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DROUGHT AND PACIFIC DECADAL OSCILLATION LINKED TO FIRE OCCURRENCE IN THE INLAND PACIFIC NORTHWEST

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Abstract. Historical variability of fire regimes must be understood within the context of climatic and human drivers of disturbance occurring at multiple temporal scales. We describe the relationship between fire occurrence and interannual to decadal climatic variability (Palmer Drought Severity Index [PDSI], El Niño/Southern Oscillation [ENSO], and the Pacific Decadal Oscillation [PDO]) and explain how land use changes in the 20th century affected these relationships. We used 1701 fire-scarred trees collected in five study sites in central and eastern Washington State (USA) to investigate current year, lagged, and low frequency relationships between composite fire histories and PDSI, PDO, and ENSO (using the Southern Oscillation Index [SOI] as a measure of ENSO variability) using superposed epoch analysis and cross-spectral analysis. Fires tended to occur during dry summers and during the positive phase of the PDO. Cross-spectral analysis indicates that percentage of trees scarred by fire and the PDO are spectrally coherent at 47 years, the approximate cycle of the PDO. Similarly, percentage scarred and ENSO are spectrally coherent at six years, the approximate cycle of ENSO. However, other results suggest that ENSO was only a weak driver of fire occurrence in the past three centuries. While drought and fire appear to be tightly linked between 1700 and 1900, the relationship between drought and fire occurrence was disrupted during the 20th century as a result of land use changes. We suggest that long-term fire planning using the PDO may be possible in the Pacific Northwest, potentially allowing decadal-scale management of fire regimes, prescribed fire, and vegetation dynamics.

Key words: climate; cross-spectral; drought; ENSO (El Niño/Southern Oscillation); fire history; Pacific Decadal Oscillation; Pacific Northwest; Pinus ponderosa; *SEA (superposed epoch analysis).*

Introduction

For decades, fire ecologists have appreciated the effect of weather on fuel conditions (Schroeder and Buck 1970, Anderson 1982) on hourly to daily timescales, and the effect of climate on fuel accumulation, on seasonal to annual timescales. However, not until the last decade have ecologists investigated the relationship between multiyear climatic signals, such as El Niño/Southern Oscillation (ENSO), and fire occurrence and extent (e.g., Swetnam and Betancourt 1990, Johnson and Larsen 1991, Swetnam 1993, Veblen et al. 2000, Heyerdahl et al. 2002). From an ecological perspective, connections between fire and climate at interannual (and longer) timescales suggest the possibility that other ecosystem processes, such as nutrient cycling, regeneration, and mortality may also be linked to interannual to decadal variability in climate, through fire effects. From a management perspective, the connections between fire and interannual climatic variability allow managers to predict wildfire severity at a broad range of temporal scales, from daily and seasonal predictions of fire hazard to annual and multiannual predictions of fire occurrence and extent, where climatic controls like ENSO are important. If climatic phenomena operating on decadal timescales, such as the Pacific Decadal Oscillation (PDO), also affect fire occurrence and spread, then our perspective on ecosystem processes as well as our ability to predict fire hazard will be significantly broadened. Unlike centennial to millennial scale fluctuations in fire activity linked to climate via lake charcoal sediment reconstructions (Clark 1990, Millspaugh and Whitlock 1995), decadal scale fluctuations are still within the temporal scale at which human institutions operate and could fill a gap between interannual and centennial scale studies.

Atmospheric processes operating at different spatial and temporal scales, reflected in climate indices such as the Palmer Drought Severity Index (PDSI), El Nino/Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO) are known to be associated with local climate in the Pacific Northwest (PNW). PDSI is a composite monthly index of regional climatic conditions calculated from precipitation and temperature changes (Palmer 1965, Alley 1984, Heddinghaus and Sabol 1991), and incorporates both immediate (same

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month) and cumulative (multimonth) effects of drought. Two synoptic scale patterns centered over the Pacific Ocean (ENSO and PDO) are known to affect local level climate in the PNW. ENSO originates with anomalies in tropical sea-surface temperatures, but affects climate across western North America, especially winter conditions. El Niño conditions tend to produce warmer drier winters and La Niña conditions tend to produce cooler wetter winters in the PNW (Redmond and Koch 1991, McCabe and Dettinger 1999, Mote et al. 1999*a*). Like ENSO, the PDO is an index of variability in climate of the Pacific Ocean, in this case the northern Pacific. The PDO also affects local climate in the PNW, but at lower frequencies (20–40 years) than ENSO. The positive phase of the PDO is associated with warmer drier winters, whereas the negative phase is associated with cooler wetter winters (Mantua et al. 1997). Interestingly, the phase of the PDO may affect the strength of El Niño and La Niña events (Gershunov and Barnett 1998). During the cold phase of the PDO, the effects of El Niño on U.S. climate may be weakened, but the effects of La Niña may be enhanced.

Regional-scale relationships between fire and climate at annual to interannual timescales have been studied extensively in dry ponderosa pine ecosystems in the American Southwest (Weaver 1951, Savage and Swetnam 1990, Swetnam and Baisan 1994) and in the Rocky Mountains (Veblen et al. 2000, Donnegan et al. 2001). Prior to 20th century fire exclusion, fire regimes were closely linked to interannual variability in local moisture conditions associated with the El Niño/Southern Oscillation (ENSO) (Swetnam and Betancourt 1990, Veblen et al. 2000). Major fire years tended to occur during La Niña years or in dry years following El Niño events. Interannual climatic phenomena like ENSO may have the ability to control fire occurrence and fire spread by increasing fine grassy fuels and needle litter during wet years and then drying those fine fuels during dry years, producing high fire hazard. Although large-scale climatic patterns that affect interannual moisture availability are associated with fire regimes in moisture-limited forest ecosystems in the Southwest (Swetnam and Betancourt 1998, Veblen et al. 2000), to date these relationships are poorly understood in the Pacific Northwest (Heyerdahl et al. 2002).

Continental-scale oscillations associated with ENSO have inverse effects in the Pacific Northwest vs. the Southwest (Cayan 1996, Kunkel and Angel 1999). For example, El Niño years are typically associated with warmer, drier winters in the Northwest but cooler, wetter winters in the Southwest. Given observed relationships between ENSO and fire in the Southwest and Rocky Mountains, we may expect that in the Pacific Northwest the warm phase of ENSO (El Niño) may be associated with severe fire years. Also, in the Pacific Northwest, other climatic patterns besides ENSO may be important for fire regimes. For example, the Pacific Decadal Oscillation (PDO) is associated with decadal-scale patterns in precipitation (Mantua et al. 1997), productivity in high-elevation forests (Peterson and Peterson 2001), and possibly with large fire occurrence in the 20th century (Mote et al. 1999*b*). Given the relationship between fire occurrence and climatic variability in the Southwest and the Rocky Mountains, it is possible that decadal scale, quasi-periodic climatic variability in the Pacific Northwest and associated dry conditions over several years could predictably affect the occurrence of fires in a given year, particularly in arid ecosystems through either fine fuel development prior to the fire season or through fuel moisture condition during the fire season. Alternatively, wholly different climatic patterns, unassociated with ENSO or PDO, may affect fire occurrence in the Pacific Northwest.

Human disturbance, especially fire suppression but also timber cutting patterns that produce fuel discontinuity, have had strong effects on fire frequency in the western United States (Agee 1993, Swetnam and Baisan 1994, Grissino-Mayer et al. 1995, Veblen et al. 2000, Heyerdahl et al. 2001). Fire frequency has been significantly reduced in ponderosa pine forests in the 20th century, likely the result of fire suppression and possibly heavy grazing in some areas (Savage and Swetnam 1990). Changes in fire severity from surface fires to less frequent stand-replacing fires are a consequence of this change in fire frequency. Annual area burned in the western United States has steadily increased since the mid-1970s, possibly due either to accumulating fuels caused by 20th century fire suppression (Grissino-Mayer and Swetnam 2000) or to changes in climatic conditions in the 20th century (Swetnam and Betancourt 1998), or both. Although similar changes in fire regimes have been documented at individual sites in the Pacific Northwest, human influences on fire occurrence, especially the transition from native to Euro-American management, are poorly defined. Due to the scarcity of fire history data, it has been difficult to assess the relative importance of human activities vs. climate on fire regimes.

