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Climate drivers of regionally synchronous fires in the inland Northwest (1651–1900)

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Abstract. We inferred climate drivers of regionally synchronous surface fires from 1651 to 1900 at 15 sites with existing annually accurate fire-scar chronologies from forests dominated by ponderosa pine or Douglas-fir in the inland Northwest (interior Oregon, Washington and southern British Columbia). Years with widespread fires (35 years with fire at 7 to 11 sites) had warm spring–summers and warm-dry summers, whereas years with no fires at any site (18 years) had the opposite conditions. Spring climate likely affected the length of the fire season via the effects of snowmelt on soil and fuel moisture, whereas summer climate influenced fuel moisture during the fire season. Climate in prior years was not a significant driver of regionally synchronous surface fires, likely because fuels were generally sufficient for the ignition and spread of such fires in these forests. Fires occurred significantly more often than expected by chance when the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) were both warm phase and less often when they were both cool phase. Interactions between large-scale climate patterns influenced fire synchrony in the inland Northwest because phases of ENSO and PDO were associated with changes in the frequency of warm-dry *v.* cool-wet spring–summer climate.

Additional keywords: British Columbia, El Niño–Southern Oscillation, fire scars, Oregon, Pacific Decadal Oscillation, Palmer Drought Severity Index, temperature, Washington.

Introduction

Climate was a strong driver of 20th-century fire synchrony in the interior west of North America (Gedalof *et al*. 2005; Collins *et al*. 2006; Littell 2006; Westerling *et al*. 2006; Morgan *et al*. in press). Summer climate has long been recognised as important to wildfire activity but fire-scar reconstructions and some recent studies of modern fires demonstrate that climate during the spring preceding the fire season can also be important. For example, in the western US, the frequency of large fires was relatively high during years with warm springs and summers, which are also years of relatively early snowmelt, low summertime soil and fuel moisture, and hence longer fire seasons (Westerling *et al*. 2006). Spring climate in the inland Northwest is influenced by large-scale climate patterns such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Tropical El Niño events favour anomalously dry and warm winters and springs in the inland Northwest, producing anomalously shallow snow packs, whereas La Niña events lead to anomalously deep snow packs (Redmond and Koch 1991; Moore and McKendry 1996; Gershunov *et al*. 1999; Mantua 2002). The warm phase of the PDO affects the inland Northwest in a manner similar to El Niño events. Furthermore, the effects of El Niños are amplified during warm phases of the PDO whereas the effects of La Niñas are amplified during cool phases of the PDO and vice versa (Gershunov *et al*. 1999; McCabe and Dettinger 1999). Although the occurrence of modern fires across the Pacific Northwest appears to be weakly synchronised by variation in the PDO (Gedalof *et al*. 2005) and modelling studies suggest that the combined effects of ENSO and PDO may lead to large annual area burned in the inland Northwest (Westerling and Swetnam 2003), it is difficult to confirm these relationships during the two 20th-century phase reversals in PDO. Paleorecords can provide a longer perspective, potentially yielding additional insight into the influence of climate drivers on variation in fire synchrony during periods that pre-date the era of widespread fire exclusion, industrial logging, and consequent changes in forest structure.

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Over the past decade, a network of crossdated surface-fire chronologies has been developed from fire scars across the inland Northwest, with 15 sites sampled over 7 degrees of latitude in the interiors of Oregon, Washington and British Columbia (Everett *et al*. 2000; Heyerdahl *et al*. 2001, 2007; Daniels and Watson 2003; Hessl *et al*. 2004; Wright and Agee 2004). The climate drivers of fire have been analysed for many of these sites individually or in small groups of sites (Heyerdahl *et al*. 2002; Daniels and Watson 2003; Hessl *et al*. 2004; Wright and Agee 2004). Large and/or widespread fires occurred during significantly dry years, some of which were El Niño years. The role of PDO was investigated only in eastern Washington, where its role in driving fire was ambiguous. However, climate drivers of fire emerge most strongly when fire chronologies are examined across broad areas (e.g. Kitzberger *et al*. 2007), thus the lack of strong relationships between fire and ENSO or PDO at individual sites may not reflect the role of these large-scale climate parameters in synchronising fire across the region. Furthermore, none of these studies explored the role of temperature or interactions of ENSO and PDO in driving fire.

Our objective was to infer the climate drivers of regionally synchronous surface fires (1651–1900) in the inland Northwest in the era pre-dating widespread fire exclusion and intensive forestry activities. We explored relationships between existing annually accurate fire-scar reconstructions of fire history and independent tree-ring reconstructions of both regional climate (Palmer Drought Severity Index (PDSI) and temperature) and indices of large-scale climate patterns that affect spring climate in the inland Northwest (ENSO and PDO).

Study area

Climate in the study area is continental with low annual precipitation, cold winters, and warm summers. Precipitation ranges from 200 to 450 mm, with much of this falling as snow in winter (1895–1991; www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp, verified 4 January 2008; Environment Canada 2005*a*). A secondary peak in precipitation occurs in May and June in much of interior Oregon and Washington, but not British Columbia (Ferguson 1999; Environment Canada 2005*b*). Mean January temperatures range from −3°C in the Blue Mountains of north-eastern Oregon (1895–1991) to −8°C at the Cariboo sites in British Columbia (Williams Lake A 1971–2000; Environment Canada 2005*a*) and mean July temperatures range from 16 to 18°C throughout the study region.

