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# MULTI-SEASON CLIMATE SYNCHRONIZED HISTORICAL FIRES IN DRY FORESTS (1650–1900), NORTHERN ROCKIES, USA

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*Abstract*. Our objective was to infer the climate drivers of regionally synchronous fire years in dry forests of the U.S. northern Rockies in Idaho and western Montana. During our analysis period (1650–1900), we reconstructed fires from 9245 fire scars on 576 trees (mostly ponderosa pine, *Pinus ponderosa* P. & C. Lawson) at 21 sites and compared them to existing tree-ring reconstructions of climate (temperature and the Palmer Drought Severity Index [PDSI]) and large-scale climate patterns that affect modern spring climate in this region (El Niño–Southern Oscillation [ENSO] and the Pacific Decadal Oscillation [PDO]). We identified 32 regional-fire years as those with five or more sites with fire. Fires were remarkably widespread during such years, including one year (1748) in which fires were recorded at 10 sites across what are today seven national forests plus one site on state land. During regional-fire years, spring–summers were significantly warm and summers were significantly warm-dry whereas the opposite conditions prevailed during the 99 years when no fires were recorded at any of our sites (no-fire years). Climate in prior years was not significantly associated with regional- or no-fire years. Years when fire was recorded at only a few of our sites occurred under a broad range of climate conditions, highlighting the fact that the regional climate drivers of fire are most evident when fires are synchronized across a large area. No-fire years tended to occur during La Niña years, which tend to have anomalously deep snowpacks in this region. However, ENSO was not a significant driver of regional-fire years, consistent with the greater influence of La Niña than El Niño conditions on the spring climate of this region. PDO was not a significant driver of past fire, despite being a strong driver of modern spring climate and modern regional-fire years in the northern Rockies.

*Key words: dendrochronology; El Niño–Southern Oscillation; fire history; fire scars; Idaho; Montana; Pacific Decadal Oscillation; Palmer Drought Severity Index; spring; summer; temperature.*

## Introduction

Annual extremes in fire-season climate synchronized the occurrence of fires across broad regions of western North America for at least several centuries in the past (e.g., Swetnam and Betancourt 1998, Veblen et al. 1999, Heyerdahl and Alvarado 2003, Swetnam and Baisan 2003, Kitzberger et al. 2007) and continued to do so throughout the 20th century (e.g., Westerling et al. 2003, 2006, Collins et al. 2006, Morgan et al. 2008). Although the importance of summer drought in driving regional-fire years has long been recognized, the potential role of warm springs in synchronizing regional fire in the northern United States has been suggested for historical and modern fires but only recently confirmed for the 20th century (Balling et al. 1992, Heyerdahl et al. 2002, Hessl et al. 2004, Westerling et al. 2006, Morgan et al. 2008). Late 20th-century trends toward warm, early springs have been associated with increased forest fire activity and further increases in temperatures projected under plausible climatic change scenarios imply a greater frequency of regional-fire years in the 21st century (Running 2006, Westerling et al. 2006). Assessing the potential impact of climatic change on forest fire activity in the western United States requires that we understand the climate drivers of regionally synchronous fires before any recent changes in climate.

The U.S. northern Rockies in Idaho and western Montana are a critical region for understanding both past and present climate drivers of fire. Repeatedly during the 20th century, this region experienced regionally extensive fires that led to changes in national fire policy (Pyne et al. 1996). The late 20th-century increase in large forest fires was greater in the northern Rockies than other regions of the western United States (Westerling et al. 2006), a region where fire and climate-driven changes in fire have had significant implications for vegetation composition and structure (Whitlock et al. 2003). However, this region lacks a network of annually accurate histories of pre-20th-century fire from which we could identify past climate drivers, despite abundant fire-scar evidence in dry forests, i.e., those dominated or co-dominated by ponderosa pine.

In the northern Rockies, spring and summer climate have varied through time (Briffa et al. 1992, Cook et al. 2004) and warm-dry summers have been inferred as

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TABLE 1. Dry-forest sampling sites and evidence of fire collected at each (1650–1900).

| Site no. | Site code | No. trees | Area (ha) | Elevation (m) | Latitude (N) | Longitude (W) | No. fire scars | No. years with ≥2 scars | Scar date | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | First | Last |
| 1 | VIZ | 46 | 13 | 760 | 48°58′15″ | 115°7′33″ | 1450 | 38 | 1652 | 1882 |
| 2 | HUN | 25 | 31 | 750 | 48°53′27″ | 115°13′46″ | 308 | 17 | 1652 | 1869 |
| 3 | LIB | 29 | 36 | 700 | 48°24′58″ | 115°32′16″ | 544 | 36 | 1661 | 1889 |
| 4 | MCM | 32 | 8 | 830 | 48°18′42″ | 115°29′11″ | 513 | 20 | 1661 | 1889 |
| 5 | CRN | 18 | 18 | 1050 | 47°53′46″ | 114°0′58″ | 216 | 16 | 1655 | 1892 |
| 6 | COR | 26 | 3 | 1190 | 47°36′8″ | 114°55′51″ | 439 | 24 | 1652 | 1889 |
| 7 | HOL | 19 | 38 | 1220 | 47°26′21″ | 113°38′48″ | 224 | 16 | 1671 | 1882 |
| 8 | FAV | 17 | 148 | 1130 | 47°9′19″ | 114°29′21″ | 259 | 17 | 1687 | 1895 |
| 9 | BUT | 38 | 2 | 1400 | 47°7′21″ | 14°23′36″ | 803 | 25 | 1675 | 1870 |
| 10 | LUB* | 20 | 70 | 1270 | 46°53′26″ | 113°27′17″ | 139 | 20 | 1652 | 1861 |
| 11 | BMT | 36 | 33 | 1141 | 46°49′27″ | 114°7′35″ | 770 | 40 | 1665 | 1889 |
| 12 | SML | 32 | 53 | 1520 | 46°27′4″ | 113°53′40″ | 231 | 16 | 1670 | 1889 |
| 13 | SHE | 41 | 14 | 1350 | 46°20′16″ | 114°14′25″ | 523 | 22 | 1665 | 1898 |
| 14 | FLA | 25 | 28 | 950 | 46°50′43″ | 116°53′54″ | 569 | 40 | 1660 | 1895 |
| 15 | KEA | 22 | 4 | 1530 | 45°28′1″ | 116°8′58″ | 227 | 17 | 1671 | 1889 |
| 16 | COV | 25 | 12 | 1670 | 45°25′7″ | 115°31′1″ | 250 | 14 | 1659 | 1889 |
| 17 | FRI | 31 | 47 | 1500 | 45°32′54″ | 113°56′33″ | 379 | 20 | 1656 | 1889 |
| 18 | POV | 33 | 18 | 1270 | 44°49′13″ | 115°42′7″ | 303 | 12 | 1743 | 1889 |
| 19 | WSH | 25 | 31 | 1030 | 44°2′41″ | 115°55′27″ | 508 | 21 | 1652 | 1863 |
| 20 | LOW | 9 | 45 | 1340 | 44°3′50″ | 115°36′56″ | 81 | 9 | 1656 | 1888 |
| 21 | WSR | 27 | 15 | 1530 | 43°49′33″ | 115°53′47″ | 509 | 25 | 1652 | 1878 |
| Total | | 576 | | | | | 9245 | | | |

