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Climate effects on historical fires (1630–1900) in Utah

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Abstract. We inferred climate effects on fire occurrence from 1630 to 1900 for a new set of crossdated fire-scar chronologies from 18 forested sites in Utah and one site in eastern Nevada. Years with regionally synchronous fires (31 years with fire at $\geq$20% of sites) occurred during drier than average summers and years with no fires at any site (100 years) were wetter than average. Antecedent wet summers were associated with regional-fire years in mixed-conifer and ponderosa pine forest types, possibly by affecting fine fuel amount and continuity. NINO3 (an index of the El Niño–Southern Oscillation, ENSO) was significantly low during regional-fire years (La Niñas) and significantly high during non-fire years (El Niños). NINO3 also was high during years before regional-fire years. Although regional fire years occurred nearly twice as often as expected when NINO3 and the Pacific Decadal Oscillation were both in their cool (negative) phases, this pattern was not statistically significant. Palmer Drought Severity Index was important for fire occurrence in ponderosa pine and mixed-conifer forests across the study area but ENSO forcing was seen only in south-eastern sites. Results support findings from previous fire and climate studies, including a possible geographic pivot point in Pacific basin teleconnections at ~40°N.

Additional keywords: crossdating, El Niño–Southern Oscillation, fire scars, Palmer Drought Severity Index, temperature.

Introduction

Regionally synchronous fires across interior western North America are strongly affected by climate, as shown by both multi-century fire chronologies developed from fire scars recorded in tree-ring series (e.g. Swetnam and Betancourt 1990; Swetnam 1993; Heyerdahl *et al.* 2002; Heyerdahl and Alvarado 2003; Hessl *et al.* 2004; Brown and Wu 2005; Schoennagel *et al.* 2005; Brown 2006; Sibold and Veblen 2006; Kitzberger *et al.* 2007) and in written records of 20th century fires (Collins *et al.* 2006; Westerling *et al.* 2006). Fires typically occurred when seasonal droughts resulted in dry fuel conditions, and widespread droughts resulted in regional-fire years when widely separated sites burned during the same year. Regional droughts were, in turn, affected by large-scale climate patterns. Climate forcing associated with fire occurrence has been strongly linked to atmospheric and oceanic patterns largely from the Pacific region, including the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Recent research also has highlighted probable effects of the Atlantic Multidecadal Oscillation (AMO, an index of northern Atlantic Basin sea surface temperature (SST) anomalies) on both droughts (McCabe *et al.* 2004; Sutton and Hodson 2005) and regional fires (Brown 2006; Sibold and Veblen 2006; Kitzberger *et al.* 2007) across the western US.

Here we report on a new set of 19 crossdated fire-scar chronologies from sites in Utah and eastern Nevada. This is the first systematically collected network of crossdated fire-scar chronologies yet developed from this region. Before the present study, this region lacked absolutely dated fire-scar chronologies important for examining continental-scale fire–climate relationships (Kitzberger *et al.* 2007). Sites span ~4.5° north and south of 40°N latitude, which has been identified as a possible geographic pivot point in Pacific basin teleconnections that affect a dipole pattern in droughts and pluvials between the South-west (SW) and Pacific North-west (PNW; Mock 1996; Dettinger *et al.* 1998; McCabe and Dettinger 2002; Brown and Comrie 2004; Schoennagel *et al.* 2005). In general, the SW is relatively wet when the PNW is relatively dry, and vice versa (Hidalgo 2004). Droughts tend to be enhanced in the SW when La Niñas occur during cool PDO phases, and wet conditions are enhanced under the opposite pattern (Gershunov *et al.* 1999; McCabe and Dettinger 1999). The effects of ENSO and PDO are opposite in the PNW, with relatively warm springs and anomalously shallow snow packs during positive phases of these two large-scale climate patterns and relatively cool springs and deep snow packs during their negative phases. The climate effects of these contingent states of ENSO and PDO strongly affected historical fire activity in parts of the interior west (Westerling and Swetnam 2003; Schoennagel *et al.* 2005), and an improved understanding of how fire varied across the transition area in Utah between the SW and PNW is needed.

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Our objectives were to: (1) describe the development of this new set of fire chronologies and (2) infer climate effects on historical fire occurrence across the region and how they varied by site and forest type. We compared fire chronologies from 1630 to 1900 to existing tree-ring reconstructions of climate (temperature and the Palmer Drought Severity Index, PDSI) and large-scale climate patterns (ENSO and PDO) that affected drought conditions in this region.