Methods

Historical surface fires

We used fire-scar dates from existing crossdated chronologies at 15 sites in the interior of Oregon, Washington and southern British Columbia (Fig. 1). Fire-scarred trees were sampled systematically over large areas (262 to 30 000 ha) in grids of multi-tree plots (Heyerdahl *et al*. 2002, 2007; Wright and Agee 2004) or targeted within several topographic facets (Everett *et al*. 2000; Hessl *et al*. 2004), except at Cariboo, where nine 1-ha sites were sampled along an 85-km transect on the Fraser River Plateau (Daniels and Watson 2003) (Table 1). An average of 248 trees was crossdated per site (range 86–667 trees). The sampled trees were mostly ponderosa pine (88%, *Pinus ponderosa* P. & C. Lawson), but included some Douglas-fir (7%, *Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), western larch (3%, *Larix occidentalis* Nutt.), lodgepole pine (2%, *Pinus contorta* Dougl. ex Loud.), western red cedar (<1%, *Thuja plicata* Donn ex D. Don) and western white pine (<1%, *Pinus monticola* Dougl. ex D. Don). Although fire dates range from 1257 to 1996, we investigated the relationship of climate and fire synchrony only for the period from 1651 to 1900, when 1203 trees were recording across all sites (average 80 trees per site, range 4–435 trees). After 1900, surface fires abruptly ceased, probably owing to changes in land use including logging, grazing, and active fire suppression (Galbraith and Anderson 1991; Robbins and Wolf 1994; Hessburg and Agee 2003). An average of 1716 fire scars per site were crossdated during this analysis period (range 174–6083 fire scars). We identified fire years at each site as those with scars on $\geq$2 trees, yielding an average of 65 years with fire per site (range 29–151 years). Using the number of sites recording fire, we assigned each year to one of four categories of fire synchrony: low synchrony for years with fire at one to three sites (96 years); moderate synchrony for years with fire at four to six sites (101 years); and high synchrony for years with fire at more than six sites (35 years, equivalent to the 90th percentile in sites with fire during the analysis period). Years with fire at no sites were also considered highly synchronous but termed no-fire years (18 years).

Historical climate

We used a gridded tree-ring reconstruction of warm season temperature, expressed as the departure from mean temperature during a reference period (April through September, 1951–1970; Briffa *et al*. 1992). The reconstruction at the grid point within our study area (13, 45.0°N latitude, 120.5°W longitude) was significantly correlated with modern divisional temperature in Oregon and Washington during both spring and summer but the correlations were substantially higher for spring (April through June *v.* July through August, 1895–1983, $r = 0.60$ to 0.65 and $r = 0.39$ to 0.43, respectively, $P < 0.001$, climate divisions Oregon 8 and Washington 6, 7, and 9; www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp, verified 4 January 2008). The reconstruction at this grid point is also significantly correlated with spring temperature ($r = 0.59$, $P < 0.0001$) and summer temperature ($r = 0.35$, $P < 0.01$) near the fire-scar sites in southern British Columbia (Middle and Lower Stein, 1926–1983, Lytton; Environment Canada 2005*a*), but not with spring temperature ($r = 0.34$, $P = 0.02$) or summer temperature ($r = 0.33$, $P = 0.12$) near the Cariboo sites farther north (1961–1983, Williams Lake; Environment Canada 2005*a*).

We also used a gridded tree-ring reconstruction of the summer PDSI (June through August; Cook *et al*. 2004). Instrumental PDSI is significantly correlated among the grid points surrounding the study area (30, 41–44, and 54–56, 45.0° to 52.5°N latitude and 117.5° to 122.5°W longitude; pairwise correlations $r = 0.26$ to 0.96, $P < 0.05$, 1900–90), except the northernmost grid points (30 and 41) with the southernmost (44 and 56). To capture this common variance, we extracted the principal components of reconstructed PDSI from the eight grid points