*Note:* Number of fire scars includes eroded scars (5% of total).
* Samples from LUB were collected for another study (L. A. Jones, *personal communication*).

significant drivers of historical fires in some subalpine forests of the region (Kipfmueller 2003). The fire season in dry forests here begins after annual snowpacks have melted in the late spring to early summer (Serreze et al. 1999). Despite variation in local climate and topography, empirical and modeling studies have demonstrated that relatively warm springs historically resulted in relatively earlier melting of snowpacks at sites spanning a broad range of elevations across the region (Hamlet et al. 2005, Mote 2006, Westerling et al. 2006). These relatively warm springs are partly driven by large-scale climate patterns. Following El Niño events, winters and springs in this region tend to be anomalously dry and warm which results in anomalously shallow snowpacks while La Niña events lead to anomalously deep snowpacks (Redmond and Koch 1991, Gershunov et al. 1999, Harshberger et al. 2002, Mantua 2002, McCabe and Dettinger 2002). PDO affects spring climate in the northern Rockies in a manner similar to ENSO but varies on a longer time scale (Mantua et al. 1997, McCabe and Dettinger 2002). PDO was an important driver of 20th-century fires in the northern Rockies (Morgan et al. 2008) and elsewhere in the inland Northwest (Westerling and Swetnam 2003, Gedalof et al. 2005, Collins et al. 2006). Interannual variations in PDO, sometimes interacting with ENSO, account for roughly a third of the variance in modern spring snowpack in the region (Gershunov and Barnett 1998, Harshberger et al. 2002, McCabe and Dettinger 2002). Interactions of ENSO and PDO elsewhere in the interior West are associated with historical fire activity (Schoennagel et al. 2005, Sibold and Veblen 2006, Kitzberger et al. 2007). It is likely that annually and decadally varying spring and summer climate and large-scale climate patterns synchronized past fire across the northern Rockies as well. However, the climate drivers of past fire in this region have not yet been examined across broad spatial scales using fire records with annual accuracy.

Our objective was to infer the climate drivers of past regionally synchronous fires in dry forests (dominated or co-dominated by ponderosa pine) in the northern Rockies. We reconstructed past fires from fire scars at 21 sites in Idaho and Montana west of the Continental Divide, and compared them to existing tree-ring reconstructions of climate (temperature and PDSI) and to large-scale climate patterns that affect modern spring climate in this region (ENSO and PDO).

## STUDY AREA

### *Modern instrumental climate*

The climate of the study area is continental, with cold winters and warm summers. All but one of our sites (FLA; Table 1) lie within two climate divisions (Idaho division 4 or Montana division 1; data *available online*).[4] Mean January temperature in these divisions is −5° and −6°C and mean July temperature is 18° and 19°C, respectively (1895–2005). Mean annual precipitation is low, more so in Montana than Idaho (49 and 68 cm, respectively, 1895–2005) and much of this falls as snow in winter (62%, 1963–1996; Serreze et al. 1999). Snow-water equivalent at elevations averaging 1905 m (range 960–2790 m) in the study area generally peaks in mid-April

[4] ⟨www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp⟩

and drops to zero by early July (Serreze et al. 1999). Variation in montane snow-water equivalent on 1 April is highly coherent across the region (Clark et al. 2001).

### *Tree-ring reconstructed climate*

We used tree-ring reconstructions of two climate parameters (temperature and PDSI) and two indices of large-scale climate patterns (ENSO and PDO). We used a gridded reconstruction of spring–summer temperature (April–September), which is expressed as the departure from mean temperature during the reference period 1951–1970 (Briffa et al. 1992). Reconstructed temperature at grid point 13, the one closest to our study area (Fig. 1), is significantly correlated with instrumental temperature only during the months of April, May, and August, but captures more of the variation in spring than summer (April–May, $r = 0.59$, $P < 0.0001$; August, $r = 0.38$, $P = 0.0004$, average normalized temperature from Idaho division 4 and Montana division 1, 1901–1983). The correlation of reconstructed temperature with combined spring and summer temperature (April–September) is higher than that for either season ($r = 0.69$, $P < 0.0001$) and temperature in these two seasons is not significantly correlated ($r = 0.18$, $P = 0.1064$, 1901–1983), indicating that both seasons contribute to the reconstruction.

We used a gridded reconstruction of PDSI (June–August, Cook et al. 2004). PDSI was significantly correlated among the six grid points nearest the study area and west of the Continental Divide (54, 55, 56, 67, 68, and 69, Fig. 1; pairwise $r = 0.65$–$0.98$, 1650–1900, $P < 0.0001$). Therefore, we used average PDSI across the six grid points. This average is significantly correlated with instrumental temperature only during the months of June and July ($r = -0.59$, $P < 0.0001$, 1901–1990) and with instrumental precipitation only during the months of May, June, and July ($r = 0.65$, $P < 0.0001$). Our two reconstructed indices of climate (PDSI and temperature) are significantly correlated (–0.30, $P < 0.0001$, 1650–1900).

As indices of large-scale climate patterns, we used tree-ring reconstructions of PDO and ENSO. The ENSO reconstruction is for the season with the greatest impact on spring climate in the study area (December–February Niño-3; D'Arrigo et al. 2005). Of the several published reconstructions of PDO, we selected those most highly correlated with instrumental spring PDO (March–May; $r = 0.62$, 0.70, and 0.71; all $P < 0.0001$; D'Arrigo et al. 2001, 2006, Shen et al. 2006), the season with the greatest effect on modern temperature ($r = 0.50$, $P < 0.0001$ for March–May temperature and instrumental PDO, 1901–2001) and modern regional-fire years in the Northern Rockies (Morgan et al. 2008).

## Methods

### *Fire history*

We sampled 21 sites historically dominated by ponderosa pine because fire scars are well preserved on this resinous species (Fig. 1, Table 1). The nearest-neighbor distance between sites averaged 47 km (range 8–162 km). Most sites (90%) lie between 760 and 1530 m, and slope and aspect varied within and among sites. We used a chain saw to remove fire-scarred partial sections from those trees with the greatest number of well-preserved visible scars (Arno and Sneck 1977). We sampled 11–46 (average 27) trees per site across an area of 2–148 ha (average 32 ha). At one site (LUB), 46 samples were collected over a relatively large area (379 ha) for another study (L. A. Jones, *personal communication*). To mimic sampling at our other sites, we sub-sampled these data by selecting those 20 trees with the greatest number of fire scars. These trees were sampled over 70 ha.