Study area

Sites selected for the present study extend from the Colorado Plateau of southern Utah, west to the Wah Wah Mountains and Snake Range in the eastern Great Basin, and north to the Uinta and Bear River Mountains in northern Utah (Fig. 1; Table 1). The region is a complex of valleys, mesas, canyons, plateaus, and mountains that range in elevations from ~900 to >3600 m. Sites were chosen to be representative of forested landscapes of the region. Pinyon (*Pinus edulis* and *P. monophylla*) and juniper (*Juniperus scopulorum* and *J. osteosperma*) savannas and woodlands occur at the lowest forest border between desert shrublands or grasslands and montane forests. Gambel oak (*Quercus gambelii*) and mountain mahogany (*Cercocarpus montanus* and *C. ledifolius*) often form pure stands in lower elevations or can be minor components in forests up to mid-elevations (~1800 m). Ponderosa pine (*Pinus ponderosa*) forests occur in montane zones in pure and mixed stands. Douglas-fir (*Pseudotsuga menziesii*) often occurs in the ponderosa pine zone on north aspects and in relatively mesic sites. Mixed-conifer forests occur at intermediate elevations and include ponderosa pine, Douglas-fir, pinyon, juniper, fir (*Abies lasiocarpa* or *A. concolor*), lodgepole pine (*Pinus contorta*), and blue spruce (*Picea pungens*). Mixed-conifer forests also often occur in association with aspen (*Populus tremuloides*). Aspen forms large (>100 ha) pure stands throughout the upper montane and lower subalpine zones across the study area except in the Great Basin where it is more restricted. Lodgepole pine typically forms pure stands at mid-elevations (1900 to 2800 m) in northern Utah. Subalpine forests dominated by Engelmann spruce (*Picea engelmannii*) and fir occur at upper elevations (2370 to 3500 m). At the highest forested elevations (generally above 3000 m), pure Engelmann spruce forests occur in mesic sites while high-elevation pines, including bristlecone pine (*Pinus longaeva*) and limber pine (*P. flexilis*), are typically found in dry or rocky sites (Mauk and Henderson 1984; Youngblood and Mauk 1985).

The region has a long history of Native American occupation going back at least 12 000 years. Native American ignitions probably augmented lightning ignitions in some areas and during certain periods. However, it is difficult to detect the effect of natural *v.* human factors on pre-Euro-American settlement fire regimes (Allen 2002; Griffin 2002). Intensive Euro-American land-use began after Mormon settlement in the Great Salt Lake

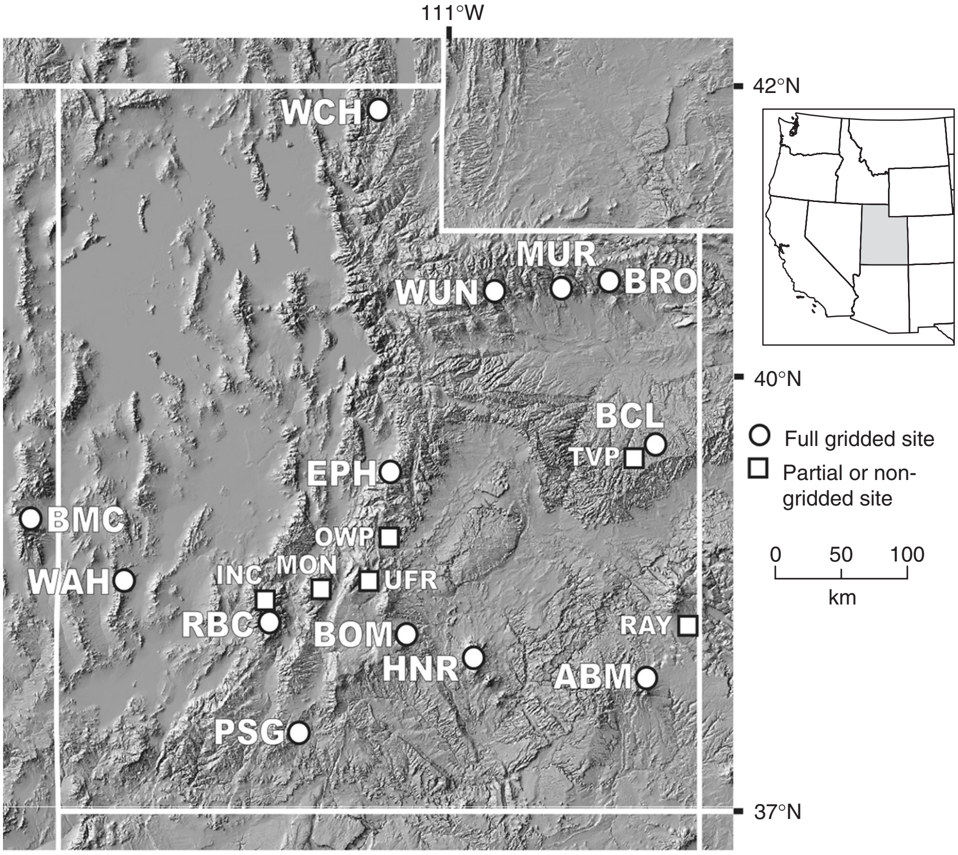

Fig. 1. Locations of study sites in Utah and eastern Nevada. Site codes are given in Table 1.