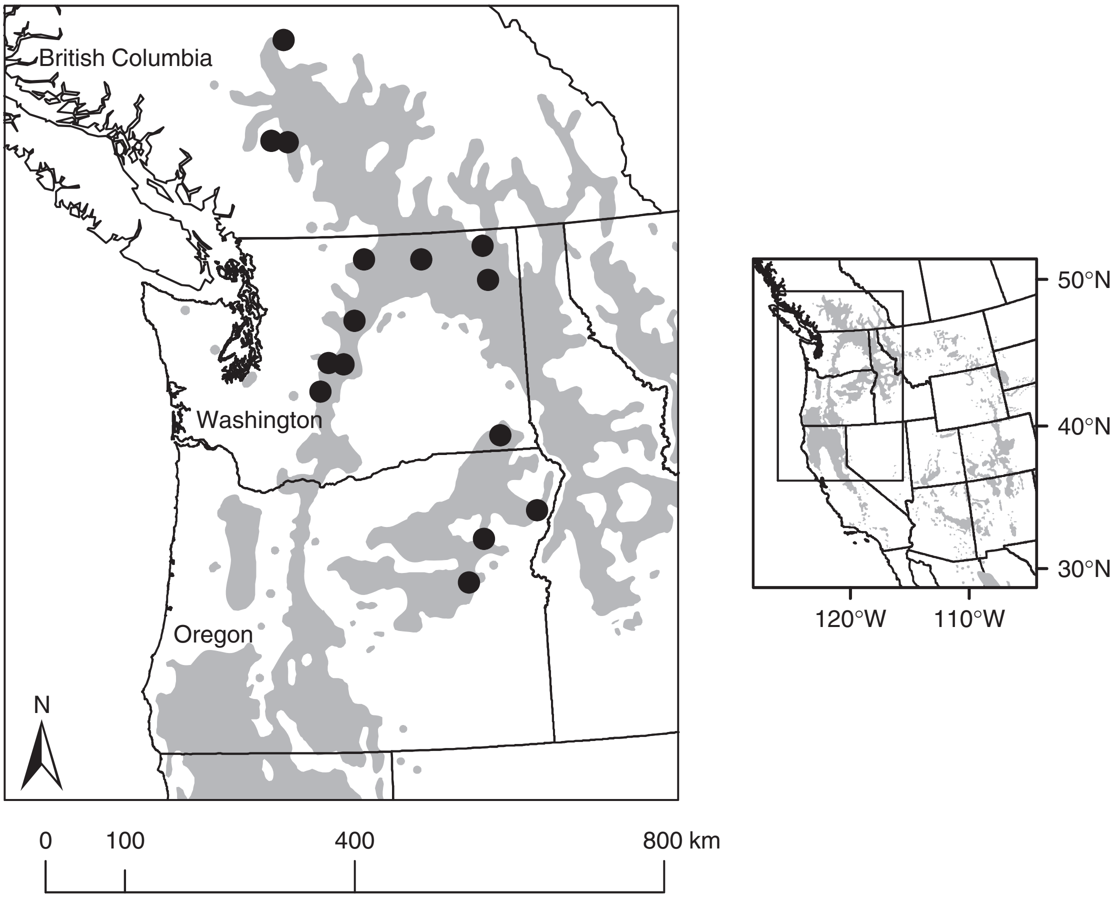

Fig. 1. Location of the 15 existing fire-scar sampling sites (black dots) used to identify climate drivers of historical fire regimes in the inland Northwest and the distribution of ponderosa pine (grey areas, after Little 1971).

(1651–1900; Preisendorfer 1988; SAS Proc Princomp, SAS Institute 2003). The first principal component explained 77% of the historical variation. The second and third principal components accounted for only an additional 19 and 2% of the variance, respectively, and were not used in further analyses.

As indices of large-scale climate patterns, we used tree-ring reconstructions of a winter ENSO index (December to February, 1651–1900, Niño-3; D'Arrigo *et al*. 2005), and an annual PDO index (1700–1900; D'Arrigo *et al*. 2001). Even though it is shorter than our analysis period, we used the D'Arrigo *et al*. (2001) PDO index reconstruction because it captures more of the variance in the modern PDO index (44%) than other published PDO index reconstructions.

Climate drivers of regional fire years

To infer climate drivers of fire at interannual scales (1651–1900), we assessed whether climate (PDSI, temperature, or Niño-3) during our four categories of fire years (no-fire, and low-, moderate-, and high-synchrony) was significantly different from climate during the preceding and following years (±3 years), using superposed epoch analysis (SEA; Baisan and Swetnam 1990; Swetnam and Betancourt 1990; Grissino-Mayer 2001). The time series of PDSI had no temporal autocorrelation but those for temperature and Niño-3 did ($P = 0.12$, $P < 0.0001$, and $P < 0.0001$, respectively; SAS Proc Arima autocorrelation test with 6 lags, SAS Institute 2003). Therefore, for the temperature and Niño-3 time series, we fitted autoregressive moving-average models based on (i) lowest Akaike's information criterion, and (ii) significant but uncorrelated parameter estimates (MA(1) after first differencing and AR(2), respectively) and used the white noise residuals in SEA (white noise test $P = 0.37$ and 0.37, respectively). In SEA, we identified significant climate departures as those exceeding 99% confidence intervals determined by bootstrapping (1000 trials; Mooney and Duval 1993; Grissino-Mayer 2001).

We assessed the effect of combined states of climate on fire synchrony using χ^2 goodness-of-fit tests ($\alpha = 0.05$) in which the observed values were the number of fire years that occurred during each of four combinations of climate (above or below average PDSI or temperature, 1651–1900) or large-scale climate patterns (positive or negative Niño-3 or PDO, 1700–1900). Expected values were derived from the proportions of years in each of the four combinations of climate or large-scale climate patterns regardless of fire activity. Because previous studies have identified variations in ENSO relationships with inland Northwest climate that depend on the phase of the PDO, we also assessed the independence of large-scale climate patterns during years when the

Table 1. Characteristics and amount of fire evidence collected at the 15 sites used to identify climate drivers of historical fire in the inland Northwest

Number of fire scars and fire years are for the analysis period (1651–1900). Fire years are those with ≥2 trees scarred per site. All fire evidence was collected for other studies (Everett *et al.* 2000; Heyerdahl *et al.* 2001, 2007; Daniels and Watson 2003; Hessl *et al.* 2004; Wright and Agee 2004)