Although a few fire history studies in the Pacific Northwest have addressed climate and human land use at small spatial scales, none has identified the relative importance of each of these variables at different temporal and spatial scales (Schmoldt et al. 1999). This paper explores the relationships between fire, climate, and human activities east of the Cascade Range in Washington by investigating a range of potentially important climatic variables, including drought, ENSO, and PDO, under different human management regimes. A multiscale analysis of the processes that controlled historical fire regimes is crucial to the management of landscapes subject to future climatic variability and change. In order to address multiple controls on past fire regimes, we used an extensive network of spatially explicit fire history data to address the following ques-

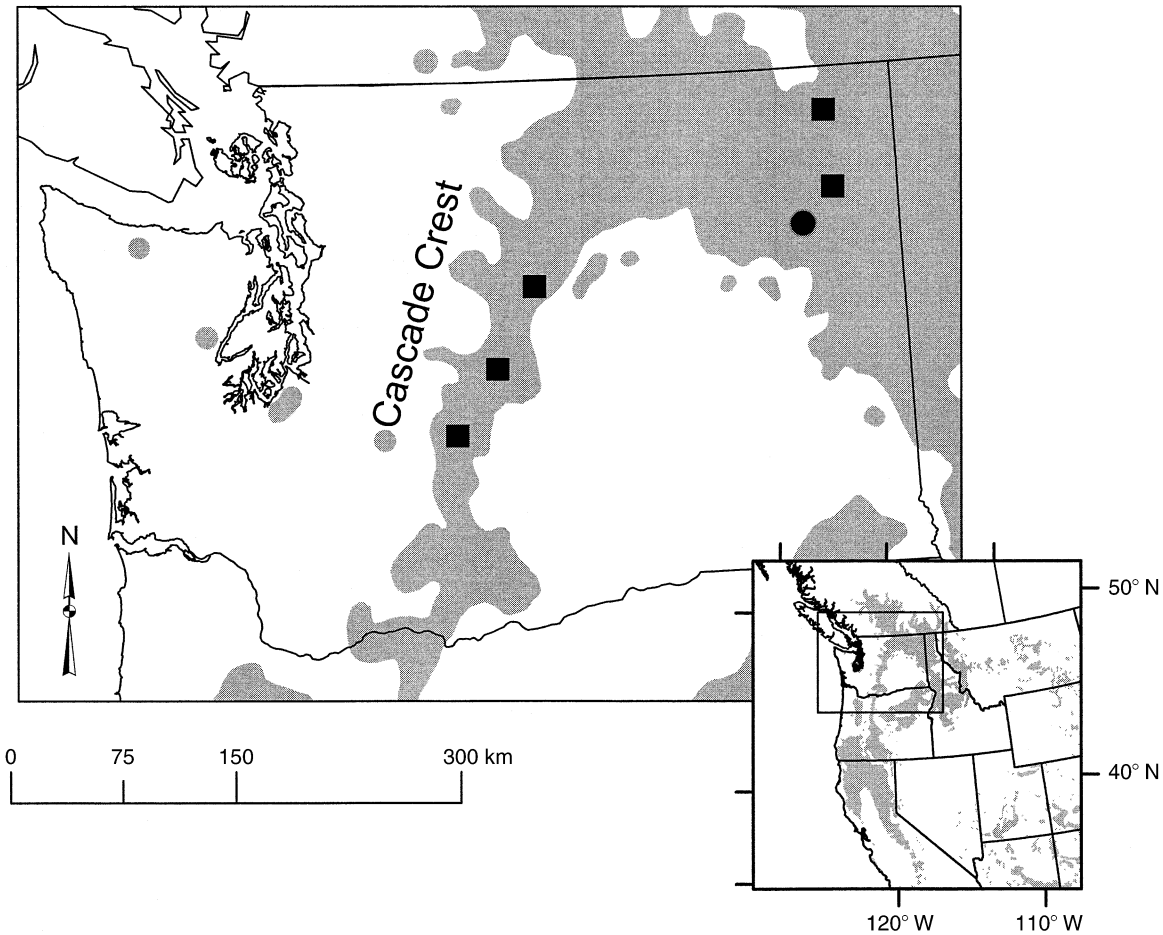

FIG. 1. Map of the study areas (black squares) and the distribution of ponderosa pine (gray areas) (after Little [1971]) in Washington State (USA).

tions: (1) What is the relationship between the temporal patterns of fire occurrence and interannual to decadal climatic variability (especially drought, ENSO, and the PDO)? (2) How do relationships between climate and fire vary in space (among watersheds) and over time (prior to and following Euro-American land use changes)?

STUDY AREA AND METHODS

Everett et al. (2000) produced a detailed, spatially explicit data set of fire history data from 1701 fire-scarred trees collected in five study sites (3116–12 747 ha) extending from the Okanogan-Wenatchee National Forest in central Washington to the Colville National Forest in northeastern Washington (Fig. 1, Table 1). These study sites occupy a 300-km northeast to southwest gradient across the Okanogan Highlands and down the east side of the Cascade Range. Mean annual temperatures range from 7.2°C at 500 m elevation (Colville, Washington, 48°33′ N, 117°54′ W, 1946–2001) to 9.8°C at 323 m (Yakima, Washington, 46°34′ N,

TABLE 1. Location, area, sample sizes, and analysis time frame of fire scarred trees at each of the five sites in central and northeastern Washington, USA.

Site	Location		Sampled area (ha)	Trees	No. fire scars	Fire scars		Analysis years	
	Latitude (N)	Longitude (W)				First	Last	Begin	End
Entiat	47°48′	120°20′	12 747	490	3904	1530	1988	1667	1994
Nile	46°52′	121°05′	3237	234	2314	1367	1970	1671	1996
Swauk	47°15′	120°38′	11 088	667	7048	1257	1942	1675	1997
South Deep	48°45′	117°40′	12 019	168	680	1399	1986	1729	1999
Quartzite	48°17′	117°37′	3116	142	1300	1384	1989	1708	1999
Total			42 207	1701	15 246				

120°32′ W, 1946–2001) (Western Regional Climate Center 2003 [data available online]).[5] Precipitation is more variable and ranges from 20.8 cm/yr in Yakima to 48.7 cm/yr in Colville. Precipitation peaks in December, although the north central region of Washington State experiences a secondary peak in precipitation associated with convective activity during late summer (Daly et al. 1994). Over most of the region, a subtropical high-pressure system in the northern Pacific Ocean during summer generates the low precipitation and high temperatures associated with the late-summer peak fire season (Ferguson 1998).

The study sites are located within forests dominated by ponderosa pine and occupy a narrow band (15–30 km wide) along a northeast–southwest gradient (Fig. 1; Franklin and Dyrness 1988). Ponderosa pine forests in Washington typically occur between 600 and 1200 m elevation and transition into Douglas-fir, grand fir (*Abies grandis* [Dougl.] Lindl.), western larch (*Larix occidentalis* Nutt.), and lodgepole pine (*Pinus contorta* Dougl. ex Loud.) at higher elevations and grassland or sagebrush (*Artemisia tridentata* Nutt.) at lower elevations. Soils in these forests are coarse textured Haplumbrepts or Haplorthods (Franklin and Dyrness 1988). The northeastern study sites (South Deep and Quartzite) are underlain with crystalline bedrock parent materials, whereas the southwestern study sites (Swauk, Nile, and Entiat) occur on steep-sided valleys with either partly metamorphosed sedimentary rock or volcanic/pyroclastic materials (Williams and Lillybridge 1983, Williams et al. 1990, Lillybridge et al. 1995).

Lightning has long been considered the primary ignition source in the Northwest, even though lightning is not so common as in other parts of the western United States (Rorig and Ferguson 1999). The eastern portion of the study area receives more cloud-to-ground lightning than the western portion, but these strikes are more likely to be associated with precipitation than those occurring in the western part, and consequently produce fewer ignitions (Rorig and Ferguson 1999).

Native Americans may have also been an ignition source prior to the major population and cultural changes of the early 1900s. Archeological evidence indicates that Native Americans first settled the inland Pacific Northwest ~13 000 years ago (Robbins 1999). Documentary and anecdotal evidence describe the Entiat, Methow, and Spokane people burning low elevation ponderosa pine forest and grasslands in the region (Robbins and Wolf 1994, Boyd 1999, Robbins 1999, Ross 1999). Natives may have set fires to: remove undergrowth, stimulate new growth of species important for game, reduce the likelihood of more destructive fires, or enhance growth of food-producing species (Barrett 1980). Other native groups, such as the Okanogan, Colville, Yakima, and Salishan (Walker 1998) may have also set fires, although evidence is lacking.

European-American trappers, miners, and early settlers were occasionally present in the inland Pacific Northwest early in the 19th century (Hessburg and Agee 2003), but extensive settlement did not occur until the completion of the Northern Pacific Railroad in 1877 (Ross 1999). Cattle and sheep grazing peaked between 1880 and 1890 (Galbraith and Anderson 1991) but continued to reduce fine fuels into the 1930s. Logging of ponderosa pine forests boomed between 1920 and 1950 when engines used for cutting, transport, and milling moved from steam to gasoline power (Robbins and Wolf 1994). Approximately 50% of the fire scar samples in this study were collected from stumps remaining following logging.

Active fire suppression began as early as 1878 when the Northern Pacific Railroad forbade native burning (Ross 1999), and increased after 1908 when the U.S. Forest Service began a program of fire suppression (Pyne 2001), but may not have been fully effective until the mid-20th century. Logging between 1880 and 1950 also likely reduced the spatial continuity of large woody fuels. At the same time, cattle and sheep grazing likely reduced fine fuels. In our study area, within lands currently managed by the Wenatchee and Colville National Forests, fire suppression, prescribed burning, and logging are currently practiced.

Field Sampling

Low and moderate severity fires, typical of ponderosa pine and Douglas-fir forests east of the Cascade crest (Agee 1994), often kill only a portion of the cambium of living trees, leaving a scar that can be identified in cross section. The year of the fire generating each scar can be identified and crossdated using a master chronology for the region (Fritts and Swetnam 1986). Individual trees can record a large number of surface fires, preserving a history of fire at a particular point in space. Although many factors influence the likelihood that a tree will record a fire (position of the tree on a landscape, bark thickness, lean of the tree, burning-off of previous scars by subsequent fires, and tree vigor [Swetnam and Baisan 1994]), it is possible to characterize past surface-fire regimes with a large number of accurately crossdated fire scar samples.

Everett et al. (2000) generated an extensive, spatially distributed network of geo-referenced, crossdated fire scar chronologies, ideal for spatial and temporal analysis of regional surface-fire history. To date, chronologies have been developed for five study sites (Fig. 1). Within each study site, aerial photographs and topographic maps were used to identify and map aspect polygons, delineated by aspect (northerly or southerly) and slope (flat, moderate, or steep). Sizes of aspect polygons ranged from 32 to 1700 ha, and the number within each site ranged from 2 to 21 polygons. Polygons were internally stratified into four to five sub-

[5] URL: ⟨http://wrcc.sage.dri.edu/⟩.