Table 1. Sites sampled in Utah and eastern Nevada

Some sites were not sampled with plots (TVP, OWP, and MON) and plots in some vegetation types at some sites did not have fire-scarred trees (both indicated by ‘x’)

Site (code)	Area (ha)	No. fire-scarred trees	Elevation (m)		Biophysical settings												
			Min.	Max.	Shrubland	Sagebrush	Oak brush	Pinyon–juniper	Mountain mahogany	Ponderosa pine	Mixed-conifer	Aspen–mixed conifer	Aspen	Lodgepole	Limber, bristlecone	Spruce–fir	Total plots
Wasatch Range (WCH)	652	16	2255	2588							1		x	4		x	5
West Uinta Mtns (WUN)	712	65	2243	3184						4	5			7		x	16
Uinta Mtns (MUR)	583	84	2308	3250						6		x	x	7		4	17
Uinta Mtns (BRO)	536	73	2372	2948	x	x		1		1	6	1	1	4		4	18
Tavaputs Plateau (BCL)	527	20	2122	2244				3		1	4						8
Tavaputs Plateau (TVP)	22	22	2250	2285				x									0
Ephraim Canyon (EPH)	572	30	2318	2887			x				x	4	x			1	5
Snake Range (BMC)	457	110	2366	3232	x	x		2	1	1	6				4	1	15
Old Woman Plateau (OWP)	20	16	1980	1995						x							0
Wah Wah Mtns (WAH)	431	137	2195	2686				3			16				1		20
Upper Fremont River (UFR)	396	16	2800	3039							4	x	x			1	5
Monroe Mountain (MON)	–	11	–	–						x	x						0
Tushar Mtns (INC)	130	35	2365	2549						3	2						5
Tushar Mtns (RBC)	910	167	2359	3079						6	8	1	3			8	26
Ray Mesa (RAY)	133	20	2249	2279				3		2							5
Boulder Mountain (BOM)	496	125	2405	3377				4		7	5	3	1			6	26
Henry Mtns (HNR)	704	18	2407	3138		x		x		1	1		x			x	2
Abajo Mtns (ABM)	636	68	2558	3232			1			10	1	x	1			2	15
Paunsaugunt Plateau (PSG)	723	52	2310	2737	2			x		5	6		x			1	14
Total	8640	1085			2	0	1	16	1	47	65	9	6	22	5	28	202

Valley in 1847 (Young *et al.* 1979). Settlement spread throughout the region after this date, with the result that timing of Euro-American impacts varied among our sites during the late 1800s. However, by at least 1890, intensive livestock grazing in most areas severely depleted the forage on many of the mountains and high plateaus of Utah and eastern Nevada. Many of the lower elevation forests also experienced at least limited timber harvest, with local areas near settlements or mines heavily impacted by the early 20th century.

Methods

Fire chronologies

Fire-scar data were collected as part of a broader study of spatial variation in fire regimes and forest histories in Utah. For the broader study, we collected both fire-scar and tree recruitment data to reconstruct all components of past fire regimes, including fire frequency, severity, and spatial patterning, across forest types. Here we report on fire dates reconstructed only from fire-scar records, and not from even-aged forest structure that post-dated stand-opening fires.

We systematically sampled most sites (16 of 19) with a grid of plots with 500-m spacing that spanned the range of elevation and forest type at each site (Table 1). Grids were oriented on cardinal directions and located to maximise sampling of forest types found in each site. We sampled full grids at 13 of the sites (~30 plots, range 24 to 44) and partial grids at three sites (5 to 15 plots). Plot centres were determined from Universal Transverse Mercator (UTM) coordinates and located in the field with handheld global positioning system (GPS) receivers. At each plot, we searched for fire-scarred trees (living and dead) within a radius of ~80 m (corresponding to an area of ~2 ha), and used a chainsaw to remove one to several scarred sections per tree. We also opportunistically sampled additional fire-scarred trees encountered between plots. There were no fire-scarred trees within ~80 m of the centre of half our plots (50%), mainly in high-elevation subalpine forests or low-elevation woodlands. In addition to fire-scar data from gridded sites, we also include in the present study fire-scar data from three additional sites (MON, OWP, and TVP) from which fire-scarred trees were collected using targeted sampling methods (Van Horne and Fulé 2006).

All fire-scarred samples were sanded until the cell structure was visible with 7 to 30× magnification under a binocular microscope. We assigned calendar years to tree rings using a combination of visual crossdating of ring widths and other ring characteristics and cross-correlation of measured ring-width series. We excluded samples from our analyses if there was any question about the absolute crossdating of their tree-ring series. We determined the calendar date of each fire scar and assigned it an intra-ring position: dormant season, early earlywood, middle earlywood, late earlywood, latewood, or unknown (owing to narrow or indistinct rings or erosion of the scar surface; Dieterich and Swetnam 1984). From ring characteristics alone, we could not determine if dormant-season scars were created by fires that burned late in the fall of the preceding year or early in the spring of the following year. In many cases, we were able to assign dormant-season scars to either the preceding or following year based on the presence of within-ring scars on other trees in the same site. However, in other cases we found only dormant-season scars for a given fire date. In these cases, for sites to the north (WCH, WUN, MUR, BRO, BCL and TVP), we assigned dormant-season scars to the preceding calendar year as most modern fires burn in the late summer or early fall in that part of the study area (Schmidt *et al.* 2002). We assigned dormant-season scars in the southern part of the study area to the following calendar year as most modern fires in southern Utah burn in early summer (e.g. Schmidt *et al.* 2002; Kitchen and McArthur 2003).

