pine, and western juniper (Juniperus occidentalis ssp. occidentalis) may be an associate on the driest sites. Mixed conifer forests dominate the landscape above the lower montane zone to about 2000 m. In this zone, any of six conifer species ponderosa pine, Douglas-fir (Pseudotsuga menziesii), sugar pine (Pinus lambertiana), incense cedar (Calocedrus decurrens), Jeffrey pine, and white fir (Abies concolor) – may co-occur and share dominance in a stand depending on site conditions and stand history. A subcanopy of the hardwoods black oak, Pacific madrone (Arbutus menziesii), big leaf maple (Acer macrophyllum), Pacific dogwood (Cornus nuttallii), and canyon live oak (Quercus chrysolepis) may be present in stands found on the more temperate west side of the range. In the mixed conifer zone, the tree cover is often interrupted by stands of montane chaparral. Chaparral shrubs are usually <2 m tall and the most common species are green-leaf manzanita (Arctostaphylos patula), California lilac (Ceanothus sp.), and shrub oaks (Quercus sp). Montane chaparral shrubs are fire adapted (e.g. sprout following fires or regenerate from fire-stimulated seeds) and chaparral appears to occupy sites that once experienced high-severity fire or are too poor to support trees (Wilken 1967; Nagel and Taylor 2005). Mixed white fir and red fir (Abies magnifica var. shastensis) forests occur above the mixed conifer zone. Above 2000 m white fir is replaced by red fir and western white pine (Pinus monticola), which are upper montane zonal dominants. Topographic lowlands that receive cold air drainage are dominated by either Jeffrey pine or lodgepole pine (Pinus contorta). In these locations, lodgepole pine is more common on the more mesic sites or sites that have experienced high severity fire. Forests and woodlands above 2400 m are dominated by mountain hemlock (Tsuga mertensiana) or whitebark pine (Pinus albicaulis) (Barbour 1988; Parker 1991).

Fire occurrence and extent were studied at seven sites that include the dominant montane and upper montane forest types found in the southern Cascades (Fig. 1; Table 1). Elevations for sites ranged from 1136 to 2646 m and study areas ranged from 2 to 26 km^2, except for Lassen Meadows (LM), which covered 700 km^2 (Table 1). Climate in the southern Cascades is characterized by warm, dry summers and cold, wet winters. Annual precipitation decreases from west (Mineral, 137 cm; elevation 1486 m) to east (Susanville, 36 cm; elevation 1300 m) and is generally lower north of Mount Shasta on either side of the range due to the rain shadow of the Klamath Mountains. Most (> 75%) precipitation falls as snow between November and April. Depth of April snowpack in the upper montane zone commonly exceeds 2 m on the west side of the range where snow may persist into mid – late June in wet years (Taylor 1990). Mean monthly temperatures in Mineral on the west side of the range are lowest in January (-1.1 ˚C) and highest in July (16.9 ˚C). The snowpack on the east side of the range is usually shallower and temperatures are more continental. Mean monthly temperatures for Mount Hebron at 1295m in January are –2.7^{o}C and 17.1^{o}C in July (Skinner and Taylor 2006). Additional details on site conditions are provided in references cited in Table 1.

Human influence on fire regimes in the southern Cascades has varied over time. Native Americans are known to have used fire to collect insects, to drive game and to encourage certain plants used for food and fiber (Schulz 1954). Euro-American settlement began c. 1850. Sheep and cattle grazing, which influences the continuity of grassy fuels, began in the 1860s (Norman and Taylor 2005). A policy of suppressing fire was first implemented along railroad lines in the 1880s (Skinner and Taylor 2006) and became more widespread with establishment of the Forest Reserve system in 1905 (Strong 1973; Norman and Taylor 2005).

Fire record

Fire occurrence and extent during the pre fire suppression period were reconstructed using fire-scarred cross sections removed from fire-scarred stumps, logs, and trees (Arno and Sneck 1977). Samples were widely distributed in each study area to capture spatial variability in fire regimes related to environmental and species compositional gradients (Table 1). The number of fire scar samples per site ranged from 39 to 152; a total of 530 samples are included in this study (Table 1). Cross sections were sanded to a high polish and each sampled tree-ring series was crossdated using standard dendrochronological techniques (Stokes and Smiley 1968). The calendar year of a tree-ring with a fire scar lesion in it was then recorded as the fire date. Fire scars that could not be crossdated were not used in subsequent analyses.

Fire regimes were characterized for each site and for the southern Cascades region (all sites). For each site we identified fire years recorded by any, 10% or more, and 25% or more of samples. For the southern Cascades region, we first identified fire years that were recorded by two or more samples at each site and used these fire dates for characterizing regional fire extent. An index of variability in regional annual fire extent was calculated by first determining the percentage of samples that recorded a fire in each year at each site. We then summed the site percentages as our index of annual fire extent for the southern Cascade region (Figure 2). This index provides a measure of how widespread burning was both within and among sites but no assumptions are made about the number or spread of fires represented by the index.

Climate record

Four tree-ring based reconstructions of climatic variables were used to evaluate the relationships between climate and fire. First, we used the Palmer Drought Severity Index (PDSI) as an index of drought (Palmer 1965). PDSI is a composite index that integrates immediate and lagged precipitation and temperature in estimating drought severity. We used the reconstructed summer PDSI at grid point 35 to represent drought conditions in the southern Cascades (Cook and Krusic 2004). Second, as an index of temperature we used the reconstruction of western North American summer temperature (TEMP) by Briffa et al. 1992 (gridpoint 16) which expresses temperature variation relative to the 1951-1970 base period. Third, we used a reconstruction of NINO3, a measure of tropical Pacific SST temperature variation that is frequently used as an ENSO index (Cook 2000). Finally, a reconstruction developed by Gedalof et al. (2002) was used as our index of the PDO.