Site	Latitude (N)	Longitude (W)	Sampled area (ha)	No. of			First scar	Last scar
				Trees	Fire scars	Fire years		
Cariboo[A]	51°40′	121°40′	9	136	174	29	1575	1971
Middle Stein	50°18′	121°58′	1507	154	862	68	1511	1949
Lower Stein	50°16′	121°39′	262	162	532	62	1619	1989
South Deep	48°45′	117°40′	12 019	169	471	34	1399	1986
Twentymile	48°40′	120°06′	3364	403	2560	39	1342	1990
Frosty	48°37′	118°56′	6991	420	3877	83	1299	1956
Quartzite	48°17′	117°37′	3116	142	1110	78	1384	1989
Entiat	47°48′	120°20′	12 747	490	3689	76	1530	1988
Teanaway	47°16′	120°54′	30 000	220	761	87	1567	1994
Swauk	47°15′	120°38′	11 088	667	6083	151	1257	1942
Nile	46°52′	121°05′	3237	232	2092	69	1367	1996
Tucanon	46°11′	117°36′	2002	86	337	36	1526	1982
Imnaha	45°07′	116°59′	2095	109	462	34	1526	1961
Baker	44°47′	118°00′	3812	114	934	57	1428	1962
Dugout	44°12′	118°22′	8585	215	1789	71	1478	1926
Total			100 834	3719	25 733			

[A]Cariboo is a composite of nine 1-ha plots sampled along an 85-km latitudinal transect.

effects of ENSO and PDO are amplified (Niño-3 and PDO index of the same sign) and when they are dampened (Niño-3 and PDO index of the opposite sign). We tested only three categories of fire synchrony: high (more than six sites), moderate (four to six sites) and a combined category for low synchrony and no-fire years (zero to three sites) to eliminate the low cell counts resulting from the small number of no-fire years.

To place our results in a subcontinental context, we generated composite maps of PDSI (grid points 1 to 203; Cook *et al.* 2004) across western North America for no-fire years and for two subcategories of highly synchronous fire years: dry westwide (1671, 1731, 1735, 1798, 1812, 1822, 1863, 1864, 1886, and 1895) and dry in the inland Northwest but wet in the Southwest (1652, 1706, 1720, 1729, 1751, 1756, 1759, 1771, 1776, 1783, 1794, 1800, 1828, 1833, 1834, 1839, 1840, 1843, 1844, 1869, 1883, 1888, 1889). We identified significant departures from mean values at each grid point (Brown and Hall 1999).

We developed a generalised linear model of the binomial family to hindcast the probability that a given year would have highly synchronous fires as a function of climate (PDSI, Niño-3, PDO; 1700–1900). We did not include temperature in these models because it is correlated with PDSI ($r = 0.39$). We fitted full models and used backward elimination to identify the best predictors (likelihood ratio tests, $\alpha = 0.05$). The models were estimated using maximum likelihood (McCullagh and Nelder 1989; Splus 6.2 for Windows, Insightful Inc. 2002). We estimated a generalised classification accuracy by computing the area under the receiving operating characteristic curve (AUC; Murphy and Winkler 1987; Swets 1988). AUC ranges from 0.5 (50% accuracy expected at random) to 1.0 (perfect accuracy), and we assumed that values of >0.7, 0.8, or 0.9 indicate fair, good, or excellent accuracy, respectively (Swets 1988).

Results

Historical surface fires

Fires were highly synchronous across the inland Northwest every 7 years on average, but the intervals between such years varied through time (Fig. 2). Before 1725, 4 high-synchrony fire years occurred at intervals of 14 to 35 years. More than half of the no-fire years occurred between 1651 and 1725 (11 of 18 years) although it is only approximately one-third of the total analysis period. From 1725 to 1800, the intervals between successive high-synchrony fire years were relatively consistent, occurring every 2 to 16 years. However, during the 19th century, longer intervals of 10 to 19 years separated short periods with more frequent synchronous fire years. These pulses of fire included five 1-year intervals, in which fires burned at more than six sites in consecutive years. The year of maximum synchrony was 1828, when fire was recorded at 11 of the 15 sites.

Climate drivers of regional fire years

Interannual variation in climate was a strong driver of fire synchrony across the inland Northwest. Highly synchronous years were ones with warm temperatures and warm-dry PDSI, whereas years with fires at no or a few sites had cool temperatures and cool-wet PDSI (Fig. 3). Prior year's climate was not an important driver of current year's fire (1 to 3 prior years tested; Fig. 3). The occurrence of years with highly synchronous fire (more than six sites with fire) or with fire at zero to three sites was not independent of combined states of regional temperature and PDSI ($P < 0.001$). In contrast, the occurrence of years with fire at four to six sites was independent of combined states of climate ($P = 0.19$).