We sanded the scarred sections until the cell structure was visible with a binocular microscope and assigned

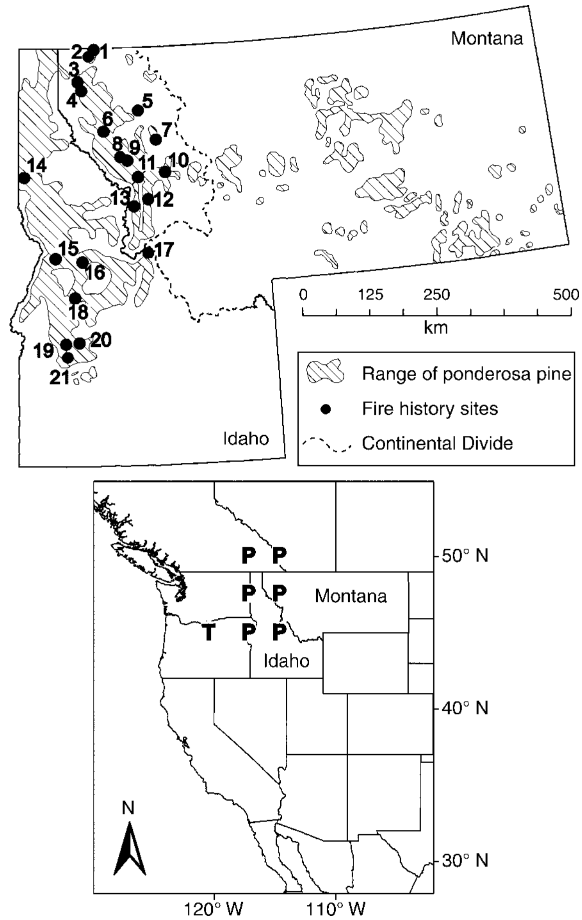


FIG. 1. The study area, showing the location of 21 dry-forest fire-scar sampling sites in Idaho and Montana, west of the Continental Divide, USA (top). Site numbers are as in Table 1. The range of ponderosa pine, the primary fire-scarred species sampled for this study, is hatched (range data *available online* at ⟨esp.cr.usgs.gov/data/atlas/little/pinupond.pdf⟩. Grid points of existing tree-ring reconstructed PDSI (Palmer Drought Severity Index) and temperature that we used are indicated on the lower map (P and T, respectively [Briffa et al. 1992, Cook et al. 2004]).

calendar years to tree rings by visually crossdating ring widths on each sample among trees and sites. We also cross-correlated measured ring widths with tree-ring reconstructed PDSI for 15% of the trees (grid points 68 and 69 [Grissino-Mayer 2001*a*, Cook et al. 2004]). We identified the calendar year in which each scar formed as the year of fire occurrence (Dieterich and Swetnam 1984) and noted its intra-ring position (earlywood, latewood, or ring boundary). In the northern Rockies, ring boundaries span two calendar years, from the time the cambium stops growing one year until it resumes the following year. We generally assigned ring-boundary scars to the preceding calendar year because modern fires near the study area commonly burn in mid to late summer (Schmidt et al. 2002). However, scars from a given fire can have a range of intra-annual positions because the timing of radial growth varies among trees at a site (Fritts 1976). Therefore, when some ring-boundary scars occurred in one year but many early-season scars occurred the following year at the same site, we assumed the scars in both positions were created by a fire that burned before the trees with ring-boundary scars began radial growth and therefore assigned the ring-boundary scars to the following year (37 scar dates). In addition to fire scars, we obtained a small amount of supporting evidence of fire (5% of all fire dates) from eroded fire scars, those with much of the overlapping, curled woundwood rings destroyed by subsequent fires or rot.

At each site, we combined fire-scar dates from all trees into a composite record and identified fire years as those in which at least two trees had fire scars and recording years as those for which at least two trees had scarred at least once. Although scars dated from 1501 to 1987, we analyzed the climate drivers of fire only from 1650 to 1900, the period when most sites were recording ($\geq$95% of sites recording from 1650 to 1887, $\geq$71% of sites recording from 1888 to 1900). We placed all years in this period into one of three categories: (1) no-fire years had no fires recorded at any site; (2) local-fire years had fire at one to four sites; and (3) regional-fire years had fire at five or more sites. We identified regional-fire years as those at or exceeding the 90th percentile in sites with fire, i.e., those with five or more sites. However, because there are eight years with five or more sites with fire, the actual percentile is the 88th.

### *Climate drivers of fire*

To infer the influence of climate on fire, including climate during antecedent years, we assessed whether climate during no-, local-, or regional-fire years differed significantly during the fire year or the preceding or following years ($\pm$3 years) using superposed epoch analysis (SEA; Baisan and Swetnam 1990, Swetnam and Betancourt 1998, Grissino-Mayer 2001*b*). For each fire-year category, we computed departures in three indices: temperature, PDSI, and Niño-3. The time series of PDSI was white noise but those for temperature and Niño-3 were not ($P = 0.1071$, $P < 0.0001$, and $P < 0.0001$, respectively; SAS PROC ARIMA autocorrelation test for white noise using six lags [SAS Institute 2003]). Therefore, to meet the assumptions of SEA, we prewhitened the temperature and Niño-3 time series by fitting autoregressive integrated moving average models based on lowest Akaike's information criterion and significant but uncorrelated parameter estimates (MA(1) after first differencing and AR(2), for temperature and Niño-3, respectively) and used the white noise residuals in the SEA (white noise test $P = 0.3702$ and 0.3709, respectively). We identified significant climate departures as those exceeding 99% confidence intervals determined by bootstrapping (1000 trials; Mooney and Duval 1993, Grissino-Mayer 2001*b*). Because the regional-fire years that occurred when temperature was below average were all after 1700, we repeated the SEA with regional-fire years from 1700 to 1900.

To identify the influence of combined climate phases for each category of fire synchrony (no-, local-, or regional-fire years), we tested whether the distribution of years among four climate phases (above or below average temperature and PDSI, 1650–1900) differed significantly from the distribution of all years among the four climate phases regardless of fire activity (chi-square goodness-of-fit tests, $\alpha = 0.01$ [Zar 1984]). We similarly tested the distribution of years among combined phases of large-scale climate patterns (ENSO and PDO) for each of the fire synchrony categories. We repeated these tests with each of the three PDO reconstructions (D'Arrigo et al. 2001, 2006, Shen et al. 2006). If we rejected the null hypothesis of no difference, we repeated the test with subsets of climate phases to determine if the disagreement between observed and expected numbers of fire years was significantly concentrated in those subsets (Zar 1984).

## Results

### *Fire history*

We removed fire-scarred partial sections from 614 trees (average of 1.6 partial sections per tree), most of which were dead when sampled (93%). Most were ponderosa pine (98%), but we sampled a few western larch (*Larix occidentalis* Nutt.) and Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) trees. We could not cross-date sections from 7% of the sampled trees and so excluded them from further analyses. From the 576 cross-dated trees, we identified 9245 fire scars and eroded fire scars during the analysis period (1650–1900) from which we identified nine to 40 years (average 22) with at least two fire scars per site (Table 1).