Fire-Climate analysis

We used a combination of correlation analysis and superposed epoch analysis (SEA) to examine interannual and interdecadal relationships between TEMP, PDSI, ENSO, PDO, and fire (Haurwitz and Brier 1981; Baisan and Swetnam 1990). For the interannual analysis SEA was used to evaluate the relationship between events (fire years) and climate, by superposing a window of contemporaneous and lagged climatic conditions over each event year. Significance levels between events and climatic conditions were determined from bootstrapped confidence interval estimates (95%) based on Monte Carlo simulations (Mooney and Duval 1993). SEA was performed separately for each site for fire years of different fire extent (any, ≥10% of samples) and for years of different fire extent in the region (≥1, ≥2 or ≥3 sites), and for non-fire years, to identify climatic conditions conducive and unfavorable for fire.

Correlation analysis was also used to identify the association between interannual variability in fire extent and climate. For each site, and for the region, we calculated the

Pearson product moment correlation coefficient of fire extent with each climate variable for the period 1700-1900. We used first differences (value (year t) – value (year t-1)) for each variable to calculate correlation coefficients to emphasize the interannual variability in each time series.

Decadal-scale relationships between fire and climate were identified using correlation analysis. Pearson product moment correlation coefficients were calculated for fire and climate time series of sequential 21-year non-overlapping means (Swetnam 1993). We extended the time series for the decadal analysis back to 1600 to increase sample size (n=10 to n=15) for calculation of the correlation coefficients. Four of the seven sites had a record of fire back to 1600.

Results

Fire record and synchronicity of fire

The southern Cascade forests have a long history of fire. The record of fire spans the period AD 1375 to 1942 and the number of fire dates per site ranges from 23 to 197 (Table 1). We chose the period 1700-1900 for the climate analysis during which all sites and a minimum of 100 samples recorded fire (Fig.2).

Fire dates co-occurred among sites much more frequently than expected by chance alone ($\chi^2 = 69.2$, $p<0.001$). For example, over a 200-year period, seven fire dates are expected to co-occur among three or more sites; our record had 29 such co-occurring fire dates. Strong temporal synchrony in fire dates among widely dispersed sites suggests a strong regional influence on the occurrence and extent of fire in the southern Cascades.

Fire climate interactions

Interannual relationships --Results of the SEA and correlation analysis of fire and PDSI for individual sites were similar for the 1700-1900 period (Fig. 3; Table 2). For SEA, fire years were associated with low moisture conditions and the opposite was true for non-fire years, except in CAR and LB where fire years and PDSI were unrelated (Fig. 3; Table 2). Larger burns (≥10% and ≥25%) occurred during drier years and antecedent climatic conditions (wet) were associated with fire years only in GAMA. For the correlation analysis, variation in fire extent was associated with dry and warm summer conditions in the year of the fire (Table 2). Variation in fire extent was also positively correlated with NINO3 in three of the seven sites; no correlation was found between fire extent and PDO at any of the sites.

Fire extent among sites was also strongly associated with drought. The SEA of PDSI indicates fire years are associated with low moisture conditions with more sites burning during the driest years, and non-fire years are wet (Fig.4). The SEA shows no association between regional fire extent and ENSO, PDO, or TEMP. However, correlation analysis indicates a strong association between dry conditions, high summer temperature and regional fire extent (Fig. 5a; Table 2). Regional fire extent was not correlated with ENSO or PDO.

Temporal variability The relationship between regional fire extent, PDSI, and TEMP was not consistent over time. Correlation coefficients for first differences of fire extent with PDSI and TEMP are only significant from c. 1775 onward and the correlations are strongest between 1805-1855 (Fig. 5b). Although there was no correlation between fire extent and PDO for the 1700-1900 period (Table 2), PDO and fire extent were positively correlated for the 1805-1855 period. Fire extent and ENSO were positively correlated before 1800, but not after (Fig. 5b).

Temporal variation in the relationship between PDSI and regional fire extent is confirmed by separate SEA for the 1700-1800 and 1800-1900 time-periods (Fig. 4). Widespread fires were associated with drought after but not before 1800. Moreover, non-fire years after 1800 were wet, but this was not the case before 1800. SEA showed no differences or significant relationships between fire extent, TEMP, ENSO, or PDO

Interdecadal relationships-- There was no significant correlation between regional fire extent and PDSI on a decadal time scale. However, variation in fire extent was correlated with variation in TEMP ($r=0.45$, $P<0.01$) and ENSO ($r=0.48$, $P<0.01$) (Fig. 6).

Discussion and Conclusions

Fire occurrence in the southern Cascades was strongly synchronous despite long distances between sites and large differences in forest composition and elevation which are variables known to be locally associated with variation in fire frequency, fire extent, and fire severity in the southern Cascades (Taylor 2000; Bekker and Taylor 2001; Skinner and Taylor 2006). The expected frequency of co-occurring fire for six of seven sites is once every 13000 years. Yet, six sites burned in the same year five times (1751, 1781, 1800, 1829, 1883) during our 200-year study period. This high synchrony of fire dates among sites is probably not caused by burns that spread continuously between sites. Instead, the synchrony reflects a strong influence of regional climate that promotes conditions that are conducive to burning across the range of montane and upper montane forests present in the southern Cascades (Swetnam and Betancourt 1998, Donnegan et al. 2001).