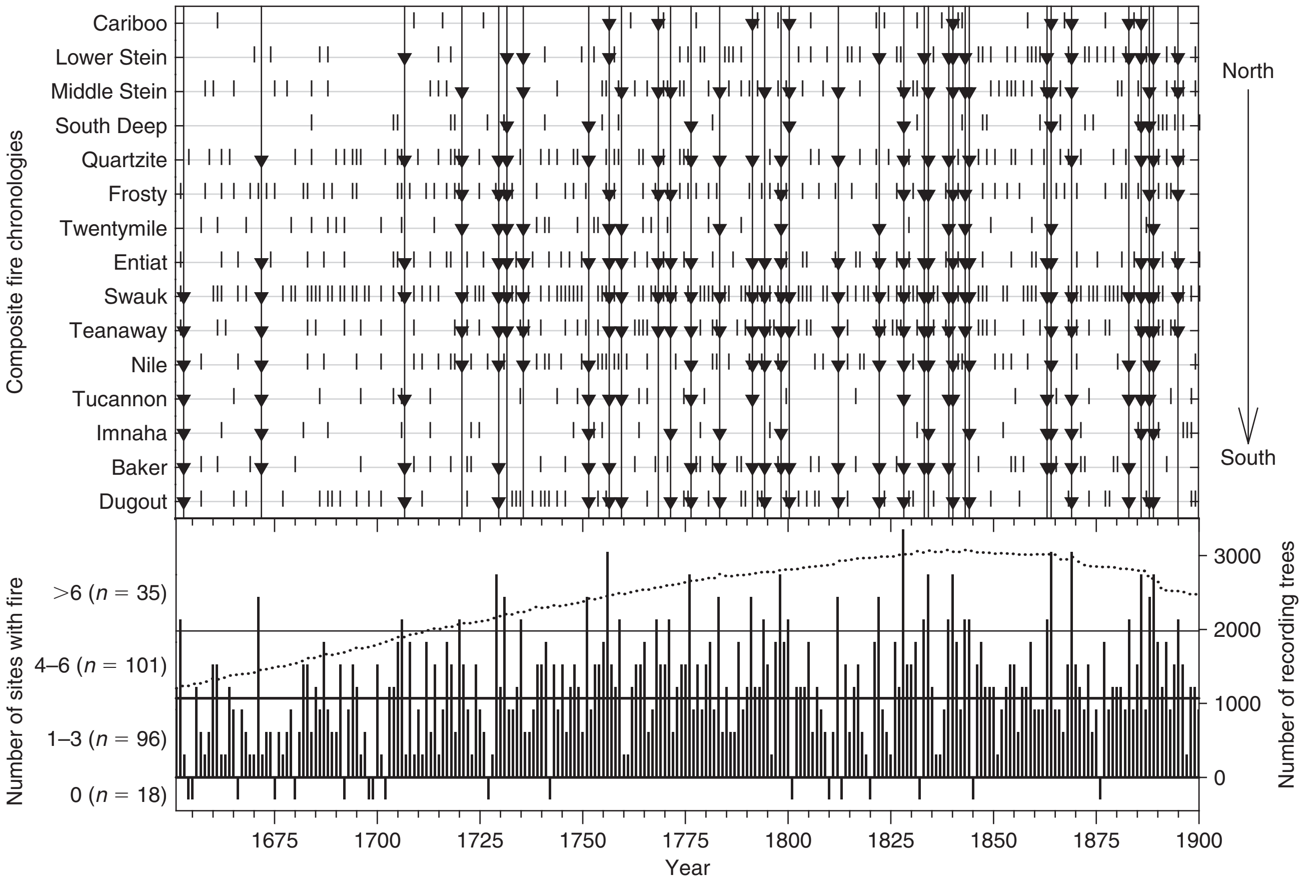

Fig. 2. Historical fire chronologies in the inland Northwest (1651–1900). For the site fire chronologies (top), each horizontal line shows the composite fire chronology from one site, vertical ticks and triangles both indicate years in which ≥2 trees were scarred by fire but triangles indicate years in which this occurred at more than six sites (high fire synchrony). In the regional fire chronology (bottom), horizontal lines indicate the degree of synchrony in fire across the region (low = one to three sites with fire, moderate = four to six sites, and high more than six sites with fire). Years in which no sites burned are synchronous non-fire years and marks during these years extend downward for emphasis. The number of recording trees is indicated as a dotted line.

ENSO and PDO were not strongly associated with fire synchrony across the inland Northwest when considered individually, but in combination these large-scale climate patterns were significantly, albeit weakly, associated with fire synchrony. There were no significant departures in average Niño-3 during any of our categories of fire synchrony or during prior years (Fig. 3). Fire years in all three categories of synchrony (zero to three sites with fire, four to six sites with fire, and more than six sites with fire) occurred independently of combined states of ENSO and PDO when all phase combinations were included ($P = 0.19$, 0.93, and 0.11, respectively). However, when we included only additive combinations (Niño-3 and PDO both positive or both negative), highly synchronous fire years did not occur independently of these combinations ($P = 0.02$) but years with fire at zero to three sites and at four to six sites did ($P = 0.05$ and 0.67, respectively). Significantly more fire years than expected by chance (56% of fire years) occurred when both Niño-3 and PDO were positive whereas significantly fewer than expected by chance (29%) occurred when both were negative (Fig. 4).

In a subcontinental context, no-fire years were significantly cool-wet in the inland Northwest and significantly warm-dry in the Southwest (Fig. 5). In contrast, we identified three subcontinental-scale patterns during our 35 highly synchronous fire years: (i) 10 years when summers were significantly warm-dry across much of the west; (ii) 23 years when summers were warm-dry to the north but cool-wet to the south; and (iii) 2 years when summers were wet across much of the west (not shown).