We assigned each plot to a historical potential vegetation type using biophysical settings (BpS) vegetation models developed for the LANDFIRE project (Rollins and Frame 2006). The LANDFIRE project is an effort to map vegetation, fuels, and fire regime data across the United States. LANDFIRE BpS models were formerly referred to as Potential Natural Vegetation Groups (PNVG; Küchler 1964) and are derived from NatureServe (a non-profit conservation organisation that provides scientific information and tools) Ecological System Classification models (Comer *et al.* 2003). LANDFIRE BpS classifications integrate both environmental site potentials (elevation, soil types, climate) and disturbance regimes to model historical vegetation distributions. We assigned a BpS classification to each of the 202 plots containing fire scars that we sampled at our gridded sites based on the density and composition of trees that were alive in those plots in 1860. Sites MON, OWP, and TVP were assigned to ponderosa pine BpS based on dominate overstorey tree composition in each site.

Climate effects on fire occurrence

Dates of fire scars found on ≥2 trees at a site were compiled into site fire chronologies using program FHX2, an integrated package for graphical and statistical analyses of fire history data (Grissino-Mayer 2001). Scar dates recorded on only one tree were excluded because there might be false positives, scars not caused by fire but assumed to be fire scars (Falk 2004; Brown and Wu 2005; Brown 2006). We assumed that scar dates recorded on ≥2 trees at a site minimised the likelihood of false positives because it is less likely that other mechanisms (e.g. lightning or falling trees) scarred more than one tree in a site during the same year. From the site fire chronologies, we created three types of composite chronologies. First, we created regional-, local- and no-fire chronologies that included all sites and forest types. We identified regional-fire years as those recorded in ≥20% of the 19 site chronologies from 1630 to 1900, equivalent to the 90th percentile of sites with fire over this analysis period. We identified local-fire years as those recorded on at least one but <20% of the site chronologies and no-fire years as those when no fires were recorded in any of the site chronologies. Second, we created site fire chronologies that included fire dates on ≥2 trees in mixed-conifer and ponderosa pine plots only. Third, we created fire chronologies for each of three most common forest types: spruce–fir, mixed-conifer (including both mixed-conifer and ponderosa pine), and pinyon–juniper (Table 1). We lacked fire scars from all three forest types at the northern sites and forest-type chronologies only include the southern sites (116 plots or 84% of all plots in southern sites). We identified fire-years in mixed-conifer plots as those with ≥20% of sites recording fire (18 fire years) but as those with ≥2 sites with fire in spruce–fir