There is a strong relationship between drought and widespread burning during the pre-fire suppression period in coniferous forests in the SW (Swetnam and Baisan 2003), the PNW (Heyerdahl et al. 2001; Hessl et al. 2004), and Rocky Mountain (RM; Donnegan et al. 2001) regions in the western USA. The overall effect of drought on temporal patterns of burning in the southern Cascades is similar. Widespread burning within the region is associated with both low moisture conditions and warm summer temperatures during the fire year. The opposite climatic conditions characterize non-fire years. Moreover, across all sites, years of widespread burning did not lag years of high moisture availability. This suggests that fires are dependent on drought and warm summer temperatures and not increased production of fine fuels, at least across sites and forest types in the region. However, in the dry mixed conifer forests at GAMA, and in dry pine forests in the northern Sierra Nevada (Taylor and Beaty 2005), wet conditions preceded years with widespread fire. Presumably, increased production of fine grass and herbaceous fuels in wet years increased fuel connectivity promoting widespread burning in subsequent dry years. This fire-climate pattern has also been documented for dry pine forests in the SW (Swetnam and Baisan 2003), northern Mexico (Stephens et al. 2003), and the RM (Veblen et al. 2000), but not in the PNW. In the dry pine forests of the PNW, increased growth of fine fuel in wet years is not necessary to precondition the landscape for widespread burning (Heyerdahl et al. 2001; Hessl et al. 2004).

Interannual variation in ENSO has been identified as a strong control on variation in fire extent in pine dominated forests in the SW (Swetnam and Betancourt 1990), northern Mexico (Stephens et al. 2003), PNW (Heyerdahl et al. 2002), and the RM (Veblen et al. 2000). In each of these regions, years with widespread burning are associated with the ENSO phase that corresponds with drier and warmer conditions. In the southern Cascades, ENSO was not a strong driver of variation in fire extent at the regional scale, though there was a weak influence of ENSO on the extent of fires in three of the seven sites. Spatial variation in the position of zonal precipitation in the ENSO pivot zone on interannual time scales may reduce the coherency of the ENSO signal on fire-climate in this region. In the northern Sierra Nevada, interannual variation in instrumental precipitation tends to be independent of ENSO (Schonher and Nicholson 1989).

Fire occurrence and extent in the western USA has been shown to vary with the PDO. In the southern RM, widespread fires in high elevation forests are associated with a negative (cool phase) PDO (Schoennagel et al. 2005; Sibold and Veblen 2006). On the other hand, in lower elevation pine forests in the PNW, widespread burning tended to coincide with a positive PDO (Hessl et al. 2004), where the PDO is a driver of multidecadal winter precipitation (Mantua et al. 1997). In some dry pine and mixed conifer forests in the northern Sierra Nevada, years with widespread burning are also associated with a negative PDO while non-fire years are associated with the opposite or positive PDO (Taylor and Beaty 2005; Moody et al. 2006). In the southern Cascades, variation in the frequency and extent of burning was not related simply to variation in the PDO. Instead, the relationship between fire extent and PDO varied by time period.

The sensitivity of fire activity in the southern Cascades to climatic variation was not consistent over time. There is a sharp peak in the strength of the association between concurrent low PDSI, warm summer temperatures and widespread burning in the c. 1800-1850 period. One explanation for the peak during this 50-year period could be methodological, related to the large amplitude switch in PDSI and fire extent between the years 1829 and 1830. Periods with high amplitude changes can inflate running correlation coefficients (Swetnam and Betancourt 1998). However, the frequency based SEA analysis confirms that drought was associated with fire during the 1800-1900 period, but not during the 1700-1800 period. Similarly, concurrent drought and fire extent in dry pine forests in the northern Sierra Nevada are associated during the 1775-1850 period, but not between 1700 and 1775 (Taylor and Beaty 2005). This suggests that the temporal change in fire-climate relationships affected a wide area.

The late 18th – early 19th century transition period (LEENT) has previously been identified as a period of shifting fire regimes and shifting fire-climate relationships in forests and woodlands in other parts of the western USA, northwestern Mexico (Stephens et al. 2003), and even Argentina (Grissino-Mayer and Swetnam 2000; Kitzberger et al. 2001). At many sites in the SW and northwestern Mexico, this period was characterized by reduced fire occurrence, and a related increase in the synchrony of fire (Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2000; Stephens et al. 2003; Swetnam and Baisan 2003; Sakulich and Taylor 2007). Some of these fire regime shifts have also been documented for forests in the RM (Veblen et al. 2000; Donnegan et al. 2001) and the PNW (Heyerdahl et al. 2002) during the same period. The hemispheric scale of the LEENT fire regime shift suggests a global-scale driver. A decadal-scale decline in ENSO frequency and amplitude during the LEENT (Anderson et al. 1992; Cleaveland et al. 1992; Mann 2000), in particular, and the corresponding dampening of dry/wet patterns, has been suggested as a driver of the fire regime shifts (Kitzberger et al. 2001, Stephens et al. 2003, Swetnam and Baisan 2003). The weak influence of ENSO on fire regimes in northern California may explain why no shifts in the frequency/synchrony of fire were observed during the LEENT in our study area.