TABLE 2. Reconstructed climate variables used in the analysis of the fire regime in central and northeastern Washington, USA.

Reconstructed variable	Time period	Season reconstructed	Correlation with instrumental index		Source
			r	*P*	
PDSI	1675–1978	Jun–Aug	0.672	0.001	Cook et al. (1999 [grid point no. 9])
SOI	1706–1977	Dec–Jan	0.632	0.000	Stahle et al. (1998)
PDO	1600–1983	Mar–May	0.520	0.000	Gedalof and Smith (2001)

Note: Abbreviations are: PDSI, Palmer Drought Severity Index; SOI, Southern Oscillation Index; PDO, Pacific Decadal Oscillation.

polygons to ensure that fire scar samples were spatially segregated in the polygon. All fire-scarred trees within each subpolygon were mapped, and between 2 and 23 ''high quality'' trees (with a large number of scars) were sampled. Sections were cut from live trees (Arno and Sneck 1977), and cross sections were collected from stumps, snags, and logs.

Sample processing

Fire scars collected from both living and dead trees were prepared using standard procedures (Arno and Sneck 1977). Live sections were planed and both live and dead sections were sanded with 80–600 grit sandpaper to identify individual tree-rings. All samples were then crossdated (Stokes and Smiley 1968) against an independent master tree-ring chronology developed from 20–50 climatically sensitive trees (without fire scars) within each sampling area. The year of each fire scar was determined by the position of the scar relative to the dated sequence of annual rings in the cross section (Dieterich and Swetnam 1984). Dates were checked by at least two technicians before being archived and summarized using FHX2 fire history software (Grissino-Mayer et al. 1995). Samples that could not be conclusively dated with annual resolution were excluded from the analysis. Based on the pattern of late season fires (July–October) in the modern record, dormant season fires were always assigned to the calendar year of the previous ring (representing a fall fire), rather than the following ring (representing a spring fire).

Fire history analysis

Using the FHX2 software, we developed a master database of fire history records for all points (fire-scarred trees), study sites, and the entire region. Trees that are scarred by fire lose protective bark and are therefore more likely to record fires again. As a result, trees are only considered ''recorder trees'' from the time of initial scarring until either the death of the tree or the sampling date (Romme 1980). Because a single tree can record many fire events and many of these events were likely quite small (recorded by only 1–2 trees), we created composite fire histories for each study site (Grissino-Mayer et al. 1995). These composites include only those years during which ≥10% of the recorder trees in a study site recorded fire, a minimum sample depth of two recorder trees were present, and at least two trees recorded fire. To identify regional fire years (representing large fire events that span more than one study site), we calculated the percentage scarred from each site and weighted (divided) it by the size of the study area. This prevented large study areas from having an exaggerated influence on our determination of regional fires. We then identified those years during which ≥10% of all recorder trees (weighted by study area size) in all study sites recorded fires (with a minimum sample depth of two recorder trees and two scars). Large regional fire years were identified using the same method, but with a minimum of 25% of recorder trees recording fire.

We created collector's curves to graphically display the number of fire years recorded given different numbers of recorder trees sampled. We used these curves to evaluate the adequacy of the sample size in each study site and to identify the time period with an adequate sample size for analysis of the fire regime. As the collector's curve flattens, additional samples add fewer and fewer new fire years to the history of fire at that site, indicating that additional samples will yield little new information.

To describe the basic fire history of our study sites and to understand changes in fire history with Euro-American settlement, we calculated fire return intervals for each point both prior to and following Euro-American influence (1700–1900 and 1901–1990, respectively). Point intervals, or the time between fires affecting a single point, are longer than composite intervals, but are not subject to the variation associated with varying sample size or sample area (Agee 1993, Baker and Ehle 2001).

Instrumental and proxy climate data

Three reconstructed climatic variables were used in this analysis (Table 2, Fig. 2). We used a reconstruction of summer PDSI based on a gridded network of tree-ring chronologies from the United States (Cook et al. 1999, gridpoint no. 9) to evaluate the effect of drought on fire occurrence. We also used a tree-ring reconstruction of the winter SOI (Southern Oscillation Index, an ENSO index) based on regionally averaged tree-ring data from Mexico and Oklahoma (Stahle et al. 1998) to compare fire history to ENSO. When SOI is positive,

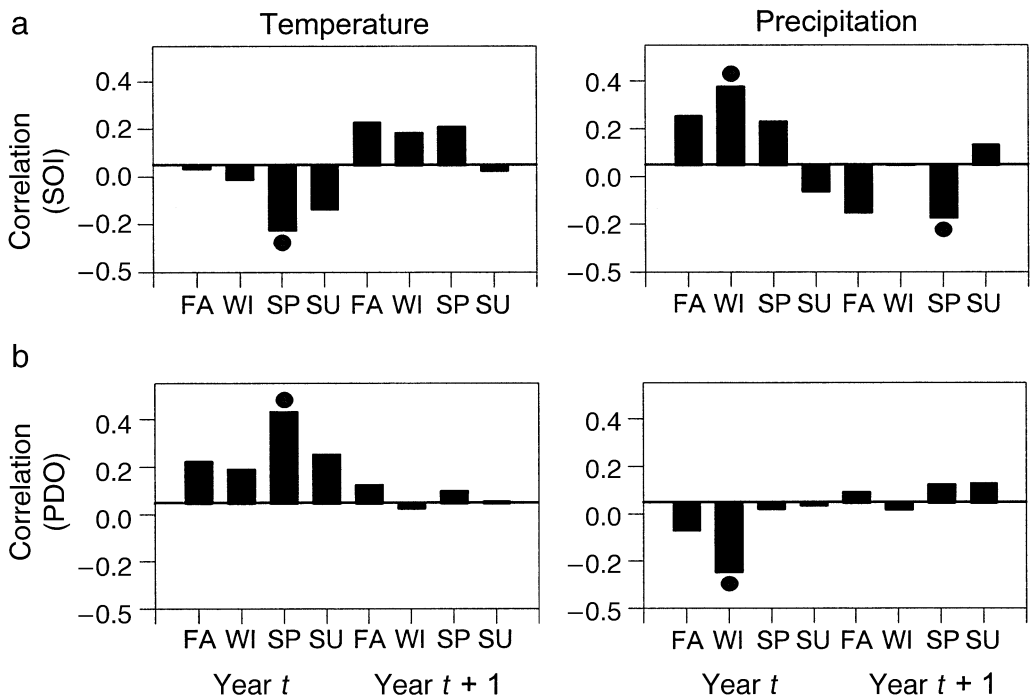

FIG. 2. Correlations between Washington State division 6 seasonal temperature and precipitation (see footnote 5) and (a) Stahle et al.'s (1998) tree-ring reconstruction of the winter mean Southern Oscillation Index (SOI; 1893–1978) and (b) Gedalof and Smith's (2001) tree-ring reconstruction of the Pacific Decadal Oscillation (PDO; 1893–1994). Dots indicate statistically significant correlations ($P < 0.05$). Years of analysis are variable and are noted within each graph. Seasons are: FA (fall), September–November; WI (winter), December–February; SP (spring), March–May; and SU (summer), June–August.

La Niña conditions (cool, wet) dominate and when SOI is negative, El Niño conditions (warm, dry) dominate. ENSO conditions may lead surface climate conditions in the Pacific Northwest by at least six months (Redmond and Koch 1991); therefore we expect to see a relationship between the reconstruction and current as well as subsequent seasons (Fig. 2). Finally, we used a tree-ring reconstruction of PDO based on Pacific Northwest trees (Gedalof and Smith 2001) to compare fire occurrence to the PDO. Although PDO and ENSO are synoptic scale indices of climate, they are both correlated with local climate conditions in the region (Table 2) and in the study area (Fig. 2). Consistent with regional relationships, SOI is negatively correlated with spring temperatures and positively correlated with winter precipitation in our study area. Also consistent with regional relationships, the PDO is positively correlated with spring temperature and negatively correlated with winter precipitation in our study area.

Fire–climate analysis

We investigated current year, lagged, and decadal frequency relationships between fire and PDSI, PDO, and SOI using graphical analysis, correlation, superposed epoch analysis (SEA) (Haurwitz and Brier 1981, Prager and Hoenig 1989, Baisan and Swetnam 1990), and cross-spectral analysis (Bloomfield 2000). Correlation was used to identify relationships between PDSI and fire occurrence prior to and following Euro-American land use changes. SEA identifies statistical, nonlinear relationships between climate variables and fire years. Mean values of reconstructed PDSI and SOI were calculated for six-year windows (three years preceding, two years following, and each composite fire year [when ≥10% of the trees in each watershed were scarred]) for each watershed. We chose six-year windows to allow us to evaluate conditions preceding fire that may be linked to multiannual climatic variability and/or fuel buildup. These values were compared with the complete climatic record during the period of analysis for PDSI and SOI, and tested for significance using Monte Carlo simulations that randomly pick years, identify six-year windows, calculate expected means, and provide 95% bootstrap confidence intervals (Grissino-Mayer et al. 1995). We did not perform SEA on fire occurrence and PDO because the frequency of PDO is too low (20–40 years) to be captured by the SEA window. Instead we used cross-spectral analysis to identify associations between both the PDO and SOI indices and the percentage of recorder trees scarred. This technique is more appropriate for examining low frequency variability in time series.