Our model identified summer PDSI as a strong driver of widespread fire in the study area. It predicted years of high synchrony with good accuracy (AUC = 86%), although the percentage deviance explained was only 29%. Most of this percentage deviance (87%) was accounted for by PDSI; PDO and Niño-3 were dropped in the backward elimination.

Discussion

Fires were widespread across the inland Northwest during some years

During our analysis period (1651–1900), years of both extensive fire and no-fire occurred synchronously across the inland Northwest. Although every site has recording trees during the entire period of analysis, the low number of highly synchronous fire years early in our analysis period might be due to mortality and decay of trees, so that the evidence of the oldest fires

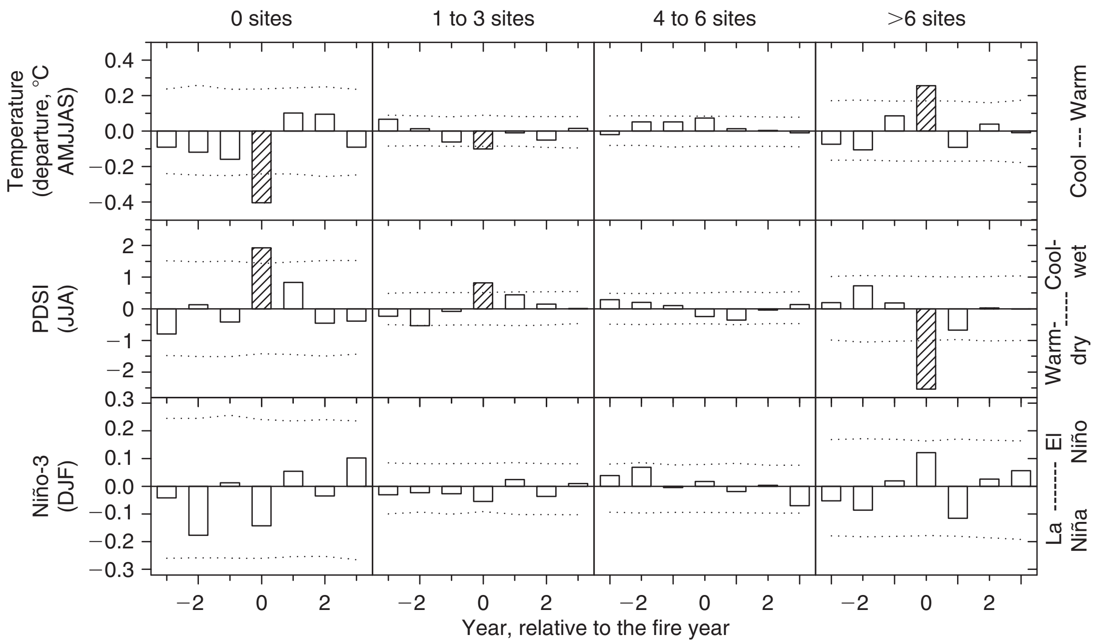

Fig. 3. Lagged interannual relationships of climate and surface fires, showing average departure from climate during 18 years with no fire at any site, 96 years with fire at one to three sites, 101 years with fire at four to six sites and 35 years with fire at more than six sites (1651–1900). Hatched bars indicate departures that exceed 99% confidence intervals, which are shown as dotted lines. The temperature and Niño-3 time series used in this analysis have been prewhitened. Although the temperature reconstruction is for April to September (Briffa *et al.* 1992), it is most highly correlated with April through May temperature in the study area.

may have been lost through time (Swetnam *et al.* 1999). We suggest that during years when fires occurred at many sites, large areas burned. Although we recognise that the number of trees scarred may be only a rough estimate of area burned and likely varies with sampling design and method of estimation (Hessl *et al.* 2007), many more trees were scarred during highly synchronous fire years than during other fire years (average of 328 *v.* 72 trees, respectively) and at eight of the sites in Oregon and Washington where area burned has been estimated, the number of trees scarred and estimated area burned are highly correlated ($r = 0.72$ to 0.97, $P \leq 0.002$).

Our study was limited to low-severity fires in dry forests. It is likely that mixed- and high-severity fires were probably also extensive in the inland Northwest during the regional fire years we identified from fire scars (Hessburg *et al.* 2007). At some of the sites in our study area, moderate- and high-severity fires were likely synchronous with low-severity fires during some years (Heyerdahl *et al.* 2001). Furthermore, each of the 20th-century regional fire years identified in the Northern Rocky Mountains, just east of our study area, burned extensively across a range of vegetation types, including subalpine forests that typically sustained mixed- and high-severity fire regimes (Gibson 2006).

Interannual variation in climate was a strong driver of regionally synchronous fires

Current year's climate synchronised the occurrence of widespread surface fires among our sites in the inland Northwest, probably by affecting the length of the fire season and the moisture content of fine fuel during the fire season. Spring climate was important in driving regionally synchronous fires across the region, likely through its effect on snowpack, soil and ultimately fuel moisture, and hence the length of the fire season (Heyerdahl *et al.* 2002; Hessl *et al.* 2004; Gedalof *et al.* 2005; Littell 2006; Westerling *et al.* 2006). Although the reconstruction of temperature that we used was for the summer half of the year (April through September), we suggest that variation in spring temperature may have been more important than summer temperature in driving fire in our study area because the reconstruction captures more of the variation in spring than summer temperature. Our regional-scale analysis of the influence of summer climate generally corroborated local-scale results from the southern part of the study area where extensive fires occurred at individual sites during dry summers (Heyerdahl *et al.* 2002; Hessl *et al.* 2004; Wright and Agee 2004), consistent with the intuitive observation that dry weather during the fire season leads to lower fuel moisture and greater flammability.