The dampening of the ENSO signal is possibly linked to a shift of PDO during the LEENT to an unusually cool phase (D'Arrigo et al. 2001), since the PDO phase affects the strength of ENSO climatic effects (Gershunov and Barnett 1998; McCabe and Dettinger 1999). PDO and fire activity in the southern Cascades in the LEENT period are positively associated, which corresponds with a strengthening of the PDO teleconnection in northern California. The strengthening of the inter-annual association between drought, summer temperature, and fire during the LEENT in the southern Cascades and northern Sierra Nevada (Taylor and Beaty 2005), however, contrasts sharply with the decline in the responses of fire to interannual climate patterns found for the same period in the Southwest (Grissino-Mayer and Swetnam 2000, Swetnam and Baisan 2003). The LEENT generally corresponds to an extraordinarily cold period over the northern Hemisphere (Mann et al. 1998), but moisture conditions vary by region. Whereas conditions tended to be wetter than normal in California (Earle 1993) and the PNW (Graumlich 1987), the Southwest was characterized by an increasing frequency of dry springs and summers (Swetnam and Baisan 2003). T

The cool and wet conditions in northern California during LEENT probably enhanced the interannual relationship between drought and fire extent.. Severe drought is a prerequisite for fire occurrence and spread during conditions that are wet and cool compared to drier periods, especially across a range of montane and upper montane forest types where fuel is not an important limitation on fire spread (Swetnam and Betancourt 1990). Snowpacks persist longer in wet and cool years in the montane and upper montane forests of the southern Cascades, shortening fire season length (Taylor 1995, 2000). During a multi-decadal period of cool-wet conditions, high summer temperatures would promote earlier snowmelt, earlier fuel moisture depletion, and a longer fire season - all conditions more favorable to fire spread.

The strengthening of fire-climate relationships during LEENT could also result from a change in the influence of Native American burning on fire regimes. Native American tribes in the southern Cascades are known to have used fire to improve wildlife habitat, drive game, encourage certain plants for food and fiber, and to collect grasshoppers (Schultz 1954). Native American population in the region declined rapidly in the 19th century after contact with Euro-Americans (Cook 1943). However, the decline in Native American populations in the southern Cascades is thought to have occurred several decades after the onset of LEENT and the interhemispheric nature of the timing of altered fire regimes suggests a global and not local driver of fire regime change

Fire occurrence and extent in the southern Cascades were also affected by inter-decadal variation in ENSO and summer temperatures. Decades in which the El Niño phase dominates coincide with widespread fires and vice versa. Similarly, decades with higher summer temperatures experienced more widespread burning than cooler decades. The decadal scale sensitivity of fire regimes to the ENSO cycle and summer temperature may be a long-term influence of ENSO and temperature on fuel production. Decadal time scale sensitivity of fire regimes has been attributed to long-term temperature-related shifts in fuel production (Swetnam 1993) and to concentration of temperature variability in decadal frequencies (Swetnam and Betancourt 1998). Variation in fire extent, however, was not related to PDSI on an inter-decadal scale, which stresses the importance for fire spread of high frequency (inter-annual) wet-dry cycles and the abrupt fuel moisture changes related to them (Swetnam 1993). The frequency dependent fire response to temperature and drought, suggests that regional fire activity is most extensive when high interannual variation in PDSI coincides with warm decades (Swetnam and Betancourt 1998).

Climate strongly influenced fire regimes in the southern Cascades during the pre-fire suppression period. Both interannual and interdecadal climatic variation promoted conditions conducive to fire, but fire-climate relationships were not stable over time. The timing of changes in fire-climate relationships is similar to the timing of changes identified in other regions in both the northern and southern hemisphere (Kitzberger et al. 2001) suggesting a strong linkage between global circulation and climatic conditions conducive to fire.

The strong relationships between climate and pre-fire suppression fire regimes in the southern Cascade, particularly the association of fire with inter-decadal temperature variations suggests that future climatic change is likely to affect fire regimes in the region. Climate models project warming for the southern Cascades with increased concentrations of green house gases in the atmosphere (Hayhoe et al. 2004). Although active fire suppression and forest management have led to less overall area being burned than was likely in the past (Skinner and Chang 1996), 20th century fire extent in the western United States remains strongly linked to climatic conditions (Westerling and Swetnam 2003; Trouet et al. 2006; Westerling et al. 2006). In fact, it may be that the relationship between climate and fire extent has been enhanced due to efficiency of fire suppression forces controlling most fires while quite small except for those under more extreme conditions. However, because of anthropogenic interference on the one hand and the complex character of fire-climate interactions on the other, predicting which years will have big fires remains a challenge.

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Table 1. Location and sample characteristics for sites in the southern Cascades. The forest types are: ponderosa pine (PP), ponderosa pine-Jeffrey pine (PP-JP), white fir-Jeffrey pine (WF-JP), mixed conifer (MC), red fir-white fir (RF-WF), red fir-western white pine (RF-WWP), lodgepole pine (LP), red fir-mountain hemlock (RF-MH). Additional details on forest conditions and fire regimes in each area are given in the cited reference.

Site	Elevation (m)	Area (km^2)	Samples	Time period	Reference	Dominant Forest Types
Lava Beds (LB)	1580-1670	13.7	63	1563-1904	Heyerdahl et al. 2006	PP
Goosenest (GAMA)	1495-1800	2	44	1375-1935	Ritchie 2005	MC
Thousand Lakes (TLW)	1700-2646	20.4	50	1652-1942	Bekker & Taylor 2001	RF-MH/LP/RF-WF/WF-JP
Lassen Meadows (LM)	1650-2300	700	152	1520-1944	Norman & Taylor 2003	PP
Prospect Peak (PP)	1800-2420	26.3	126	1507-1937	Taylor 2000	RF-WWP/WF-JP/JP-PP
Caribou (CAR)	2060-2390	9.5	39	1735-1982	Taylor & Solem 2001	LP/RF-WWP/WF-JP
Cub Creek (CCRNA)	1136-2044	15.9	56	1616-1926	Beaty & Taylor 2001	MC

Table 2: Pearson correlation coefficients of fire extent and climate for the period 1700-1900 for seven sites and a composite of all sites, southern Cascade Range, California. The climatic variables are Palmer Drought Severity Index (PDSI), summer temperatures (TEMP), the El Niño Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO)*p<0.05 or **p<0.01.

site	PDSI	TEMP	ENSO	PDO
LB	-.06	-0.23	.057	-.01
GAMA	-.208**	.163*	-.05	-.01
TLW	-.251**	.171*	.157*	0.07
LM	-.206**	.145*	.153*	.08
PP	-.228**	.192**	.155*	0.03
CAR	-.185**	.07	-.049	.03
CCRNA	-.2**	.222**	.04	.10
Composite	-.356**	.252**	.129	.08

Figure 1. Location of study sites with fire scar samples in the southern Cascade Range, California. National Forest and National Park lands are shown in light and dark grey, respectively.