In cross-spectral analysis, the magnitude squared coherence (MSC) is computed from the cross-spectrum of two time series and the spectral densities of each individually, and normalized to the interval (0,1) (Per-

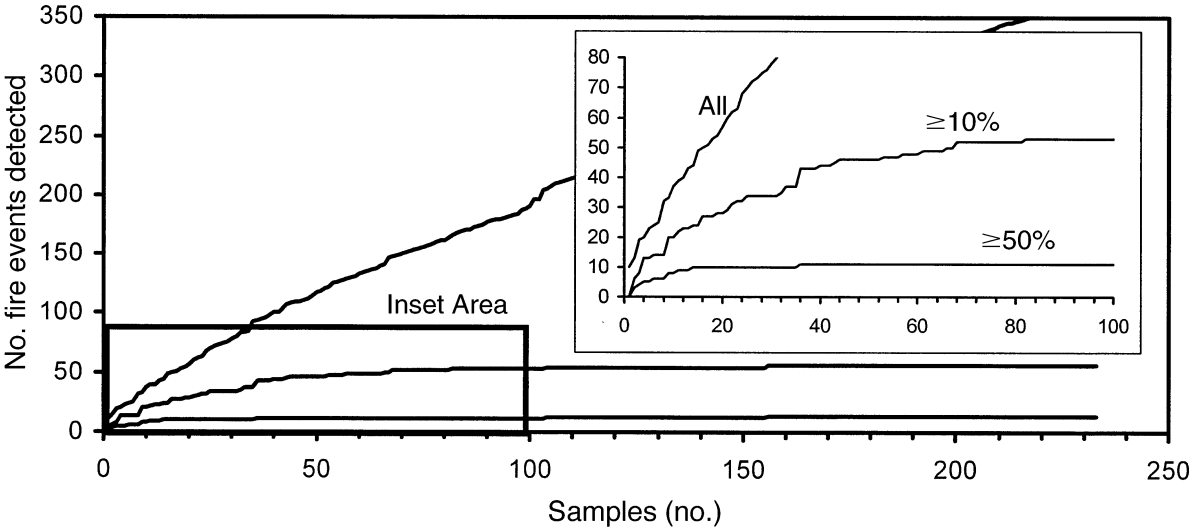

FIG. 3. Collector's curve for the Nile watershed. As the number of samples increases, the number of new events detected declines, but only when small events affecting few trees are eliminated through compositing (using events that were recorded by ≥10% or ≥50% of the recorder trees).

cival 1994). It is thus the analogue in the frequency domain to a correlation coefficient, and is maximized, in our case, when temporal variation in the percentage of trees recording fire is synchronized with temporal variation in the climatic time series. Cross-spectral analysis is only appropriate for time series with periodic or quasi-periodic components (e.g., ENSO and PDO, but not PDSI). Because there were so many zero values in the time series of percentage scarred, along with few large values (>20% scarred), we aggregated both time series in the PDO analysis to blocks of five-year means (climate) and sums (percentage scarred) to achieve second-order stationarity in the latter time series (Brockwell and Davis 1996). This procedure reduced the modeled time series length by a factor of five. We did not apply running means or sums (moving windows), because this type of smoothing can introduce spurious oscillations in time series (Howarth and Rogers 1992). This aggregation technique was not possible with SOI, however, because the ENSO cycle often

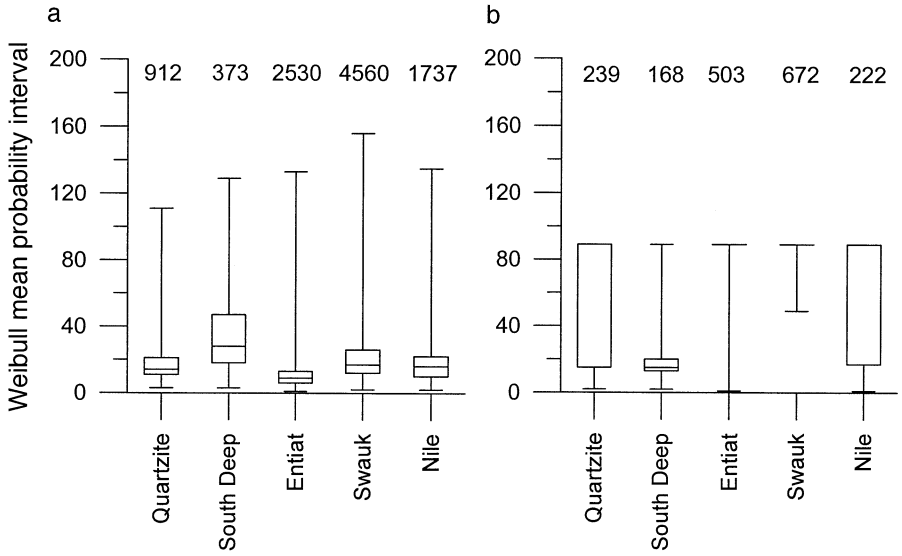

FIG. 4. Box plots of Weibull median probability intervals for points within each site during (a) 1700–1900 and (b) 1901–1990. The bars for each site represent the minimum value, the lower quartile, the median, the upper quartile, and the maximum value, from bottom to top. Numbers above each box represent the total number of intervals recorded at each site during each period. Boxes in (b) are truncated at 89 years because this is the maximum interval possible between 1901 and 1990.

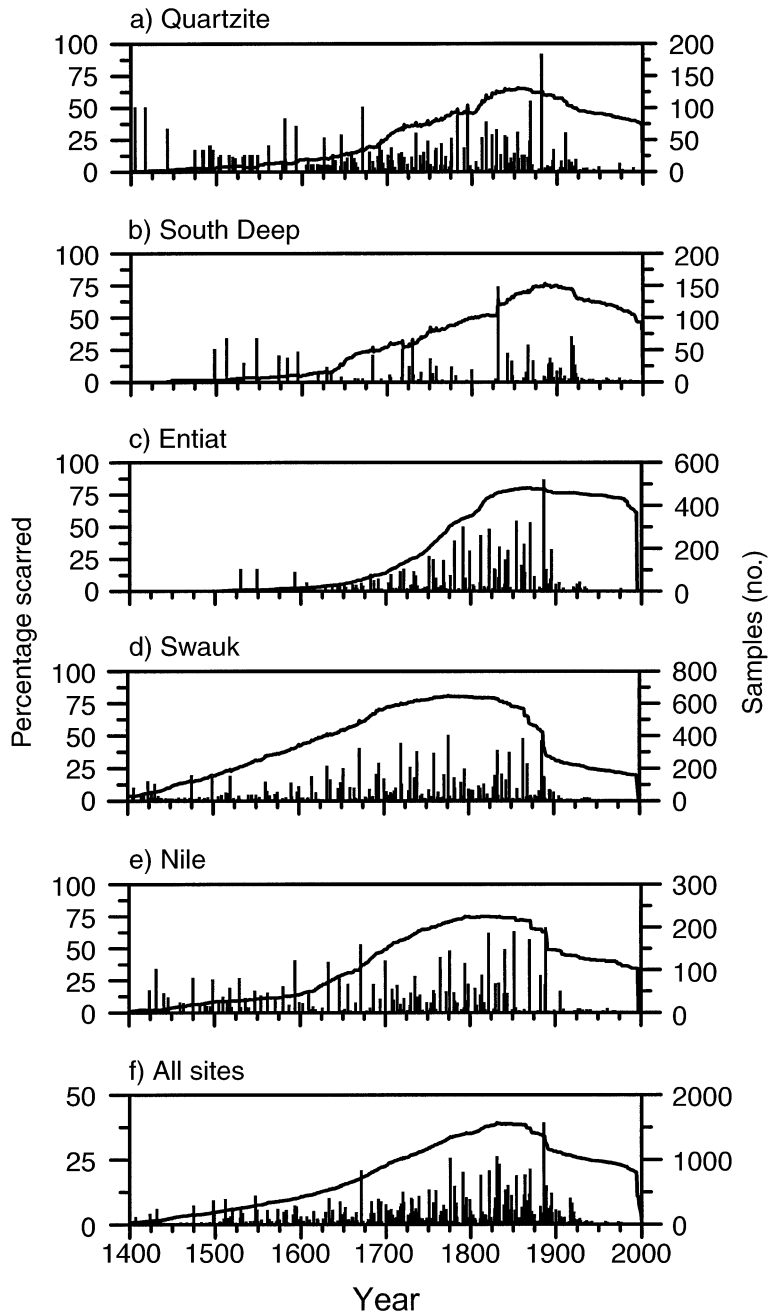

FIG. 5. Percentage of recorder trees scarred (thick line) and sample depth (thin line) for (a) Quartzite, (b) South Deep, (c) Entiat, (d) Swauk, (e) Nile, and (f) all sites combined, 1400–2000.

fits within a five-year time step. Both cross-spectrum were computed using a smoothed periodogram with Daniell smoothers and a split cosine taper applied to the outer 20% of the time series (Percival and Walden 1993).