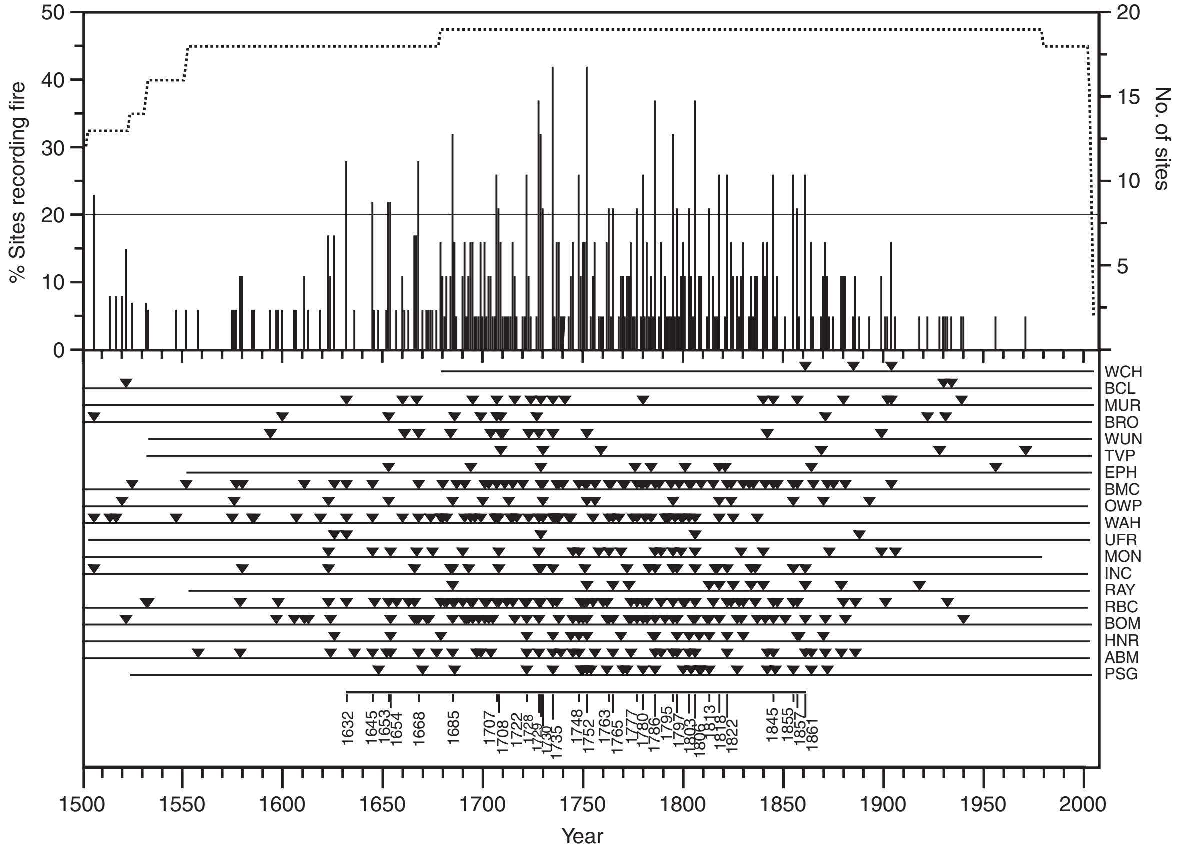

Fig. 2. Summary fire chronologies for the 19 sites. Top: dotted line is the number of sites per year with the percentage of sites recording fires for individual years marked by histograms. Bottom: time spans of site chronologies are represented by horizontal lines. Triangles represent fire dates recorded on ≥2 trees at each site. Dates of regional-fire years (recorded on ≥20% of the sites) are indicated at the bottom of panel.

(5 years) and pinyon–juniper plots (3 years) because fire was less frequent in these forest types and no years had fire at ≥20% of sites.

We graphically and statistically compared our regional, individual-site, and forest-type fire chronologies to independently derived tree-ring reconstructions of climate and large-scale climate patterns to assess potential climate forcing. We used four reconstructions: (1) gridded summer PDSI (June through August) averaged over four grid points in the study area (grid points 86, 87, 102, and 103; Cook *et al.* 2004); (2) warm-season temperature (April through September) at one grid point in the study area expressed as departure from mean temperature from 1951 to 1970 (grid point 17; Briffa *et al.* 1992); (3) winter NINO3 (December through February) SST index (D'Arrigo *et al.* 2005); and (4) annual PDO (D'Arrigo *et al.* 2001). The NINO3 index is average SST from mid-tropical Pacific recording stations, the region with the largest SST variability on ENSO (3 to 4-year) time scales. We used the D'Arrigo *et al.* (2001) PDO index reconstruction even though it is shorter than our analysis period because it captures more of the variance in the modern PDO index (44%) than other published PDO reconstructions.

We used superposed epoch analysis (SEA) to compare average annual climate conditions during years in our regional, individual-site, and forest-type fire chronologies, and during preceding and following years (4 years before, 1 year after; Swetnam 1993). We computed absolute departures in three climate parameters: PDSI, temperature, and NINO3. The time series of these parameters were not white noise ($P < 0.0001$, SAS Proc Arima autocorrelation test for white noise using six lags, SAS Institute 2003) and we prewhitened them before use in SEA. Prewhitening was done 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 for the temperature series and AR(2) models for NINO3 and PDSI). We identified significant climate departures as those exceeding 95% confidence intervals determined by bootstrapping (1000 trials, Grissino-Mayer 2001).

We assessed the influence of contingent phases of ENSO and PDO using a χ^2 goodness-of-fit test in which the observed values were the number of regional-fire years that occurred under each of four phase combinations (positive and negative NINO3 and PDO) and the expected values were derived from the proportions of years in each of the four phase combinations regardless of fire activity ($\alpha = 0.05$). We also graphically compared regional-fire years with reconstructed AMO (Gray *et al.* 2004) to assess