Figure 2. Proportion of samples scarred in each study area and cumulative proportion for all sites in the southern Cascades, California. n=number of fire scar samples.

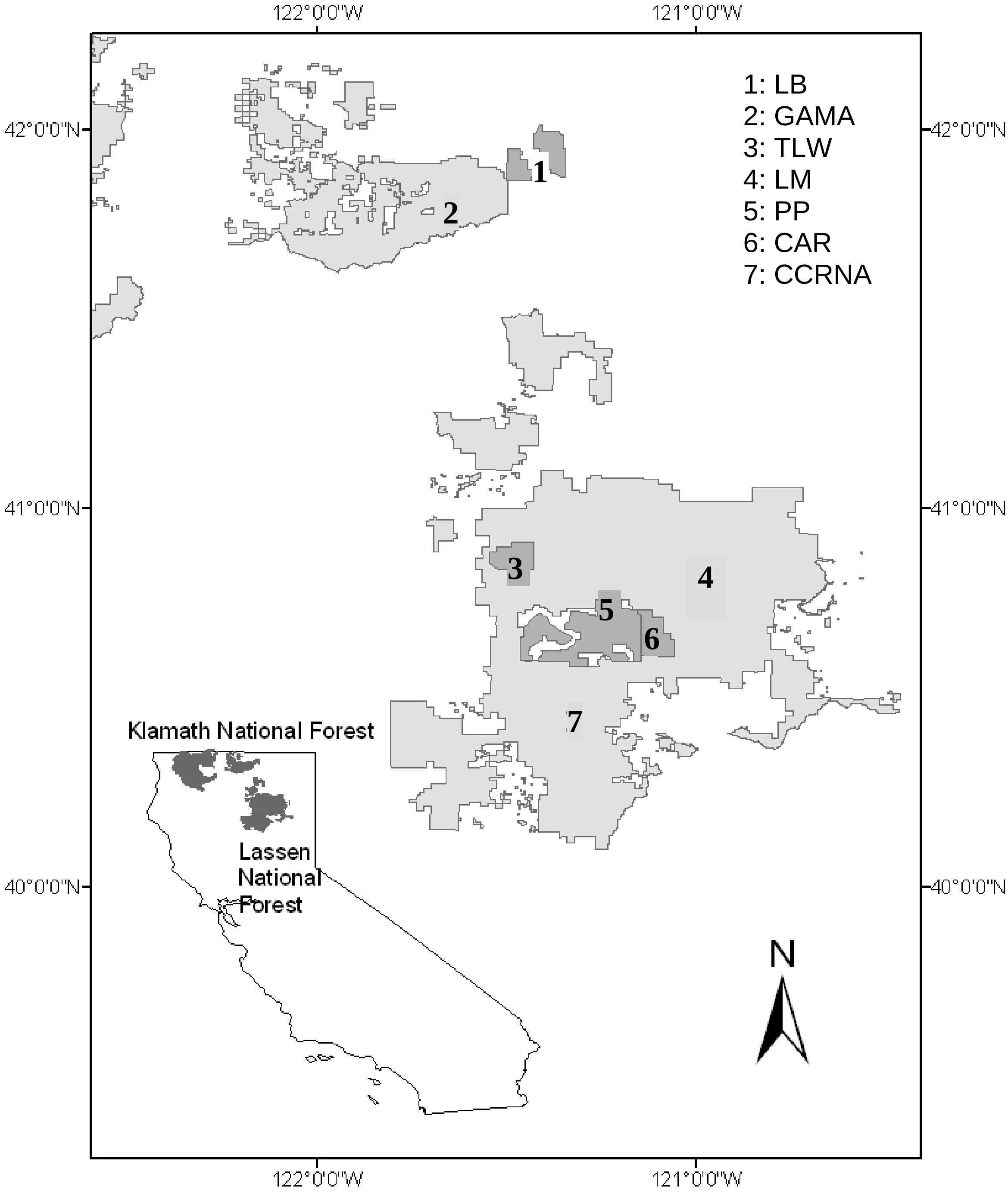
Figure 3. Superposed Epoch Analysis (SEA) of reconstructed PDSI (Cook and Krusic 2004) with non-fire years and fire years of different extent (i.e. at least one sample, ≥ 10%, and ≥25% of samples scarred) in the southern Cascades, California for the period 1700-1900. The analysis window includes up to 5 years before and 2 years after each fire or non-fire year. Values with filled symbols were statistically significant ($P<0.05$).

Figure 4. Superposed Epoch Analysis (SEA) of reconstructed PDSI with non-fire years and fire years of different extent (≥1, ≥2 or ≥3 sites) in the southern Cascade Range, California, for the periods 1700-1800 and 1800-1900. There were too few fires to conduct an SEA for burns of larger extent (4 or more sites burned). The analysis window includes up to 5 years before and 2 years after each fire or non-fire year. Values with filled symbols were statistically significant ($P<0.05$).