Confidence intervals can be constructed around the MSC by deriving expressions for the variances and covariance of smoothed spectra and a bias-reduction factor using the inverse hyperbolic tangent (Bloomfield 2000). A 95% confidence interval around the MSC is

$$\tanh(\tanh^{-1}(\mathrm{MSC} \pm 1.96(\mathrm{df}_{\mathrm{spec}}^{-1/2})))$$

where $\mathrm{df}_{\mathrm{spec}}$ is the equivalent degrees of freedom of the cross-spectral estimate (Bloomfield 2000). Computation of the lower confidence band permits a significance test for whether the MSC is different from zero at $\alpha = 0.05$ (if the lower confidence band exceeds zero), analogously to a test of a Pearson's correlation coef-

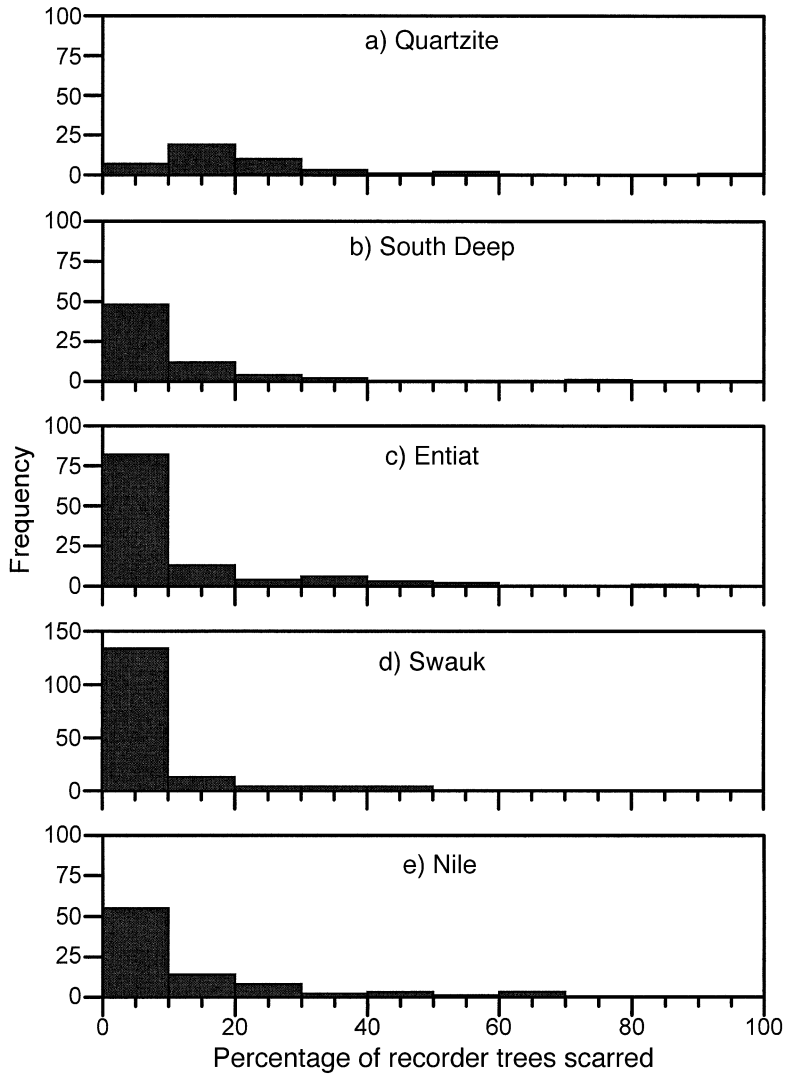

FIG. 6. Frequency of fire events (black bars) by percentage of recorder trees scarred for (a) Quartzite, (b) South Deep, (c) Entiat, (d) Swauk, and (e) Nile.

ficient or the slope of a regression line. Cross-spectral analyses used Splus 6 for Windows (Insightful 2002).

RESULTS

A total of 1701 fire scar samples, recording 15 246 fire scars, were collected from ~42 200 ha in five study sites (Table 1). Samples recorded fires as early as 1257 and all watersheds recorded some fires in the 20th century. Collector's curves for each study site indicate that between 1700 and 1997, all five study sites maintained a sample depth adequate to record ~85% of the total events recorded during that period (Fig. 3, Table 1).

Fire return intervals and settlement

Point fire intervals suggest that prior to Euro-American settlement, fire intervals at individual trees were highly variable (Fig. 4). Between 1700 and 1900, mean point fire intervals for each study site range from 11 years for Entiat to 37 years for South Deep. Interestingly, the mean point fire interval for South Deep actually decreases from the presettlement to the postsettlement period, from 37 years to 27 years. At all other sites during the 20th century mean point fire intervals increase from two to six times their length between 1700 and 1900. For all sites, the total number of intervals (and number of trees recording fire) sharply declined after 1900.

Between 1700 and 1900, the longest fire intervals were in South Deep (Fig. 4). Although Quartzite is also located in the northeastern portion of the study area and is adjacent to South Deep, this site experienced shorter fire free intervals during that same period. South Deep is also unique among sites in its response to climatic variability (see *Results: Fire occurrence*).

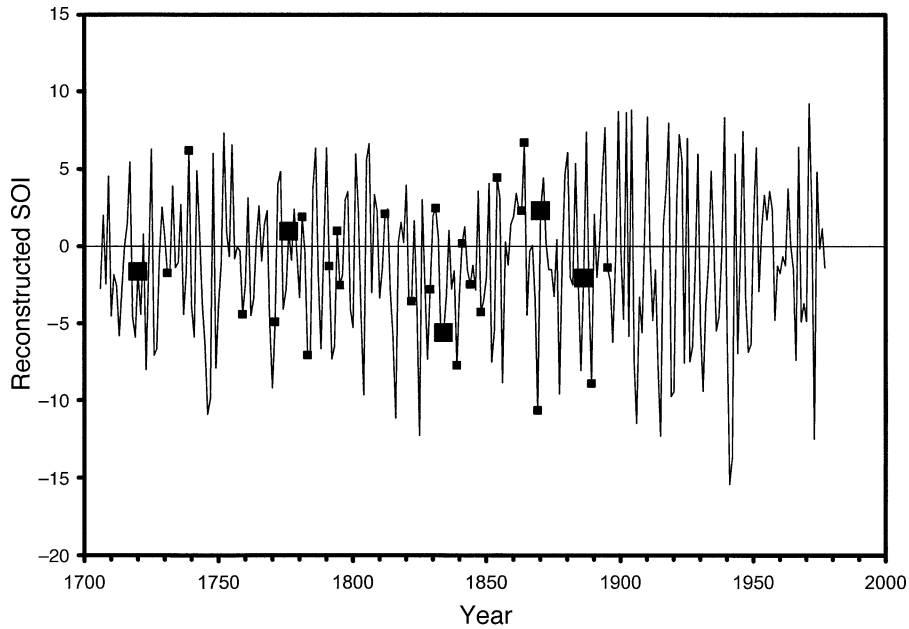

FIG. 7. Southern Oscillation Index (SOI; Stahle et al. 1998), 1706–1977, plotted with large squares for regional fire years (≥25% of all recorder trees in all watersheds recording fire, $n = 5$) and with small squares for smaller regional fires (≥10% of all recorder trees in all watersheds recording fire, $n = 23$).

Fire occurrence over time

Quartzite is unique among the study sites because it is characterized by long fire intervals, with most fires recorded by only 10–20% of the trees (42 events) (Figs. 5a and 6a). However, several extensive events occurred throughout the period of analysis in Quartzite, with three events recorded by >50% of the recorder trees (1795, 1869, 1882) and one event recorded by 91% of recorder trees (1882). Quartzite demonstrates a pattern of increasing frequency of major fires through the 1800s. In the 20th century, fire intervals increased, but a relatively major fire occurred in 1910, scarring 30% of recorder trees.

South Deep has the longest fire free intervals of all five sites and only one major fire event (1831, 73% of recorder trees scarred) during the period of analysis (Fig. 5b). This event follows a fire free interval of 27 years that is unprecedented between 1700 and 1990. During this same period, other sites have longer fire free intervals (Entiat) or reduced percentage scarred (Swauk), but only South Deep shows a complete absence of large fires. Fires continued in South Deep well into the 20th century, with relatively major fires in 1904 (10% scarred), 1917 (34% scarred), 1919 (28% scarred), and 1921 (13% scarred). After 1921, long fire free intervals with fires recorded by few trees continued to occur.

Entiat is the largest site (12 747 ha) and experienced many minor fires and several major fires in the 1800s, culminating in the fire of 1886, the most extensive fire during the period of analysis at this site (Figs. 5c and 6c). Fire intervals in Entiat also increased after 1900.

The Swauk watershed has a history of short fire free intervals with minor fires (<10% scarred) and relatively frequent (nine) major fires (>30% scarred) (Figs. 5d and 6d). Fires recorded by >30% of recorder trees were common in the 1700s and late 1800s, but a gap occurred between 1777 and 1834 during which there were no fires recorded by >30% of the recorder trees. Extensive fires resumed in the late 1800s through 1886 but fire free intervals abruptly increased after 1900 and no fires were recorded after 1942.

In the Nile, extensive fires that burned >50% of the recorder trees in the watershed were relatively common (five fires) compared to the other sites (Figs. 5e and 6e). However, Nile's sample area is relatively small (3237 ha) and the fires may not have been as extensive as those that occurred in larger sites. The fire free intervals suddenly increased at the beginning of the 20th century.

Regionally, major fires (≥25% scarred) occurred three times between 1700 and 1900 (1776, 1834, and 1886) (Fig. 5f), but only the 1776 event was extensive in all watersheds. Fire frequency increased between 1771 and 1795, then decreased between 1796 and 1811, a pattern also observed in the southwestern United States and northern Patagonia (Kitzberger et al. 2001). Fire frequency and extent then increased between 1812 and 1900 with a short gap between 1870 and 1886. Following 1895, no fires were recorded in ≥10% of the recorder trees, signaling a major change in the fire regime.