Fuels can act as a limiting factor to fire spread in two ways: via fuel availability or fuel condition. The former mechanism is linked to a longer memory for climate, e.g. previous-year conditions conducive to productivity, whereas the latter is associated with fire weather on scales of days to months. In contrast to the current year's spring and summer climate, climate in antecedent years did not synchronise fire in our region, likely because fine fuels were sufficiently continuous and abundant that they did not limit fire ignition and spread in the forests we sampled. Dry forests in the inland Northwest have little memory for climate during years preceding fire, unlike the Southwest, where the abundance and spatial continuity of fine fuels may be greatly enhanced by a previous-year El Niño, providing

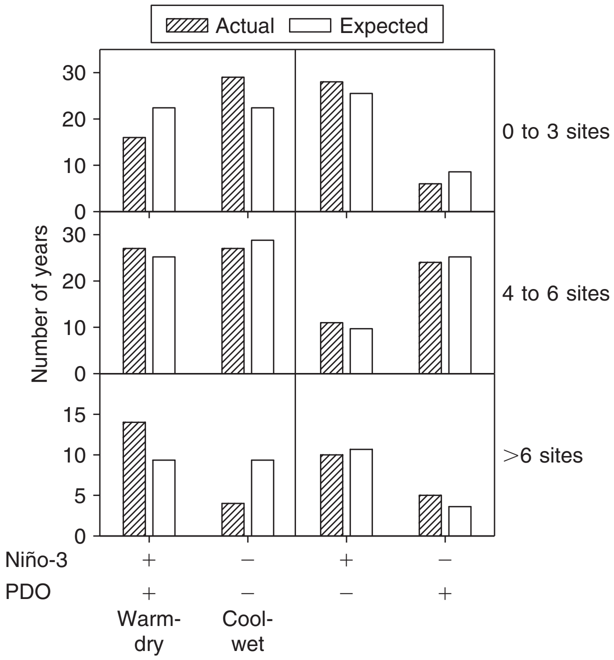

Fig. 4. Synchrony in occurrence of fire (1700–1900), as a function of contingent states of ENSO (Niño-3 above or below zero) and PDO (above or below zero) during 79 years with fire at zero to three sites, 89 years with fire at four to six sites and 33 years with fire at more than six sites. The no-fire and low-synchrony categories were combined for this analysis to eliminate low cell counts. The effects of ENSO and Pacific Decadal Oscillation are amplified when both indices are of the same sign (left) but dampened when they are of opposite sign (right).

antecedent conditions conducive to fire spread (Swetnam and Betancourt 1990).

Most of the years when fires were not recorded at any site were also synchronised by climate. During all no-fire years, spring–summer temperatures were average to below-average and summers were generally cool-wet (Fig. 3). Although 5 of our 18 no-fire years occurred when reconstructed summer droughts were mild (PDSI from −0.126 to −1.407), our predictive model indicated that the probability of highly synchronous fire years is not 100% during years of extremely dry PDSI, because lack of ignition even during a dry year can also yield a no-fire year.

Large-scale climate patterns were weak drivers of regionally synchronous fires

Interaction between ENSO and PDO also synchronised fire during some years, consistent with their effect on spring temperature and spring snowpack in our region, where springs are relatively warm when both indices are positive and relatively cool when both are negative (Redmond and Koch 1991; Moore and McKendry 1996; Gershunov *et al*. 1999). In contrast, neither ENSO or PDO acting independently was a strong driver of fire, consistent with local-scale analyses in dry forests of the inland Northwest (Heyerdahl *et al*. 2002; Hessl *et al*. 2004; Wright and Agee 2004) and with regional-scale analysis in dry forests of the Northern Rocky Mountains just to the east, where historical fires were not strongly driven by variation in PDO (Heyerdahl *et al*. in press).