Figure 5. Pearson product moment correlation coefficients of first differences for regional fire occurrence and PDSI (a); and 50-year running correlation, plotted on the 26th year of the period, between fire occurrence, PDSI, summer temperature (Temp), ENSO, and PDO (b). The PDSI values and corresponding correlation coefficients were inverted for presentation.

Figure 6. Interdecadal variation in regional fire extent, PDSI, summer temperature (TEMP), and ENSO (NINO3). All series were computed from 20-year, non-overlapping means (sums in the case of fire extent) and were smoothed using a cubic spline for presentation.

Fig.1



122°0'0"W
121°0'0"W
42°0'0"N
41°0'0"N
40°0'0"N
1: LB
2: GAMA
3: TLW
4: LM
5: PP
6: CAR
7: CCRNA
1
2
3
4
5
6
7
Klamath National Forest
Lassen National Forest
N

Fig. 2

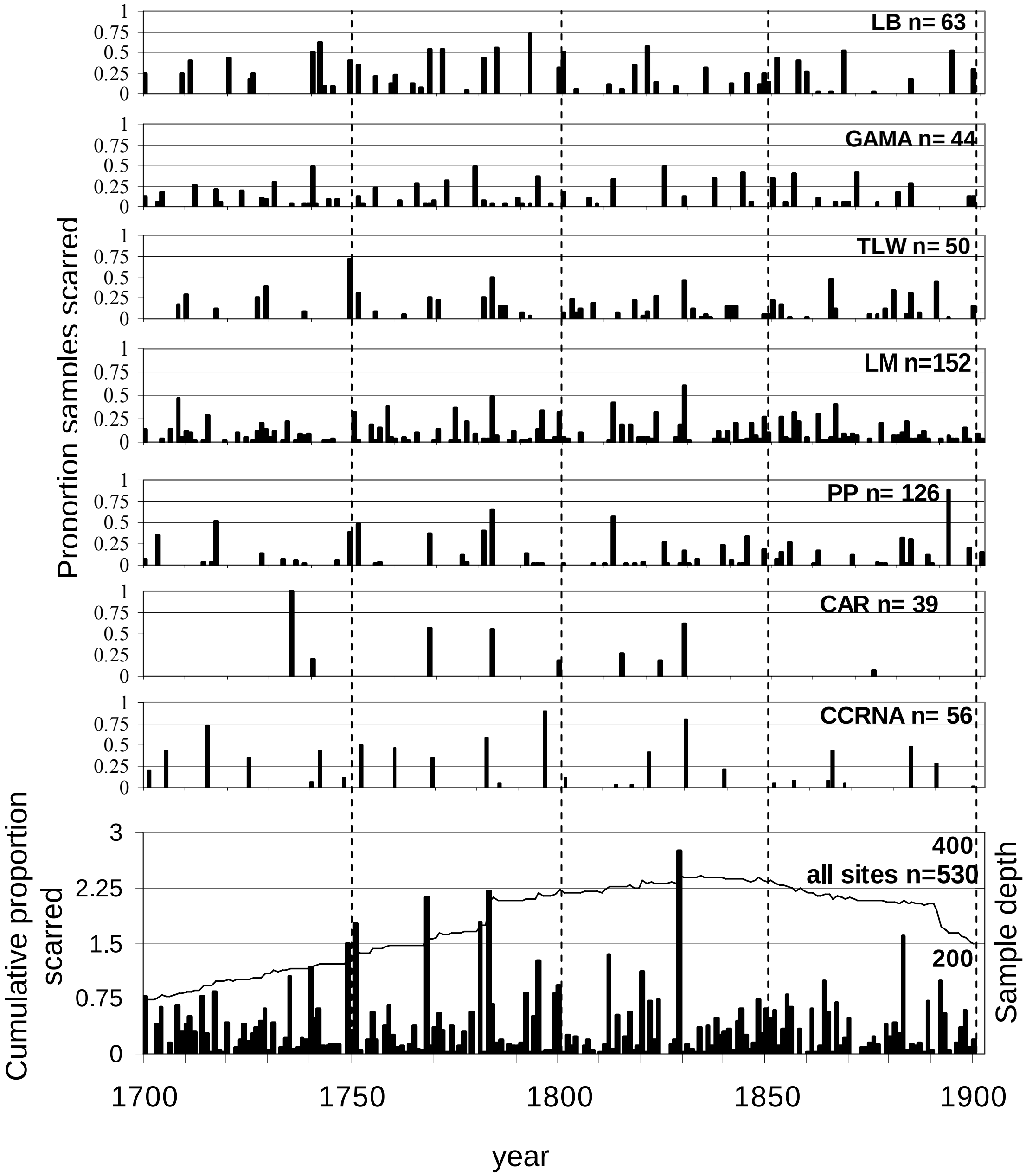
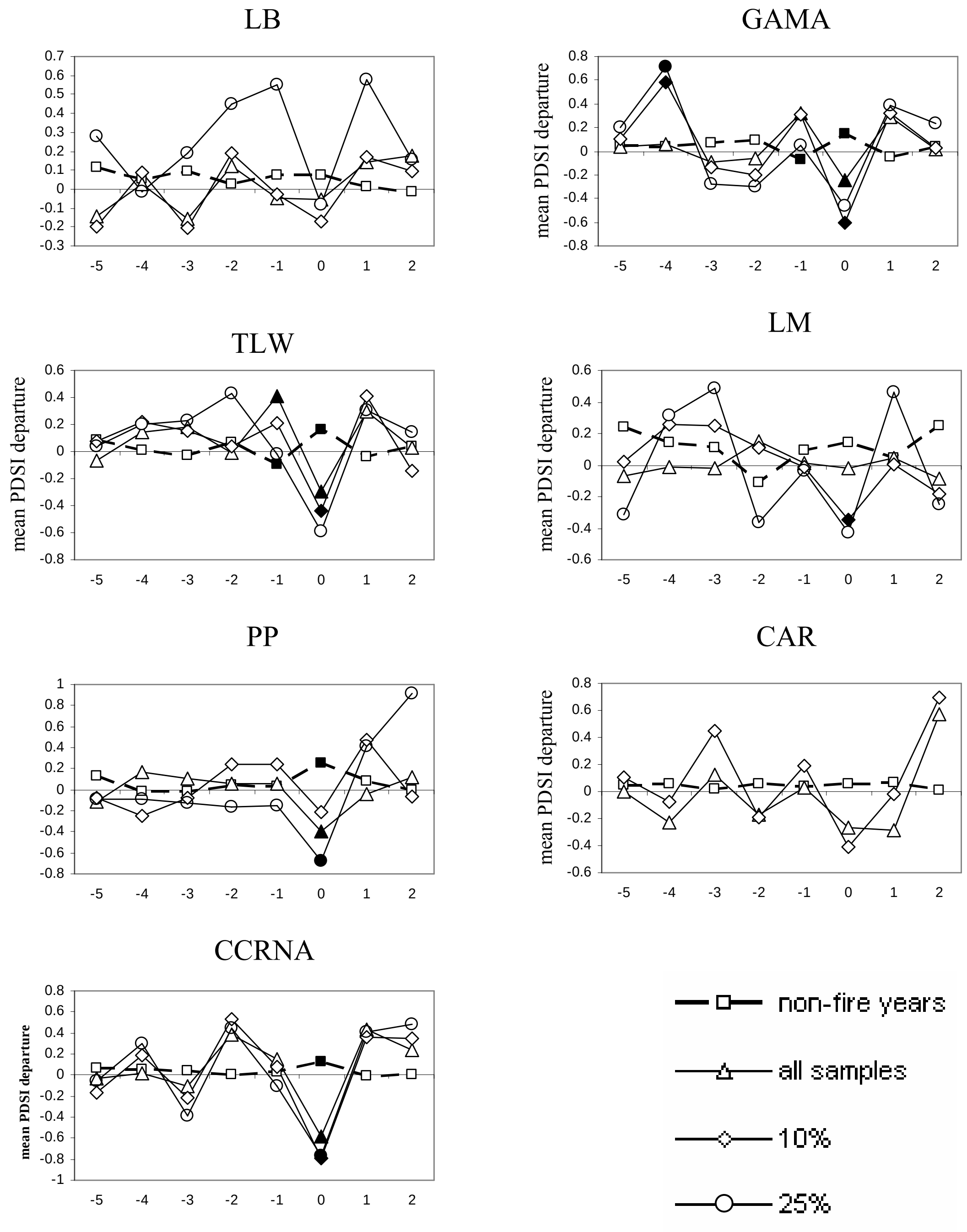
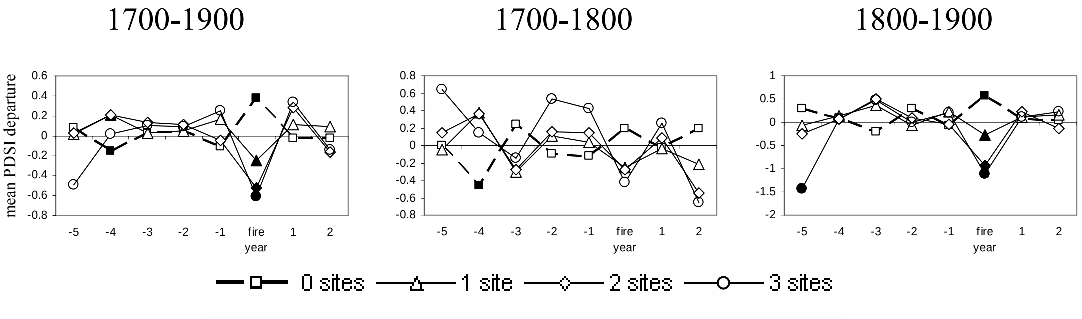