Fire and climate

Regional and large regional fire events occur during both El Niño and La Niña events (Fig. 7). SEA of SOI

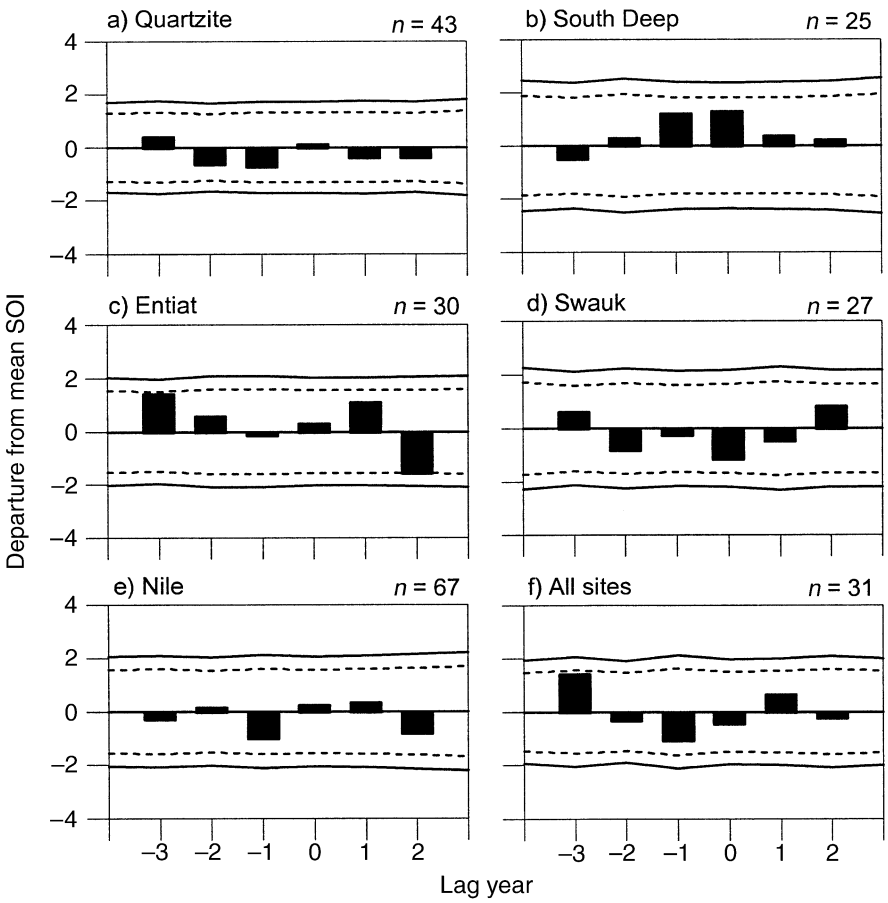

FIG. 8. Superposed epoch analysis for each watershed showing departures from mean annual Southern Oscillation Index (SOI) during fires that affected ≥10% of the recorder trees in (a) Quartzite, (b) South Deep, (c) Entiat, (d) Swauk, (e) Nile, and (f) all sites combined. SOI is shown during the fire year (lag year 0), prior to the fire year (lags −3 to −1) and following the fire year (lags 1 to 2). The horizontal solid and dashed lines are the 95% and 99% confidence intervals derived from 1000 Monte Carlo simulations performed on the entire SOI data set (1706–1977).

at both the site level and the regional level indicates that there is no significant difference between ENSO during fire years vs. simulated years or during the three years preceding a fire year (Fig. 8). However, the coherence spectrum (MSC) of SOI with percentage scarred shows a strong peak, significant at $\alpha = 0.05$, at ~6.3 yr, with a phase shift (SOI leading percentage scarred) of ~3.3 yr (Fig. 9a). With a lag of approximately half the frequency (at maximum coherence), the two series are almost exactly out of phase so when SOI is positive (negative) and La Niña (El Niño) conditions predominate, percentage scarred is low (high). Thus fires tend to occur during El Niño events when winter and early spring conditions are warm and dry rather than during La Niña events when winter and early spring conditions are cool and wet.

Regional and large regional fire events have occurred more frequently during the positive phase of PDO than during the negative phase. Five out of five large regional fire years (≥25% scarred) and 16 out of 27 regional fire years (≥10% scarred) occurred during the positive phase (Fig. 10). The correlation between (annual) PDO and (annual) PDSI is 0.125 ($P = 0.03$) indicating that any relationship between PDO and fire is only weakly associated with interannual drought and instead may represent a long-term influence on fuels through soil moisture, foliar moisture, and needle mortality.

The coherence (MSC) of PDO with percentage scarred for all five watersheds during the period 1700–1900 had one significant peak (lower 95% confidence limit > 0) (Fig. 9b). The time series were coherent with a period of ~47 years, with a phase-spectrum value at that frequency of 5.62, corresponding to a five-year lag between PDO and regional fires (Bloomfield 2000). Because each of the two phases of PDO normally lasts for 20–30 years, 47 years approximates one full cycle.

Regional fire years (≥10% scarred) have occurred when PDSI is both low and high; however, 17 out of 26 fire years occurred when reconstructed PDSI was below the mean (Fig. 11). Large regional fire years (≥25% scarred) occurred when PDSI is below the mean

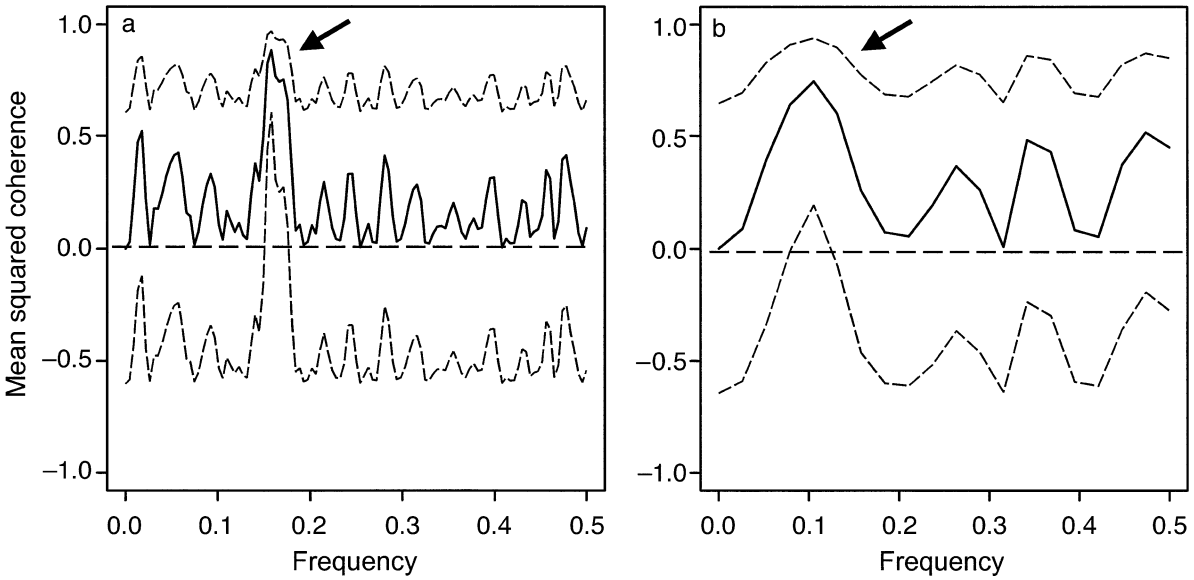

FIG. 9. (a) Coherence spectrum of reconstructed SOI (Stahle et al. 1998) with annual values of percentage of recorder trees scarred for each year. The maximum coherence occurs at a period of ~6 years (1/frequency), with a lag (phase) of three years with SOI leading percentage scarred. (b) Coherence spectrum of reconstructed PDO (Gedalof and Smith 2001) with five-year sums of the percentage of recorder trees scarred for each year. The maximum coherence occurs at a period of ~47 years ([1/frequency] × 5 years), with a lag (phase) of five years (PDO precedes percentage scarred). Dotted lines represent 95% confidence intervals computed sensu Bloomfield (2000).

(four fire years) or following a multiyear period with below average PDSI (one fire year). In summary, not every dry year produced a fire, but most fire years were associated with dry years.

SEA of PDSI and fire indicated that for all sites, drought is associated with fire occurrence. Reconstructed PDSI during the year of the fire ("0") was negative (representing warm, dry conditions) and was below the lower 95% bootstrapped confidence limit in all sites except South Deep (Fig. 12). In South Deep, fire years appear to be centered on multiyear warm, dry periods, but the pattern was not statistically significant. The pattern of reconstructed PDSI in the three years leading up to the fire year varied between sites. For Entiat, two years prior to fire events ("−2") were significantly wet and cool ($P < 0.05$, $n = 30$) but the year before the fire was approximately average. Although this pattern of increased moisture leading up to fire years has been observed in southwestern ponderosa pine forests, it was only evident in one (Entiat) of the five areas studied here. In both Quartzite and Nile, the year before the fire year ("−1") was also warm and dry, with reconstructed PDSI values less than the lower 95% bootstrapped confidence limit. In the SEA for all sites combined (≥10% recorders scarred, minimum of two recorder trees, minimum of two scars, weighted by sample area), PDSI the year of the fire ("0") is below the 99.9% bootstrapped lower confidence limit, suggesting that regional fires occurred during drought years. But fire years were not necessarily preceded by any consistent climatic conditions, either dry or wet (Fig. 12f).