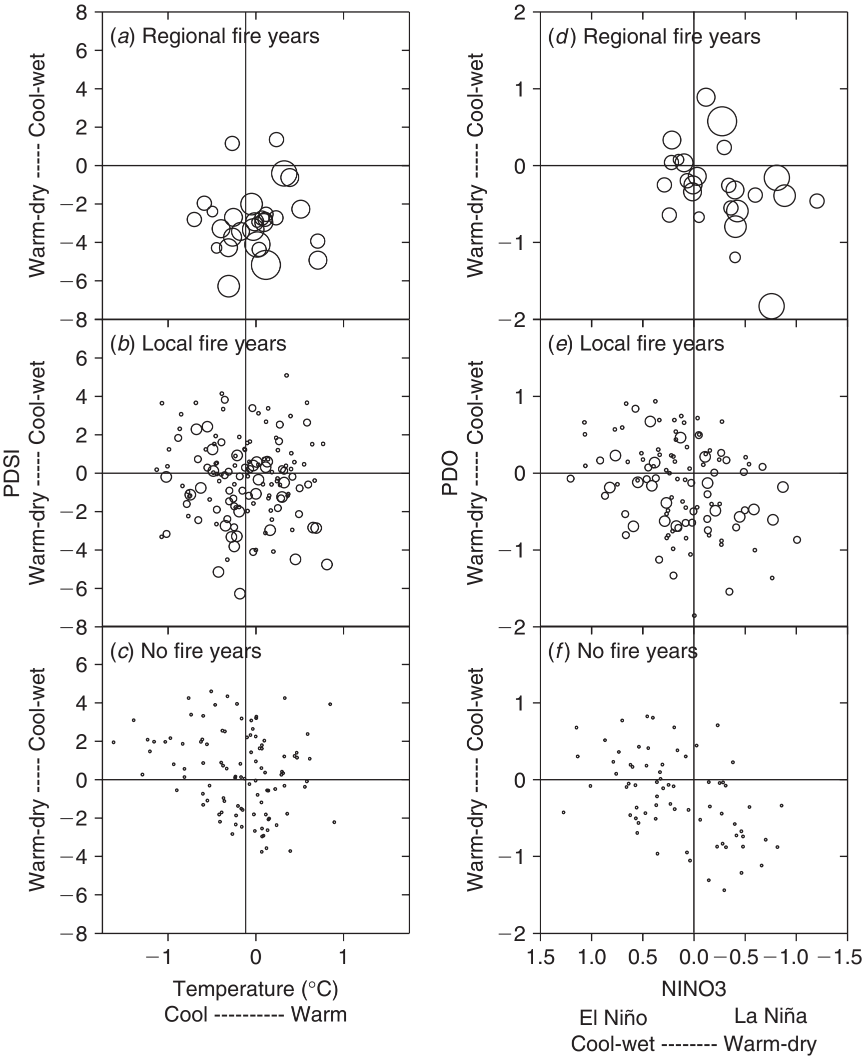

Fig. 3. Interactions between temperature and Palmer Drought Severity Index (PDSI) (*a–c*) from 1630 to 1900 and indices of large-scale climate patterns (*d–f*) from 1700 to 1900 during regional-, local- and no-fire years identified across all sites and forest types. Diameter of the circles is proportional to the percentage of sites recording fire, from no sites for the smallest diameter to 42% of sites for the largest diameter. Letters in *y*-axis labels refer to months, e.g. JJA is June, July and August. The axis for NINO3 has been inverted so that warm-dry conditions fall into the lower right quadrant for all panels.

possible relationships with this index (see Sibold and Veblen 2006; Kitzberger *et al.* 2007).

Results

Fire chronologies

We sampled 1187 fire-scarred trees and were able to crossdate 1085 (91%) of these, which yielded 2472 fire scars. Fire-scarred trees were mostly ponderosa pine (53%) with some Douglas-fir (15%), lodgepole pine (8%), Engelmann spruce (7%), limber pine (4%), white fir (4%), and <1% each of other species. Over half the crossdated fire-scarred trees were dead when sampled (57%, stumps, logs or snags). In our gridded watersheds, we assigned over half of the 202 plots that contained fire-scarred trees to the mixed-conifer (32%) or ponderosa pine (23%) vegetation types (Table 1). We assigned the rest to the spruce–fir (14%), lodgepole pine (11%), pinyon–juniper (8%), aspen–mixed conifer (4%), aspen (3%), or limber pine or bristlecone pine (2%) types, with ≤1% of plots with fire scars assigned to shrubland, oak brush, mountain mahogany, or sagebrush BpS.

Dated fire scars extended from 1234 to 1974. However, we analysed the climate effects on fires only from 1630 to 1900 because there was only one regional-fire date (recorded at ≥20% of sites) before this period (1506), and the number of fire dates declined at all sites in the late 1800s (Fig. 2). Across all sites and forest types, we identified 31 regional-fire years, 140 local fire years, and 100 no-fire years from 1630 to 1900 (Fig. 3). Regional-fire years occurred every 8 years on average (range 1 to 23 years) and were recorded at 21 to 42% of our sites.