LB n= 63
GAMA n= 44
TLW n= 50
LM n=152
PP n= 126
CAR n= 39
CCRNA n= 56
all sites n=530
Proportion samples scarred
Cumulative proportion scarred
Sample depth
400
200
1
0.75
0.5
0.25
0
3
2.25
1.5
0.75
0
1700
1750
1800
1850
1900
year

Fig. 3



LB
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
GAMA
mean PDSI departure
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
TLW
mean PDSI departure
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
LM
mean PDSI departure
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
PP
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
CAR
mean PDSI departure
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
CCRNA
mean PDSI departure
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-5
-4
-3
-2
-1
0
1
2
non-fire years
all samples
10%
25%

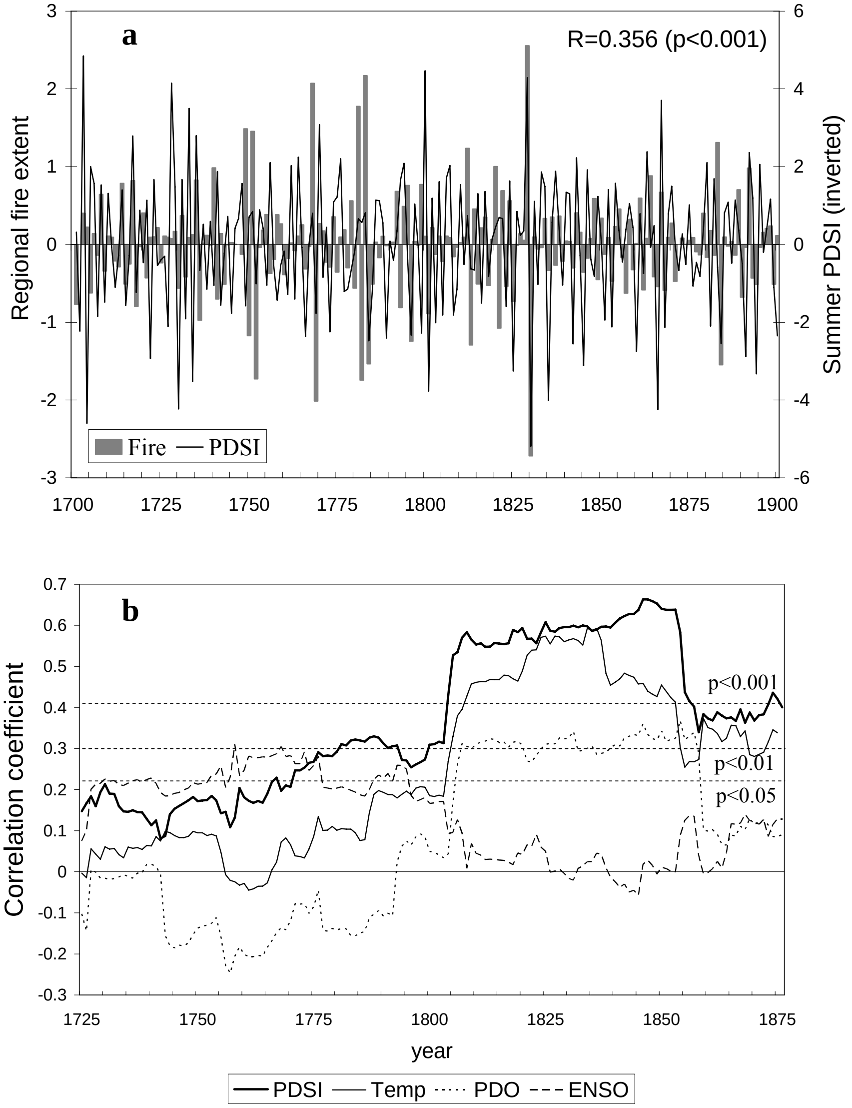
Fig. 4


1700-1900

1700-1800

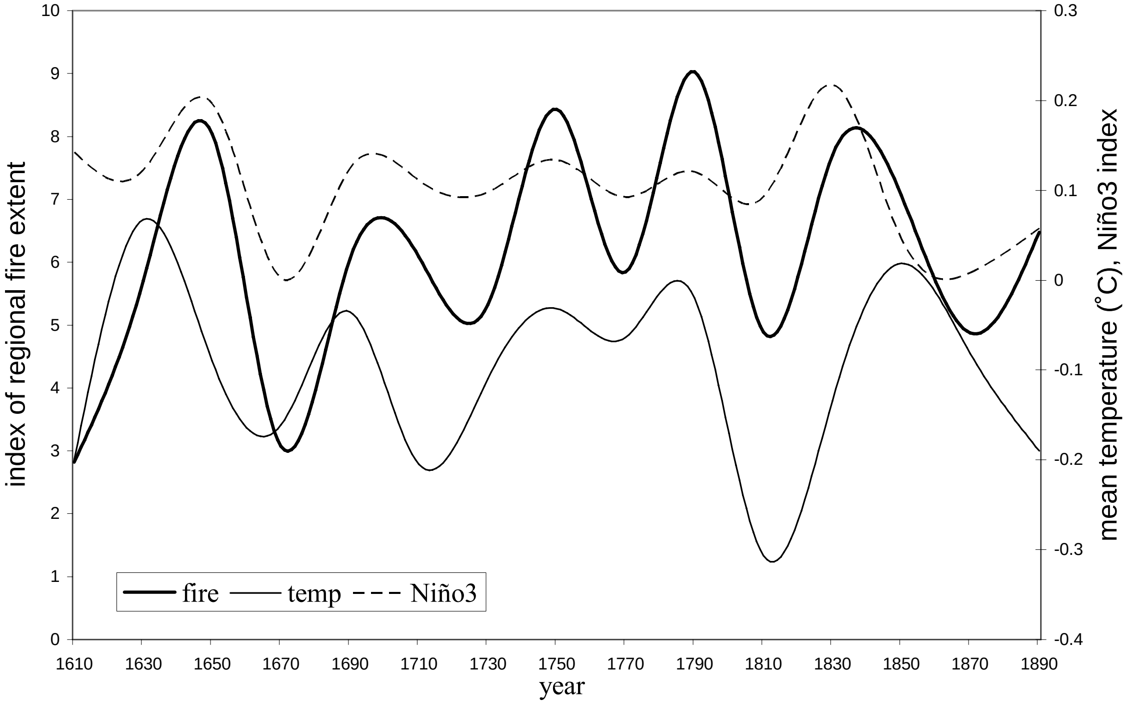
1800-1900

Fig. 5



a
R=0.356 (p<0.001)
Regional fire extent
Summer PDSI (inverted)
3
2
1
0
-1
-2
-3
6
4
2
0
-2
-4
-6
1700
1725
1750
1775
1800
1825
1850
1875
1900
Fire
PDSI
b
Correlation coefficient
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
p<0.001
p<0.01
p<0.05
1725
1750
1775
1800
1825
1850
1875
year
PDSI
Temp
PDO
ENSO

Fig. 6



10
9
8
7
6
5
4
3
2
1
0
index of regional fire extent
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
mean temperature (°C), Niño3 index
1610
1630
1650
1670
1690
1710
1730
1750
1770
1790
1810
1830
1850
1870
1890
year
fire
temp
Niño3