We categorized the analysis period into 99 no-fire years, 120 local-fire years, and 32 regional-fire years. Regional-fire years occurred every eight years on average (range 1–19, Fig. 2). The year of maximum fire synchrony was 1889, when 12 sites (57%) had two or more fire scars. Fires were recorded at sites in both

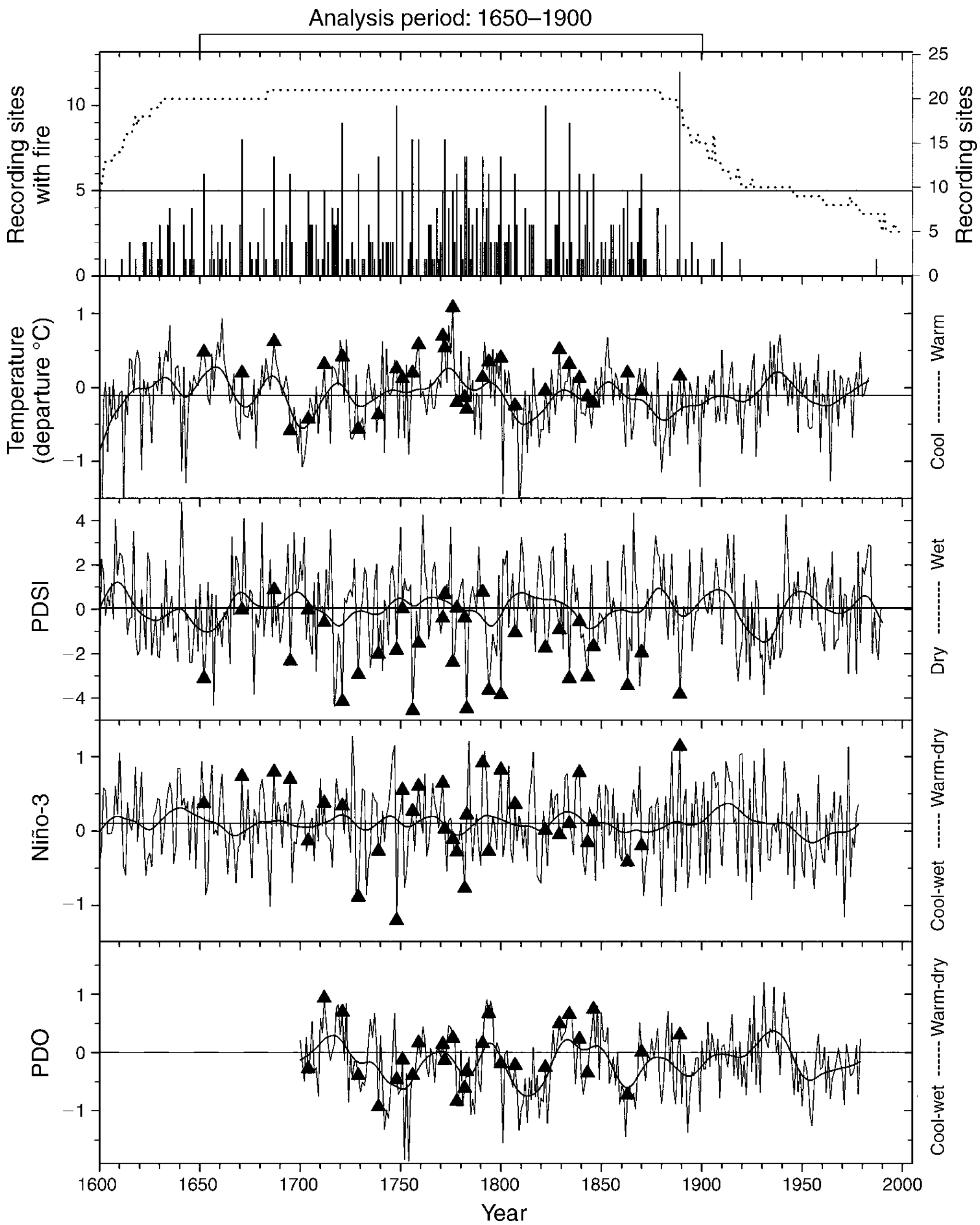


FIG. 2. Synchrony of fire in dry forests across the northern Rockies, USA (top panel; vertical bars, number of sites with fire), and number of dry forest fire-scar sampling sites with ≥2 trees recording (top panel; the dotted line indicates recording sites). We identified regional-fire years (solid triangles in bottom four panels) as those with ≥5 sites with fire (horizontal solid line in the top panel). Lines are tree-ring reconstructed climate, and heavy lines are climate smoothed with cubic splines that retain 50% of the variance at periods of 25 years. The Pacific Decadal Oscillation (PDO) reconstruction is from D'Arrigo et al. (2001). The temperature time series shows departure from −0.11°C, the mean temperature during the reference period from 1951 to 1970 (Briffa et al. 1992). Niño-3 is the ENSO reconstruction for the season with the greatest impact on spring climate in the study area. PDSI is the Palmer Drought Severity Index. Climate condition gradients are on the right-hand axes.

Montana and Idaho during all but three of the 32 regional-fire years. The fire-scar dates and associated metadata are available from the International Multiproxy Paleofire Database (*available online*).[5]

[5] ⟨www.ncdc.noaa.gov/paleo/impd/paleofire.html⟩

### *Climate drivers of fire*

Climate during the fire year synchronized historical fire activity in dry forests across the northern Rockies but climate in antecedent years did not (Fig. 3). Average temperature was significantly warm during regional-fire years during both periods tested (1700–1900 not shown)

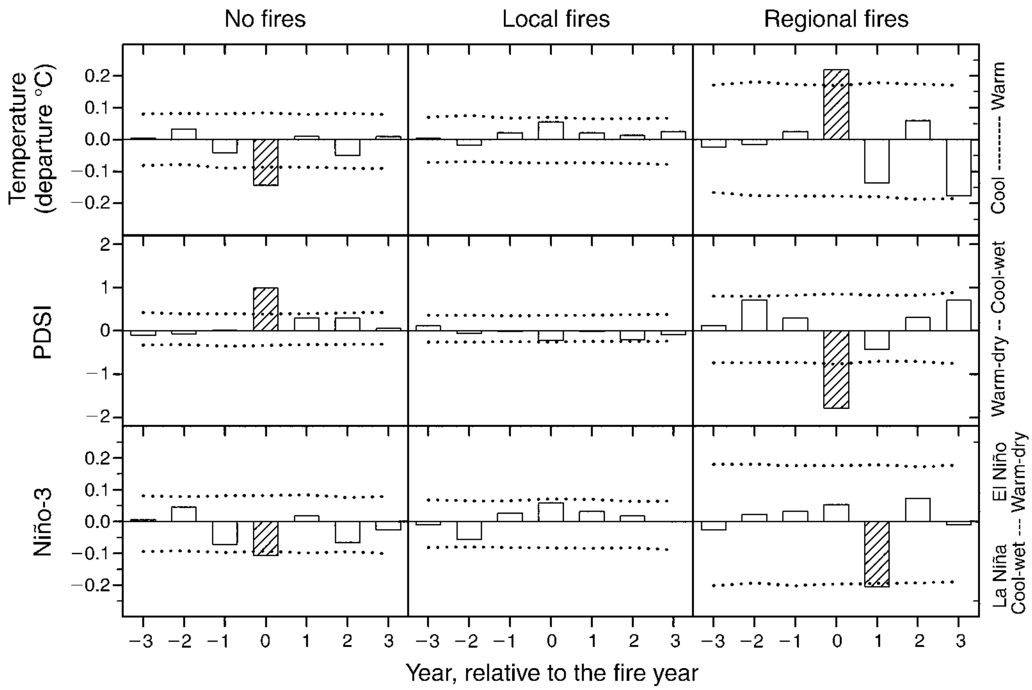


FIG. 3. Lagged relationship of tree-ring reconstructed climate and fire (1650–1900), showing average departure in climate during 99 no-fire years (no fires at any site), 120 local-fire years (fires at 1–4 sites), and 32 regional-fire years (fires at five or more sites). Departures exceeding the 99% confidence intervals (dotted lines) are hatched. For this analysis, the temperature and Niño-3 time series were prewhitened to remove autocorrelation. The temperature time series shows departure from −0.11°C, the mean temperature during the reference period from 1951 to 1970 (Briffa et al. 1992).

and significantly cool during no-fire years. The longest period with no fires at any site (1697–1702, Fig. 2) occurred during a cool period (average reconstructed departure of −0.7°C) that included three of the 12 coldest years during the analysis period. Consistent with the results for temperature, average PDSI was significantly warm-dry during regional-fire years and significantly cool-wet during no-fire years. Neither temperature nor PDSI departed significantly during local-fire years or during years preceding or following no-, local-, or regional-fire years.