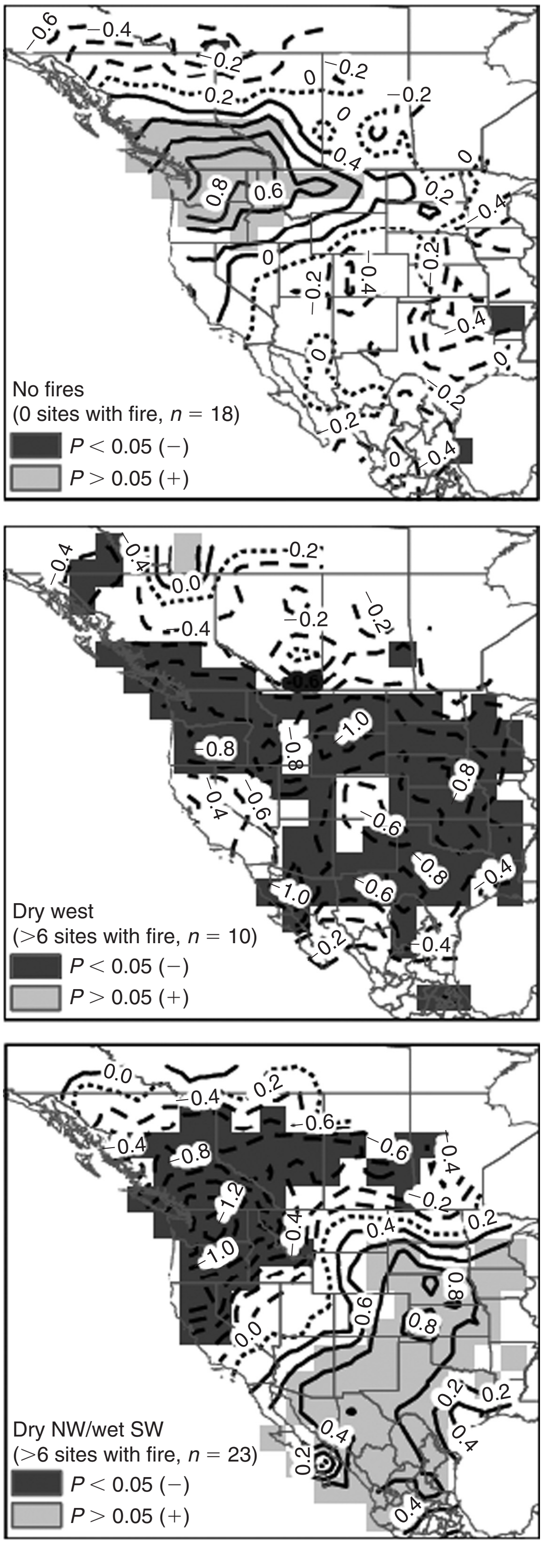

Fig. 5. Contrasting spatial patterns of anomalies in composite tree-ring reconstructed Palmer Drought Severity Index (1651–1900, grid points 1–203, Cook *et al*. 2004), for 18 no-fire years (top panel), and two subjectively identified categories of highly synchronous fire years when it was dry westwide (10 years, middle panel) *v.* dry in the inland Northwest but wet in the SW (23 years, bottom panel).

The occurrence of our highly synchronous regional fire years is consistent with climate and large-scale climate patterns across western North America (Kitzberger *et al*. 2007). Over half (67%) of our highly synchronous fire years occurred under a northwest–southwest dipole in summer PDSI (Fig. 5). During the period for which we have a reconstruction of the PDO (1700–1900), nearly half (42%) of the 33 highly synchronous fire years occurred during years when Niño-3 was positive (El Niño) and the PDO was in its warm phase. During the 20th-century, the northwest–southwest dipole in winter–spring precipitation was especially prominent during years when ENSO and PDO were in phase (Gershunov *et al*. 1999) and the carryover effects of cool-season precipitation, temperature, and snowpack played an influential role in determining fire-season soil and fuel moisture (Seager *et al*. 2005). In support of the dipole effect of ENSO on climate in the inland Northwest *v.* the American Southwest, only one highly synchronous fire year is common to both regions (1729), a year of west-wide drought (Swetnam and Baisan 2003). Of the 2 highly synchronous fire years that occurred when summers were generally cool-wet across the west (1768 and 1791), both had relatively warm springs, and positive Niño-3 (El Niño) and PDO, suggesting that occasionally widespread fires may have occurred early in the fire season when snow packs melted relatively early, as has happened late in the 20th-century (Westerling *et al*. 2006). As a consequence, subsequent cool-wet summers would have had little impact during these few years.

Implications for the future

Nearly a century of fire exclusion in the inland Northwest reduced fire frequency at most of our sites in the mid 20th-century. However, a recent study suggests that relatively long snow-free seasons late in the 20th-century may have resulted in more large fires in the western United States (Westerling *et al*. 2006). Our work indicates that the relationship between spring–summer temperature and area burned observed in the modern record was also present in a 250-year period that pre-dates the recent era of major land-use change (1651–1900). Our results therefore lend strong support to the hypothesis that variations in climate, including springtime temperature and summertime soil and fuel moisture, have historically had large effects on area burned. Over the past century, changes in fuel amount, structure, and continuity resulting from fire exclusion in dry forests across much of the region make high-severity fires more likely, although such fires may have occurred at least occasionally at fine scales in all forests except the driest ponderosa pine woodlands.

Our examination of over 3700 fire-scarred trees across 15 sites confirms and extends existing knowledge of the climate drivers of fire in the inland Northwest and suggests that top-down controls on fire are consistent across temporal scales. More broadly, Holocene records, the fire-scar record, and contemporary records link drier and warmer climates to increased fire (McKenzie *et al*. 2004). Climatic variability provides top-down controls on fire regimes in the inland Northwest, at seasonal, interannual, and even longer time scales. Significance tests and predictive models identified warm season drought as the variable most clearly associated with fire synchrony across the region. Of the variety of fire regimes in inland Northwest ecosystems, the low-severity type is the best understood, but may become less prevalent if increasing temperatures interact with fuel structures conducive to higher-severity fires. Our understanding of historical fire climatology will be most relevant to current fire regimes when coupled with research on climatic controls on mixed- and high-severity fire (e.g. Taylor and Skinner 2003; Gedalof *et al*. 2005; Morgan *et al*. in press). A focus on climatic controls across the complete range of fire regimes in future research may provide the greatest benefit to management and policy.

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