Ten-year running means of percentage scarred and summer PDSI indicate a strong relationship between fire occurrence and summer drought prior to 1900, and a much weaker relationship in the 20th century (Fig. 13). Years with low fire occurrence happened during periods of cool, moist climate throughout the period of record (1684–1978). Major fires followed abrupt changes in PDSI from positive to negative in the 1700s. During the 1800s, decadal frequency variability and a long (~50 year) drought were reflected in increased frequency of fire events. Between ~1890 and 1910 cool, wet conditions dominated and regional fire events were rare. However, minor, less frequent fires occurred throughout the exceptionally droughty conditions of the 1920s and 1930s, a pattern inconsistent with the previous two centuries of inverse relations between drought and fire. The 10-year running means of PDSI and percentage scarred are correlated ($r = -0.375$, $P < 0.001$) during the period of record (1684–1978). Prior to 1901, the 10-year running means of PDSI and percentage scarred are more strongly correlated ($r = -0.577$, $P < 0.001$), indicating that the relationship between fire and climate in the 20th century is weaker than in the previous two centuries. Although temporal autocorrelation introduced by the running means may elevate these r values, visually there is a clear relationship between the two variables prior to 1901, which is also supported by the results of the SEA.

DISCUSSION

Major land use changes in the 20th century altered not only the fire regime, but also the relationship be-

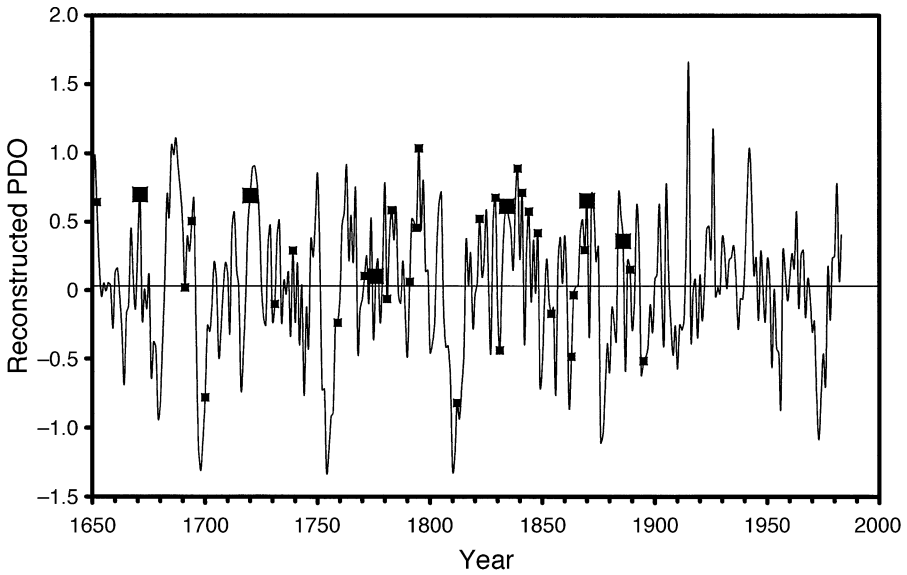

FIG. 10. Pacific Decadal Oscillation (PDO) reconstructed from tree-rings (Gedalof and Smith 2001), 1650–1983, plotted with large squares for large regional fire years (≥25% of all recorder trees in all watersheds recording fire, $n = 6$) and with small squares for smaller regional fires (≥10% of all recorder trees in all watersheds recording fire, $n = 26$). Large regional fires have occurred six out of six times when the PDO is positive (warm, dry phase); however, smaller regional fires have occurred only slightly more often during the positive phase (16 years) vs. the negative phase (11 years).

tween climate and fire on annual timescales. Fire frequency and the number of trees recording fire decreased dramatically in the 20th century in all study sites, reflecting a period of regional land use and land cover change that coincides with reduction of Native American ignition sources, major Euro-American settlement (1890–1910), introduction of domestic livestock, logging, and active fire suppression (>1908). During the 20th century, summer drought was relatively less important in affecting fire extent than previously. A wet

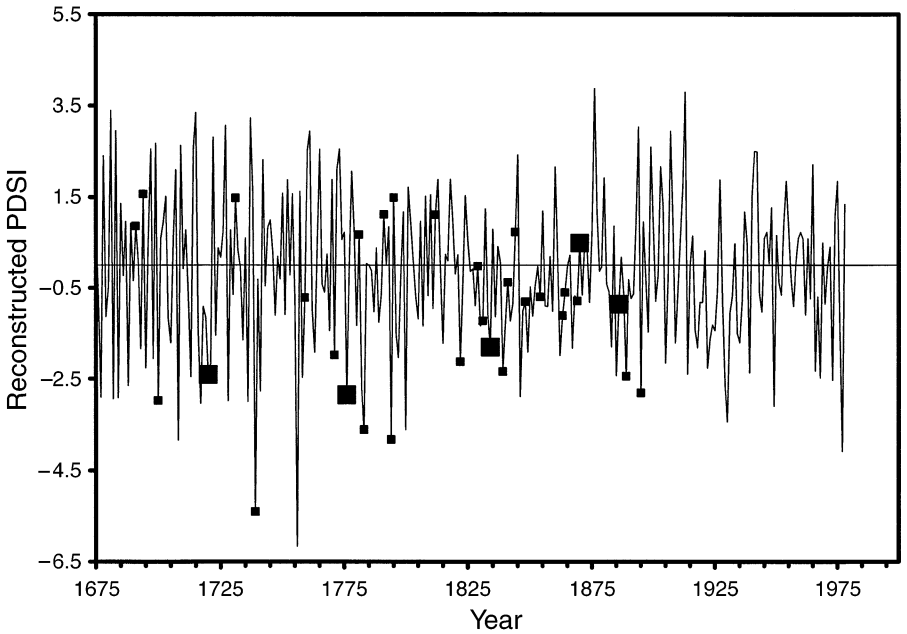

FIG. 11. Palmer Drought Severity Index (PDSI) reconstructed from tree-rings (Cook et al. 1999), 1675–1978, plotted with large squares for large regional fire years (≥25% of all recorder trees in all watersheds recording fire, $n = 5$) and with small squares for smaller regional fires (≥10% of all recorder trees in all watersheds recording fire, $n = 26$). Note the large number of fires that occurred between ~1820 and 1895 when PDSI was consistently low, while the drought period between 1915 and 1935 did not produce regional fires.

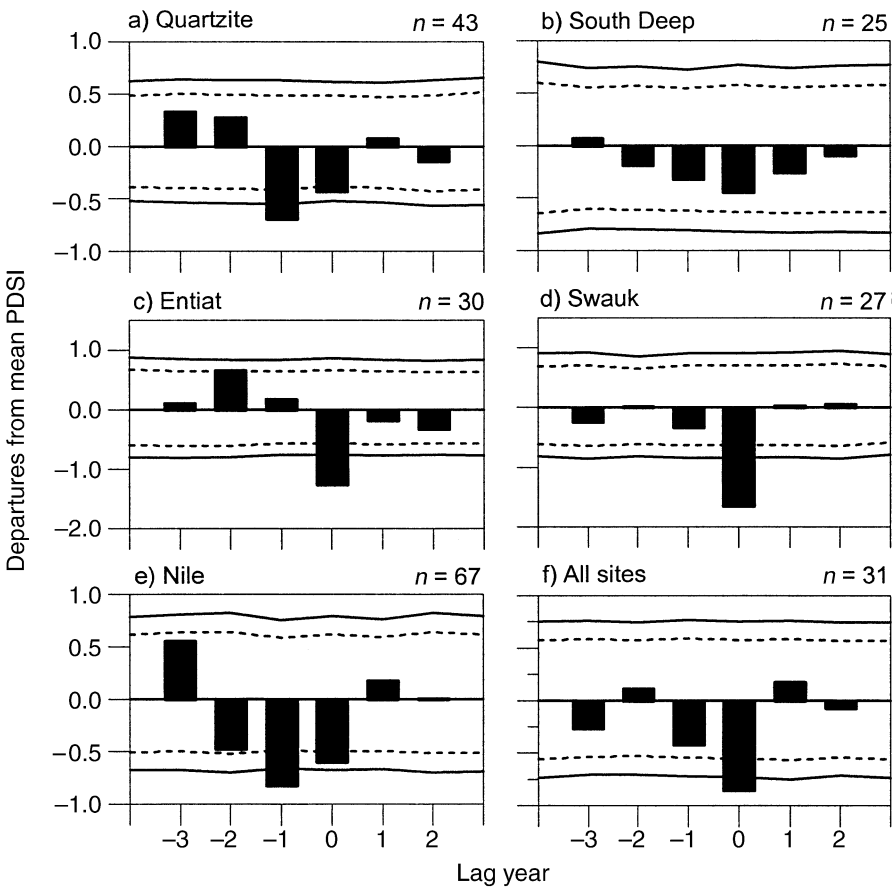

FIG. 12. Superposed epoch analysis for each watershed showing departures from mean annual Palmer Drought Severity Index (PDSI) during fires that affected ≥10% of the recorder trees in (a) Quartzite, (b) South Deep, (c) Entiat, (d) Swauk, (e) Nile, and (f) all sites combined. PDSI is shown during the fire year (lag year 0), prior to the fire year (lags −3 to −1), and following the fire year (lags 1 to 2). The horizontal solid and dashed lines are the 95% and 99% confidence intervals derived from 1000 Monte Carlo simulations performed on the entire PDSI data set (1675–1978).

period occurred between 1900 and 1920 that may have been related to the initial decrease in fire occurrence. However, low annual PDSI values representing severe drought (<−3) did occur seven times during the 20th century. Even so, fires, if they occurred, remained isolated and relatively small and were not detected by this study. Recent large fires in the PNW (not included in this study) associated with drought conditions indicate that although fire extent and climate were weakly associated in the 20th century, current fuel levels may have elevated average fire risk to a point that thresholds will once again be sensitive to the influence of climatic variability in coming decades, regardless of fire suppression activities.