Combined phases of climate synchronized fire activity in dry forests of the northern Rockies during regional- and no-fire years but not during local-fire years (Table 2, Fig. 4). For regional- and no-fire years, the distribution of years by combined phases of temperature and PDSI differed significantly from the distribution of all years by those phases ($P < 0.0007$, Table 2, Fig. 4a, c) and the greatest differences were significantly concentrated in years when the temperature and PDSI departures were of opposite sign ($P < 0.0001$). More regional-fire years than expected (181%) occurred when temperature was above average and PDSI was below, and the nine years with the greatest number of sites recording fire occurred under these conditions (years with eight or more sites with fire). Fewer regional-fire years than expected (11%) occurred during the opposite climate conditions (cool and cool-wet). For no-fire years, fewer than expected (52%) occurred when conditions were warm and warm-dry while more than expected (164%) occurred under the opposite climate conditions (cool and cool-wet). The number of observed vs. expected regional- or no-years did not differ significantly when the departures of temperature and PDSI were of the same sign ($P > 0.0851$). The distribution of local-fire years by combined phases of PDSI and temperature did not differ significantly from the distribution of all years ($P = 0.2089$, Table 2). Local-fire years did occur when it was warm and warm-dry (temperature above average and PDSI below) but they also occurred under all other combinations of temperature and PDSI departures (Fig. 4b).

The large-scale climate patterns we examined did not strongly synchronize fire activity in dry forests of the northern Rockies. Average Niño-3 was significantly low (La Niña years) during no-fire years but not during local-fire years or the years preceding or following no- or local-fire years (Fig. 3). Average Niño-3 was significantly low during the year following regional-fire years but we have no ecological explanation for a significant departure in climate following fire and suggest that this result is spurious. For all fire-year categories, the distribution of years by combined phases of ENSO and any of the PDO reconstructions (D'Arrigo et al. 2001, D'Arrigo and Wilson 2006, Shen et al. 2006) did not differ significantly from the distribution of all years

TABLE 2. Influence of combined phases of climate (Palmer Drought Severity Index [PDSI] and temperature; top) and large-scale climate patterns (Niño-3 as an index of the El Niño-Southern Oscillation [ENSO] and the Pacific Decadal Oscillation [PDO] [D'Arrigo et al. 2001] bottom) in synchronizing fire activity in the Northern Rockies.

| | Fire-year category | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Regional | | | Local | | | No fire | | |
| Climate | No. observed | Percentage of expected | P | No. observed | Percentage of expected | P | No. observed | Percentage of expected | P |
| Temperature/PDSI | | | 0.0007 | | | 0.2089 | | | 0.0001 |
| Below/above | 1 | 11 | | 25 | 71 | | 48 | 164 | |
| Above/above | 4 | 58 | | 27 | 105 | | 23 | 108 | |
| Above/below | 18 | 181 | | 43 | 115 | | 16 | 52 | |
| Below/below | 9 | 157 | | 25 | 116 | | 12 | 68 | |
| Niño-3/PDO | | | 0.8611 | | | 0.1899 | | | 0.1158 |
| Positive/negative | 7 | 79 | | 38 | 119 | | 20 | 86 | |
| Positive/positive | 9 | 113 | | 32 | 113 | | 16 | 77 | |
| Negative/positive | 4 | 125 | | 11 | 96 | | 7 | 84 | |
| Negative/negative | 8 | 101 | | 19 | 67 | | 30 | 145 | |

*Note:* For each of the six combinations of fire-year category and combined climate phases, significance of departures from expected distributions was tested using a chi-square goodness-of-fit test.

($P > 0.0709$; Table 2 and Figs. 2 and 4d–f show results using the PDO of D'Arrigo et al. [2001] only).

## Discussion

### *Fires occurred synchronously*

For several centuries (1650–1900), years of regionally synchronous fire occurred frequently across our dry-forest sites in the northern Rockies and were remarkably widespread during some of those years. In 1748, fires were recorded at 10 sites across what are today seven national forests plus one site on state land. No doubt fires were even more widespread during these years than we detected because the extent of 20th-century regional-fire years was quite large (117 167–1 167 458 ha; Gibson 2006) whereas we sampled a relatively small area (21 sites with a combined area of 667 ha).

Our fire-scar record contains little evidence of the 20th-century regional-fire years identified from a northern Rockies digital polygon fire atlas (Gibson 2006), likely because most (77%) of our sampled trees were not alive to record fires after 1900 and because we selected sites lacking recent fires as such fires often consume existing fire scars. We purposefully sampled stumps, logs, and snags to obtain a long record. While we did not exclude live fire-scarred trees, they were not common at our sites. Only 50 (0.5%) of our fire scars formed after 1900 and we found evidence of only two of the 11 20th-century regional-fire years identified from the digital fire atlas (1910 and 1919; Gibson 2006).

The frequency of past regionally synchronous fires in dry forests of the northern Rockies was similar to that in the southwestern United States (Swetnam and Baisan 2003), consistent with sub-continental-scale teleconnections in climate and the climate drivers of fire synchrony (Hidalgo 2004, Kitzberger et al. 2007). From 1700 to 1900, 28 years in the northern Rockies and 20 years in the southwest exceeded the 90th percentile in sites with fire (equivalent to ≥25% of 63 sites in the southwest and ≥24% of 21 sites in the northern Rockies). Maximum annual synchrony in the Northern Rockies was 57% of sites recording fire vs. 65% in the Southwest. Although the frequency of regional-fire years is similar in these two regions, only three regional-fire years are common to both: 1729, 1748, and 1870, all years of west-wide drought (Cook et al. 2004). This similarity in the frequency of regional-fire years and their degree of synchrony occurred despite the fact that fires were generally less frequent at sites to the north. Although sites were not selected systematically in either region, our sites in the Northern Rockies recorded 8–36 fire years each (average 20 years per site), whereas sites in the southwest recorded 7–97 fire years each (average 32 years per site) during the same time period (1700–1900) over similarly sized sample areas (2–148 ha in the north vs. approximately 10–100 ha in the south).