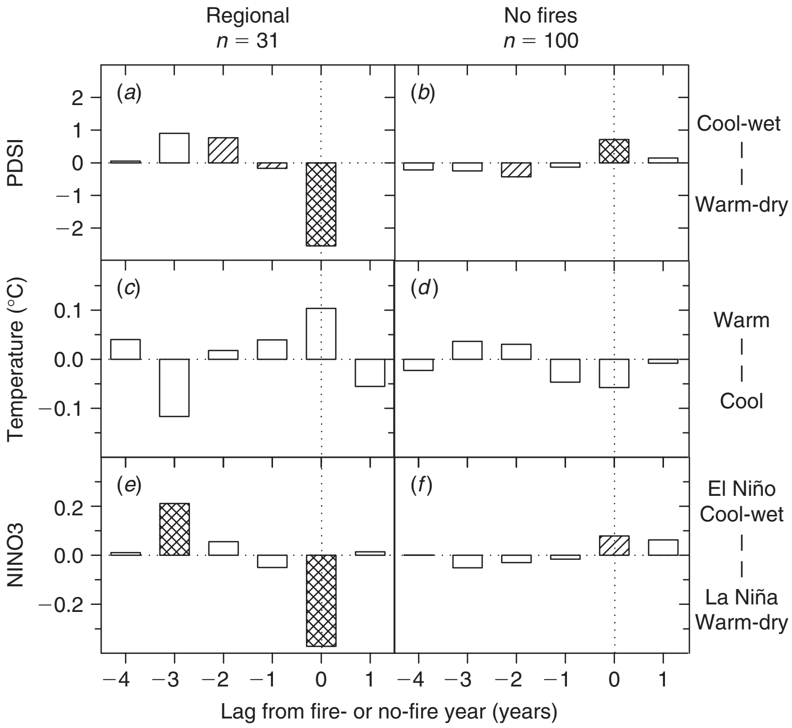

Fig. 4. Superposed epoch analysis of average climate departures during regional-fire years (left) and no-fire years (right) including all forest types and all sites. Departures exceeding 95% confidence intervals are hatched and those exceeding 99% confidence intervals are crosshatched. Climate time series were prewhitened before analysis.

Climate effects on fire occurrence

Regional-fire years that occurred in all sites and forest types (bottom panel dates in Fig. 2) occurred during years of low PDSI and low NINO3 (La Niña years), the latter of which are dry in the SW (Figs 3*a* and *d*, 4*a* and *e*, 5*a* and *c*). All but two of our regional-fire years (1797 and 1803) occurred when PDSI was low (Fig. 5*a*). In contrast, no-fire years occurred during years of high PDSI and high NINO3 (El Niño years), which are wet in the SW (Figs 3*c* and *f*, 4*b* and *f*). Antecedent climate was also important for regional-fire years. PDSI and NINO3 were above average (wet conditions) 2 to 3 years before regional-fire years (Fig. 4*a* and *e*). Temperature tended to be above average during regional-fire years and below average during no-fire years, but neither departure was significant ($P > 0.05$; Fig. 4*c* and *d*). During local fire years, climate did not differ significantly from average during the fire year or during lagged years ($P < 0.05$; Fig. 3*b* and *e*; SEA results not shown).

Half the regional-fire years (13 of 25 years from 1700 to 1900) occurred when NINO3 and PDO were both negative (Table 2). Although this is nearly twice the expected number of regional-fire years for this phase combination, the distribution of regional-fire years by phases of NINO3 and PDO was not significantly different from the distribution of years by these phase combinations regardless of fire activity ($P = 0.0581$). Furthermore, the occurrence of regional-fire years did not vary with AMO (Fig. 5*e*).

Across the southern sites, we identified 5 fire years in spruce–fir plots, 41 in mixed-conifer, and 3 in pinyon–juniper (Fig. 6). PDSI was low during these fire years for all three forest types but antecedent PDSI was significantly high only in mixed-conifer. NINO3 was significantly low (La Niña years) during fire years only in mixed-conifer but was not significantly different during antecedent years for any forest type. Temperature was above average during fire years in all forest types but not significantly so.

We identified 7 to 58 fire years per site in mixed-conifer (i.e. mixed-conifer plus ponderosa pine BpS plots) site fire chronologies (Fig. 7). PDSI was significantly low during fire years at the majority of sites (9 of 12) and during antecedent years at some sites (5 of 12). NINO3 was significantly low (La Niña years) at three sites in the south-eastern portion of the study area (OWP, BOM, and ABM, Fig. 1) and during antecedent years at PSG. NINO3 was high (El Niño years) during antecedent years at two sites (INC and ABM). Temperature was significantly above average during fire years at one site (INC).

Discussion

The number of fire dates declined in the early portion of the regional record relative to the number of sites (Fig. 2) because our systematic sampling design captured trees from young forests that burned relatively infrequently. This sampling design is in contrast to previous fire-scar studies that focussed exclusively on ponderosa pine or mixed-conifer forests in which older trees with abundant fire-scar records have been targeted for collection.