Unlike ponderosa pine fire regimes of the Southwest (Swetnam and Betancourt 1990, 1998) and the Colorado Front Range (Veblen et al. 2000) where ENSO is an important driver of fire, the relationship between ENSO and fire occurrence remains ambiguous in our study area. At the site scale, the results of the SEA show no clear pattern leading up to or during fire years (Fig. 8). At the regional scale, fire years are preceded by negative SOI (El Niño conditions) during the year before the fire year, and positive SOI (La Niña conditions) three years before the fire year, but these relationships are not statistically significant (Fig. 8f). Also at the regional scale, large fire years appear to occur during both El Niño and La Niña conditions (Fig. 7). In contrast to these results, the cross-spectral analysis of SOI and the regional time series of percentage scarred suggests synchrony between SOI and fire extent over time (Fig. 9a). Whereas the SEA represents fire history as a binary time series of fire years and nonfire years, cross-spectral analysis uses the complete continuous time series of percentage scarred, without the loss of information associated with the transformation to a binary variable. As a result, the cross spectral analysis includes information about smaller but more frequent fires, which are left out of the SEA because of both compositing and the binary nature of the analysis.

Heyerdahl et al. (2002) also observed an inconsistent pattern of ENSO and fire relations in the Blue Mountains (~100 km southeast of our study sites) where

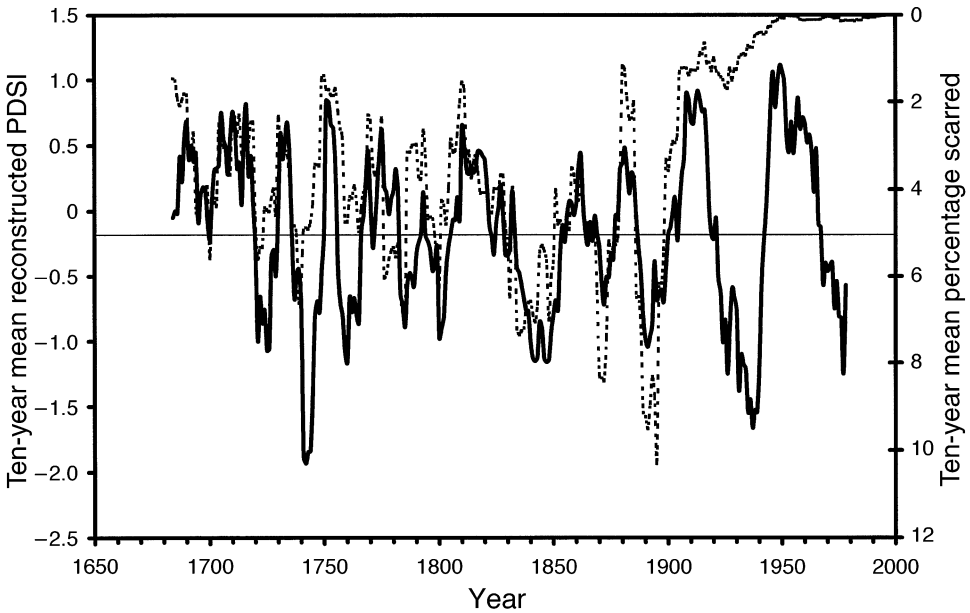

FIG. 13. Ten-year average of Palmer Drought Severity Index (PDSI) reconstructed from tree-rings (Cook et al. 1999), 1684–1978 (black line), and 10-year average of percentage scarred over time (gray line). The *y*-axis for the 10-year average percentage scarred is inverted.

extensive fires tended to occur during El Niño years in some sites but not in others. In the Southwest and the Colorado Front Range, the relationship between ENSO and fire is thought to be closely linked with fine fuel development between fire events such that wet years (El Niño) produce excess grassy fuels and needle litter that are subsequently dried during dry years (La Niña), creating extreme flammability. ENSO is less clearly a driver of fire occurrence in the PNW, either because fuel structures are not responsive to climatic variability on the temporal and seasonal scale of ENSO, or simply because the ENSO signal is weaker in the PNW. For example, although ENSO does influence winter snowfall in the PNW (Cayan 1996, Kunkel and Angel 1999, Smith and O'Brien 2001), the linkage between summer PDSI and ENSO is much weaker (Cole and Cook 1998). As a result, fuel conditions (both volume and moisture) during the fire season (late summer) cannot be directly linked to ENSO. In addition, the SEA and the results of the cross-spectral analysis (with the two time series being perfectly out of phase) indicate a lack of consistent conditions (wet or dry) in the years leading up to fires. Rather than affecting fuel loads, Heyerdahl et al. (2002) suggest that in the PNW, ENSO may influence the length of the fire season through its effect on the timing of snowmelt, thereby changing the likelihood of large fires. Multiyear fuel studies that compare fuel accumulation and fuel moisture to climatic variability as well as studies of the effect of the snow-free season on area burned are necessary to establish a direct link between ENSO and fine fuel buildup as opposed to an indirect link between ENSO and the length of the (snow-free) fire season.

At decadal timescales, the apparent relationship between PDO and fire occurrence warrants further investigation. The coincidence of large, regional fire years and positive phases of the PDO (Fig. 10), in combination with the results of the cross-spectral analysis (Fig. 9b), indicate a broad-scale, low frequency synchrony between PDO and fire in the inland PNW before the onset of fire exclusion in the 20th century. The PDO is a driver of multidecadal winter moisture conditions (Mantua et al. 1997) and may represent a long-term influence on fine-fuel condition (through variations in foliar moisture) and abundance (through variations in productivity and needle mortality). If this hypothesis is correct, this might explain the five-year lag between PDO and fire occurrence identified by the cross-spectral analysis. Given spatial variability in precipitation, it may take approximately five years for regional climate to influence foliar moisture and needle mortality at the broad spatial scales necessary to generate the conditions conducive to the spread of regional fires across all five of our study sites. Alternatively, a bottom-up explanation of the five-year lag in the cross-spectrum may involve biofeedback from the landscape (in the form of limited latent heat flux and near-surface humidity deficit) to boundary level climate that may take several years to develop (Entekhabi et al. 1999). Finally, the dominant mode of the PDO is only quasi-periodic; phase shifts do not appear with strict regularity and the length of the transition is variable (Mantua et al. 1997). A five-year lag may simply fit within errors of estimating the phase of the PDO.

We suggest that this association between PDO and fire occurrence be viewed with caution. First, recon-

structions of the PDO can only be validated with a few cycles of observed PDO in the 20th century; thus, it is difficult to evaluate the temporal stability of this climate feature back through time (Gedalof and Smith 2001). In addition, the necessary aggregation of the time series to evaluate the coherence spectra may have inflated the significance level of the coherence (Howarth and Rogers 1992). Mote et al. (1999b) found only weak relationships between area burned, ENSO, and PDO in Oregon and Washington during the period 1905–1994, with a correlation between the Niño3.4 index and burned area near 0, but correlations between winter PDO and burned area slightly stronger ($r = 0.24$, $P < 0.01$). Our results are statistically more robust than Mote et al. and represent a different time frame (presettlement fire regimes), but additional research on the strength of the PDO over time and continued work on fire occurrence and fire spread in relation to the PDO are necessary to infer a causal link. However, if the relationship between PDO and fire that we have observed in the PNW is real and the periodicity of the PDO remains stable in coming decades, our work points to a new understanding of the temporal variability in the disturbance regime and the potential development of new tools for fire and ecosystem management in the semiarid forests of the inland PNW.

Both PDO and ENSO influence winter–spring moisture and temperature conditions in the Pacific Northwest (Redmond and Koch 1991, Mantua et al. 1997, McCabe and Dettinger 1999, Mote et al. 1999*a*). However, our results suggest that on annual timescales, summer drought during the year of the fire is the clearest climatic factor associated with the occurrence of major fire years at the site and the regional level. Summer drought conditions are important in the Pacific Northwest because the fire season occurs in late summer (August–September and even into October) rather than spring or early summer, and there is ample time for high temperatures to deplete moisture generated by winter or spring conditions even in large-diameter fuels. In contrast, in the southern Rocky Mountains and the Southwest, where fires occur earlier in the summer, climatic conditions during the previous winter or summer may be more important.

The relationship between regional fire years and summer drought on annual timescales, and regional fire years and PDO on decadal timescales has several implications for fire–climate research and for ecosystem management on a regional scale. First, severe summer droughts have occurred in the PNW in the past (Graumlich 1987) and will continue to occur in the future, likely bringing extreme fire conditions like those of 2002. Although much research has focused on winter climatic conditions in the PNW, due to the dependence of agriculture, fisheries, and urban areas on spring snowmelt and run-off, additional research is needed to understand summer drought conditions and their causes (e.g., Barlow et al. 2001). Second, the link between PDO, a multidecadal phenomenon, and fire may provide an intermediate time step in fire–climate relations that bridges a gap between interannual connections (e.g., Swetnam and Betancourt 1990, Veblen et al. 2000) and centennial to millennial scale connections (e.g., Swetnam 1993, Millspaugh and Whitlock 1995). This decadal frequency connection between ecosystem dynamics and climate may have interesting implications for vegetation dynamics, biogeochemical cycles, and ecosystem management at the regional scale. For example, if the PDO remains stable in coming decades and fires continue to be tied to this phenomenon, fire planning in the PNW could occur on decadal rather than interannual timescales, with dramatic consequences for prescribed fire planning, fire suppression, and even national budgets for fire management.

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