### *Climate strongly synchronized fire activity*

We used a temperature reconstruction for spring and summer combined (April–September, Briffa et al. 1992) but suggest that variation in both seasons influenced fire activity in our study area. First, both spring and summer temperature contributed to the half-year reconstruction we used. Second, no-fire years tended to occur during La Niña conditions, when spring snowpacks tend to be anomalously deep here, indicating that spring conditions affected fire synchrony in the region. Finally, during 20th-century regional-fire years here, average temperature was significantly warm during both spring and summer (Morgan et al. 2008) and such years have been associated with early spring snowmelt (Westerling et al. 2006). During some years in the 20th century (37%), April–May was relatively warm but the following August was cool, or vice versa, and some modern regional-fire years occurred when springs were warm but the summer fire season was relatively cool. Climate in

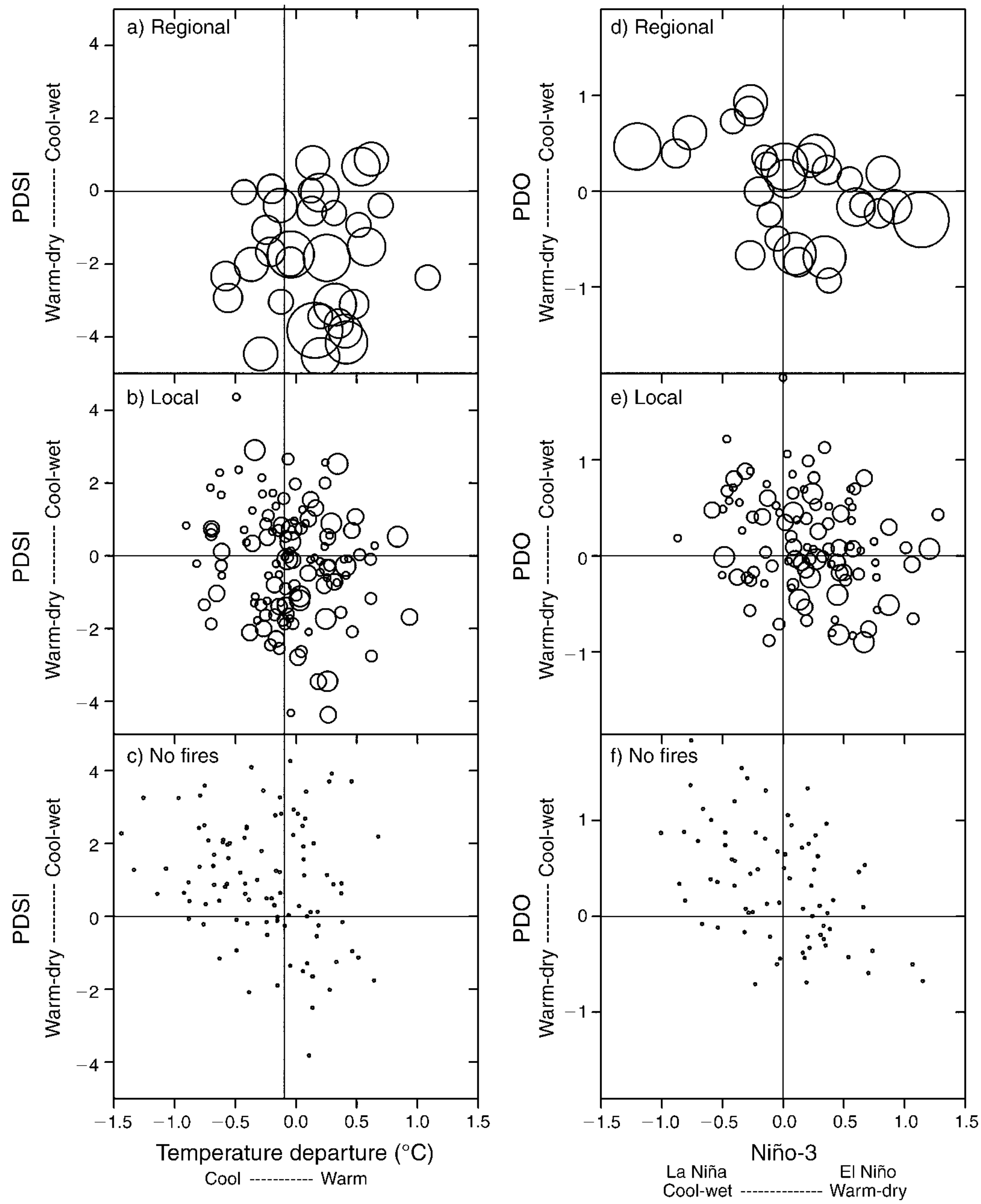


Fig. 4. Influence of combined phases of tree-ring reconstructed climate (a–c, 1650–1900) and indices of large-scale climate patterns (d–f, 1700–1900) during regional-fire, local-fire, and no-fire years. The temperature time series shows departure from −0.11°C, the mean temperature during the reference period from 1951 to 1970 (Briffa et al. 1992). The diameter of the circles is proportional to the number of sites with fire, from no sites for the smallest diameter to 12 sites for the largest. Axes have been inverted for both Niño-3 (D'Arrigo et al. 2005) and PDO (D'Arrigo et al. 2001) so that warm-dry conditions lie in the lower right quadrant in all panels.

both spring and summer likely synchronized fire activity in dry forests across this region by affecting both the length of the fire season and the moisture content of fuel during the fire season (Heyerdahl et al. 2002, Hessl et al. 2004, Westerling et al. 2006). When spring–summers were warm, the snowpack that annually covered our sites likely melted earlier during the years of warm springs, lengthening the fire season by giving fine and coarse fuels more time to dry, thus increasing the probability of an early ignition (Westerling et al. 2006). The relatively long fire seasons during these years would also allow more time for fires to spread. Not surprisingly, regional-fire years occurred when summer fire seasons were warm and dry, likely because fuel moistures were low across the region, allowing fires to ignite and spread at numerous locations.

Prior year's climate was not an important driver of regional-fire years in the northern Rockies, likely because fine fuels were generally sufficient during most years to carry fire in the dry forests we sampled. In contrast, increased moisture in prior years has been inferred as a strong driver of fire in areas where such moisture increases the amount and continuity of grassy and herbaceous fuels but prevents those fuels from drying in time to burn that same year (e.g., Swetnam and Betancourt 1998, Heyerdahl and Alvarado 2003, Westerling et al. 2003, Collins et al. 2006).

Climate also synchronized a lack of fire across the northern Rockies in the past. Nearly half the no-fire years (48 years) occurred during years of cool spring–summers and cool-wet summers, more than twice the number of no-fire years occurring under any other combination of temperature and PDSI (12–23 years; Table 2). Furthermore, the longest gap in fire in our record (seven years; 1696–1703) occurred during the longest period in which temperature was consistently below average and PDSI above average (Fig. 2). These conditions are similar to those during a period of low fire extent that occurred during the mid-20th century in this region (Morgan et al. 2008). Some no-fire years occurred under the warm-dry climate that led to regionally synchronous fire in other years, likely because fires were not ignited or the fires that were ignited did not spread. For fires reconstructed at 15 sites in the Pacific Northwest, only 18 years had no fires at any site compared to 99 such years during the same period at our sites (1651–1900), likely because the larger sampling area in the Pacific Northwest captured many more small fires (100 834 ha vs. 667 ha; Heyerdahl et al., *in press*).

Local-fire years occurred under a broad range of regionally averaged climate, highlighting the fact that the climate drivers of fire are most evident when fires are synchronized across regions. During half the years in our analysis period (48%), fires burned at only a few sites. Some of these years had regionally cool spring–summers and cool-wet summers, suggesting that regional indices of climate may not always capture variation at the local scale and that we likely did not include all the climate parameters that are important drivers of fire at the local scale.

### *Large-scale climate patterns weakly synchronized fire activity*

In the northern Rockies, the climate drivers of past fires that we inferred for dry forests are similar to those inferred across all forest types during the 20th century, despite the confounding effects of land use and fire suppression. As in the past, 20th-century regional-fire years occurred during warm springs followed by warm-dry summers but prior year's climate was not important (Morgan et al. 2008). However, the role of large-scale climate patterns in synchronizing fire activity in the past differed from that in the 20th century. Modern regional-fire years occurred primarily during warm phases of PDO (1925–1946 and 1977–present) but rarely during cool phases (1900–1924 and 1947–1976; Mantua et al. 1997). We were surprised that past regional-fire years did not also vary with PDO given that 20th-century regional-fire years varied with this large-scale climate pattern both interannually and decadally and that spring temperature, the climate parameter most affected by PDO in this region, was important for our past regional-fire years. We suggest several possible explanations. First, while PDO has been operating over at least the past several centuries, its strength has fluctuated, with a decrease during the period 1650–1850 (D'Arrigo et al. 2001, Gedalof et al. 2002, Hidalgo 2004, Shen et al. 2006). This period includes most of our tree-ring reconstruction of fire and so could explain why our past regional-fire years did not vary with PDO. Second, the influence of large-scale climate patterns on past and modern regional-fire years may differ because the fire records are derived from different forest types. Our past regional-fire years were reconstructed in dry forests only whereas the modern regional-fire years were identified across all forest types. However, when fires were widespread in dry forest during modern regional-fire years, they were widespread in other forest types as well. During the 11 20th-century regional-fire years, an average of 34% of total annual fire extent occurred in dry forest (range 23–50%) with most of the remaining extent in cold and mesic forest (31 and 11%, respectively; Morgan et al. 2008). These eleven years were also the years with the greatest fire extent in the dry forest record alone. Although this modern synchrony in fire across vegetation types suggests that the climate drivers of fire do not vary among these types, fire regimes changed abruptly in dry forests across much of the northern interior West around 1900 (e.g., Heyerdahl et al. 2002, Hessl et al. 2004). Fires in dry forests during the 20th century are less frequent and so may be more severe than they were in prior centuries so the climate drivers may vary among vegetation types but we cannot detect it with 20th-century data alone. Third, PDO may have been an important driver of past regional-fire years in this region but the tree-ring reconstructions of climate or fire that we used were not sufficient to detect such a relationship. However, one of the reconstructions of PDO that we used is significantly related to fire synchrony in subalpine forests elsewhere in the interior West (Schoennagel et al. 2005, Sibold and Veblen 2006, Kitzberger et al. 2007).

ENSO was not a significant driver of past regional-fire years but did affect no-fire years in the Northern Rockies, consistent with its influence on modern climate and fire in the region (Harshberger 2002, Morgan et al. 2008). The tendency for no-fire years to occur during La Niña years is likely due to the anomalously deep snowpacks that tend to occur in this region during such years (Redmond and Koch 1991, Gershunov et al. 1999, Harshberger et al. 2002, Mantua 2002, McCabe and Dettinger 2002). Such snowpacks are likely to take longer to melt and hence can result in shorter fire seasons and a lower probability of widespread fires. The lack of occurrence of past or the 20th century regionally synchronous fires during El Niño years with their anomalously shallow snowpacks is consistent with the fact that La Niña conditions have a greater impact on climate in this region than do El Niño conditions (Redmond and Koch 1991, Piechota and Dracup 1996, Clark et al. 2001, Harshburger et al. 2002). Spring–summer temperature and moisture are the primary drivers of fire in our study area and while ENSO and PDO are responsible for some variation in spring climate in the northern Rockies (Harshberger et al. 2002, McCabe and Dettinger 2002), the climate conditions that are conducive to regionally synchronous fires can occur here regardless of the phases of ENSO and PDO.

### *Implications for future regional synchrony of fire activity*

Anticipating the potential for major wildland fire years within and among regions of the western United States is critical both for planning wildland fire use and for allocating fire suppression resources. Climate-driven regional-fire years occurred frequently in the past and have continued to occur in the 20th century despite intensive land use and fire suppression (Morgan et al. 2008). In the future, regional-fire years may become more frequent if model predictions of earlier melting of snowpack under greenhouse gas and aerosol induced climatic change are realized (McCabe and Wolock 1999, Kittel et al. 2002, Mote 2006). Some models indicate that the snow-free season in the Northern Rockies may increase in length by one to two months by 2030, largely due to increases in spring and early summer temperatures and possibly due to less winter precipitation falling as snow (McCabe and Wolock 1999, Kittel et al. 2002). If spring temperatures continue to warm, snowpacks will likely melt at relatively high elevations in forest types where fire regimes were historically more severe. If severe fires in these forests are as widespread during regional-fire years as surface fires were in dry forests in the past, they will be difficult to manage. Although stand-replacing fires are not necessarily anomalous in high elevation forests of this region, an increase in the frequency of such fires due to greenhouse-gas induced warming may still lead to changes in forest structure and composition that are outside their historical range of variation. These more frequent severe fires could have broad ecological implications if they reset succession over large areas (Turner et al. 1998), contribute to a positive feedback whereby extensive fires become more likely (Veblen et al. 1999), affect habitat for species of conservation concern, and alter regional forest carbon, water, and nutrient cycles (Mote 2006, Running 2006).

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## Literature Cited

Arno, S. F., and K. M. Sneck. 1977. A method for determining fire history in coniferous forests of the mountain west. General Technical Report GTR-INT-42. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Baisan, C. H., and T. W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Canadian Journal of Forest Research 20: 1559–1569.

Balling, R. C., Jr., G. A. Meyer, and S. G. Wells. 1992. Climate change in Yellowstone National Park: is the drought-related risk of wildfires increasing? Climatic Change 22:35–45.

Briffa, K. R., P. D. Jones, and F. H. Schweingruber. 1992. Tree-ring density reconstructions of summer temperature patterns across western North America since 1600. Journal of Climate 5:735–754.

Clark, M. P., M. C. Serreze, and G. J. McCabe. 2001. Historical effects of El Niño and La Niña events on the seasonal evolution of the montane snowpack in the Columbia and Colorado River Basins. Water Resources Research 37: 741–757.

Collins, B. M., P. N. Omi, and P. L. Chapman. 2006. Regional relationships between climate and wildfire-burned area in the Interior West, USA. Canadian Journal of Forest Research 36:699–709.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle. 2004. Long-term aridity changes in the western United States. Science 306:1015–1018.

D'Arrigo, R. D., E. R. Cook, R. J. Wilson, R. Allan, and M. E. Mann. 2005. On the variability of ENSO over the past six centuries. Geophysical Research Letters 32:L03711.

D'Arrigo, R., R. Villalba, and G. Wiles. 2001. Tree-ring estimates of Pacific decadal climate variability. Climate Dynamics 18:219–224.

D'Arrigo, R. D., and R. Wilson. 2006. On the Asian expression of the PDO. International Journal of Climatology 26: 1607–1617.

Dieterich, J. H., and T. W. Swetnam. 1984. Dendrochronology of a fire-scarred ponderosa pine. Forest Science 30:238–247.

Fritts, H. C. 1976. Tree rings and climate. Academic Press, New York, New York, USA.

Gedalof, Z., N. J. Mantua, and D. L. Peterson. 2002. A multi-century perspective of variability in the Pacific Decadal Oscillation: new insights from tree rings and coral. Geophysical Research Letters 29:2204.

Gedalof, Z., D. L. Peterson, and N. J. Mantua. 2005. Atmospheric, climatic, and ecological controls on extreme wildfire years in the northwestern United States. Ecological Applications 15:154–174.

Gershunov, A., and T. P. Barnett. 1998. Interdecadal modulation of ENSO teleconnections. Bulletin of the American Meteorological Society 79:2715–2725.

Gershunov, A., T. P. Barnett, and D. R. Cayan. 1999. North Pacific interdecadal oscillation seen as factor in ENSO-related North American climate anomalies. EOS 80:25–30.

Gibson, C. E. 2006. A northern Rocky Mountain polygon fire history: accuracy, limitations, strengths, applications, and recommended protocol of digital fire perimeter data. Thesis. University of Idaho, Moscow, Idaho, USA.

Grissino-Mayer, H. D. 2001*a*. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Research 57:205–221.

Grissino-Mayer, H. D. 2001*b*. FHX2: software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree-Ring Research 57:115–124.

Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier. 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. Journal of Climate 18:4545–4561.

Harshburger, B., H. Ye, and J. Dzialoski. 2002. Observational evidence of the influence of Pacific SSTs on winter precipitation and spring stream discharge in Idaho. Journal of Hydrology 264:157–169.

Hessl, A. E., D. McKenzie, and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications 14:425–442.

Heyerdahl, E. K., and E. Alvarado. 2003. Influence of climate and land use on historical surface fires in pine–oak forests, Sierra Madre Occidental, Mexico. Pages 196–217 *in* T. T. Veblen, W. L. Baker, G. Montenegro, and T. W. Swetnam, editors. Fire and climatic change in temperate ecosystems of the western Americas. Springer-Verlag, New York, New York, USA.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2002. Annual and decadal climate forcing of historical fire regimes in the interior Pacific Northwest, USA. Holocene 12:597–604.

Heyerdahl, E. K., D. McKenzie, L. D. Daniels, A. E. Hessl, J. S. Littell, and N. J. Mantua. *In press*. Climate drivers of regionally synchronous fires in the inland Northwest (1651–1900). International Journal of Wildland Fire.

Hidalgo, H. G. 2004. Climate precursors of multidecadal drought variability in the western United States. Water Resources Research 40:W12504.

Kipfmueller, K. F. 2003. Fire-climate vegetation interactions in subalpine forests of the Selway-Bitterroot Wilderness Area, Idaho and Montana, USA. Dissertation. The University of Arizona, Tucson, Arizona, USA.

Kittel, T. G. F., P. E. Thornton, J. A. Royle, and T. N. Chase. 2002. Climates of the Rocky Mountains: historical and future patterns. Pages 59–82 *in* J. Baron, editor. Rocky Mountain futures: an ecological perspective. Island Press, Covelo, California, USA.

Kitzberger, T., P. M. Brown, E. K. Heyerdahl, T. W. Swetnam, and T. T. Veblen. 2007. Contingent Pacific–Atlantic Ocean influence on multi-century wildfire synchrony over western North America. Proceedings of the National Academy of Science (USA) 104:543–548.

Mantua, N. J. 2002. La Niña impacts on the Pacific Northwest. Pages 102–114 *in* M. Glantz, editor. La Niña and its impacts: facts and speculation. United Nations University Press, Tokyo, Japan.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069–1079.

McCabe, G. J., and M. D. Dettinger. 2002. Primary modes and predictability of year-to-year snowpack variations in the western United States from teleconnections with Pacific Ocean climate. Journal of Hydrometeorology 3:13–25.

McCabe, G. J., and D. M. Wolock. 1999. General-circulation-model simulations of future snowpack in the western United States. Journal of the American Water Resources Association 35:1473–1484.

Mooney, C. Z., and R. D. Duval. 1993. Bootstrapping: a nonparametric approach to statistical inference. Sage University Paper Series on Quantitative Applications in the Social Sciences 07-095. Sage University, Newbury Park, California, USA.

Morgan, P., E. K. Heyerdahl, and C. E. Gibson. 2008. Multi-season climate synchronized forest fires throughout the 20th century, Northern Rockies, USA. Ecology 89:717–728.

Mote, P. W. 2006. Climate-driven variability and trends in mountain snowpack in western North America. Journal of Climate 19:6209–6220.

Piechota, T. C., and J. A. Dracup. 1996. Drought and regional hydrologic variations in the United States: associations with the El Niño/Southern Oscillation. Water Resources Research 32:1359–1373.

Pyne, S. J., P. L. Andrews, and R. D. Laven. 1996. Introduction to wildland fire. Second edition. John Wiley and Sons, New York, New York, USA.

Redmond, K. T., and R. W. Koch. 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. Water Resources Journal 27:2381–2399.

Running, S. W. 2006. Is global warming causing more, larger wildfires? Science 313:927–928.

SAS Institute. 2003. SAS release 8.02. SAS Institute, Cary, North Carolina, USA.

Schmidt, K. M., J. P. Menakis, C. C. Hardy, W. J. Hann, and D. L. Bunnell. 2002. Development of coarse-scale spatial data for wildland fire and fuel management. General Technical Report RMRS-GTR-87. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Schoennagel, T., T. T. Veblen, W. H. Romme, J. S. Sibold, and E. R. Cook. 2005. ENSO and PDO variability affect drought-induced fire occurrence in Rocky Mountain subalpine forests. Ecological Applications 15:2000–2014.

Serreze, M. C., M. P. Clark, R. L. Armstrong, D. A. McGinnis, and R. S. Pulwarty. 1999. Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data. Water Resources Research 35:2145–2160.

Shen, C., W. Wang, W. Gong, and Z. Hao. 2006. A Pacific Decadal Oscillation record since 1470 AD reconstructed from proxy data of summer rainfall over eastern China. Geophysical Research Letters 33:L03702.

Sibold, J. S., and T. T. Veblen. 2006. Relationships of subalpine forest fires in the Colorado Front Range with interannual and multidecadal-scale climatic variation. Journal of Biogeography 33:833–842.

Swetnam, T. W., and C. H. Baisan. 2003. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and Southwestern United States. Pages 158–195 *in* T. T. Veblen, W. L. Baker, G. Montenegro, and T. W. Swetnam, editors. Fire and climate in temperate ecosystems of the western Americas. Springer-Verlag, New York, New York, USA.

Swetnam, T. W., and J. L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate 11:3128–3147.

Turner, M. G., W. L. Baker, C. J. Peterson, and R. K. Peet. 1998. Factors influencing succession: lessons from large, infrequent natural disturbances. Ecosystems 1:511–523.

Veblen, T. T., T. Kitzberger, R. Villalba, and J. Donnegan. 1999. Fire history in northern Patagonia: the roles of humans and climatic variation. Ecological Monographs 69:47–67.

Westerling, A. L., A. Gershunov, T. J. Brown, D. R. Cayan, and M. D. Dettinger. 2003. Climate and wildfire in the western United States. Bulletin of the American Meteorological Society 84:595–604.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313:940–943.

Westerling, A. L., and T. W. Swetnam. 2003. Interannual to decadal drought and wildfire in the western United States. EOS 84:545–560.

Whitlock, C., S. L. Shafer, and J. Marlon. 2003. The role of climate and vegetation change in shaping past and future fire regimes in the Northwestern US and the implications for ecosystem management. Forest Ecology and Management 178:5–21.

Zar, J. H. 1984. Biostatistical analysis. Second edition. Prentice Hall, Englewood Cliffs, New Jersey, USA.