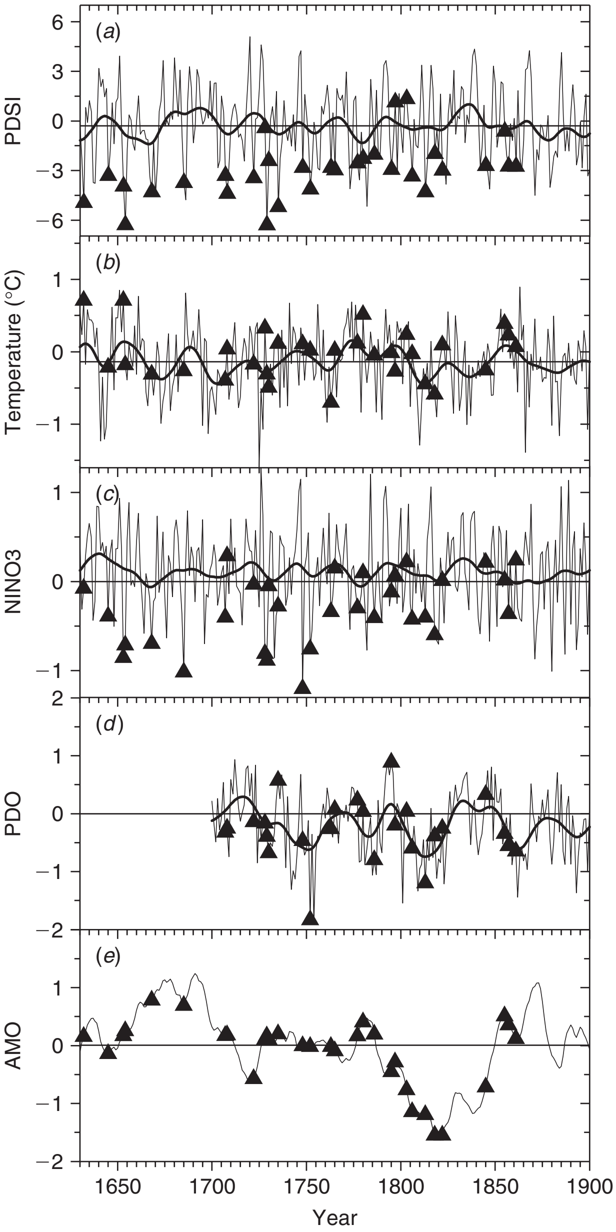

Fig. 5. Annual climate indices during regional-fire years (triangles). Light lines are tree-ring reconstructed climate and heavy lines are climate smoothed with cubic splines that retain 50% of the variance at periods of 25 years.

In these studies, fire chronologies tend to extend farther into the past (e.g. Kitzberger *et al.* 2007). The goal of our study was to reconstruct fire regimes across forest types, including fire severities as well as fire frequencies within plots. For the analysis presented here, we only focussed on fire-scar data. Future work will couple tree recruitment with fire-scar data from the less-frequent fire types such as spruce–fir and pinyon–juniper stands, and should provide additional, albeit non-absolute, fire dates from these other forest types.

Regional fires from 1630 to 1900 occurred during drought years, which were often La Niña years (Figs 3, 4 and 5). Regional fires also were usually preceded by significantly wet conditions 2 to 3 years before fire years. This finding offers support for the hypothesis that seasonal buildup of fine fuels was likely as important for regional fire occurrence in the frequent fire types as was fuel drying during droughts (e.g. Brown and Wu 2005). When broken down by forest type, the pattern of antecedent wet years was only significant ($P < 0.05$) in mixed-conifer plots, which typically had frequent fire (Fig. 6). Fuel buildup likely was not limiting to fire occurrence in the relatively productive spruce–fir plots. We were surprised that climate in the years before regional-fire years did not depart significantly from climate in other years in our pinyon–juniper plots where we expected the fine fuel amount and continuity to limit fire spread. However, climate during prior years was relatively wet in pinyon–juniper but our very small sample size (only 3 fire years) limits our ability to detect the significance of this effect if it exists. Years when no fires were recorded in any of our sites were typically wetter than average, and were preceded by drought 2 years prior. This result suggests that the opposite case may also have been important: drought years fail to produce fine fuels, and wetter fuels are more difficult to burn either locally or regionally.

We did not find any significant relationship with temperature in the regional-fire dates, although fire years tended to be warmer than average (Fig. 4). At sites to the north, regionally synchronous fires generally occurred during relatively warm spring–summers, likely because early melting of snowpack resulted in longer fire seasons (Westerling *et al.* 2006; Heyerdahl *et al.* 2008). Our lack of a temperature signal in regionally synchronous fires in Utah may be because warm springs did not result in significantly long fire seasons in this region or because the reconstruction of temperature that we used was from a single point whereas spring temperature may vary across the region.

Widespread fires generally ceased across the study area starting in the late 1800s likely owing to the effects of changes in land use brought about by Euro-American settlement. Livestock grazing that accompanied settlement in the late 1800s reduced grass and other herbaceous fuels through which fires spread, and was followed by active fire suppression by land management agencies beginning in the early 1900s. The decline in fire occurrence in the Utah forests tended to be slightly earlier than in the SW (e.g. Swetnam and Baisan 1996) because of generally earlier Mormon settlement in the region beginning in the middle 1800s (Young *et al.* 1979).

No regional fires were recorded from 1822 to 1845 (Fig. 2). This period was synchronous with a widespread fire-quiescent period in fire chronologies throughout the SW, northern Mexico, and South America (Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Kitzberger *et al.* 2001; Brown and Wu 2005; Swetnam and Brown in press). Several of these studies have suggested that a dampening of interannual wet and dry ENSO cycles was at least partially responsible for lessened fires during this period, although the early 1800s were also cooler and wetter overall than earlier and later periods (Swetnam and Brown in press). Fires were also less frequent in our northern sites (MUR, BRO, WUN, BCL, TVP) from the mid-1700s to the mid-1800s, coeval with longer gaps seen in fire chronologies from the central Rocky Mountains (e.g. Brown *et al.* 1999; Sibold and Veblen 2006). In contrast, the late 1700s to 1822 was a very

Table 2. Contingent effects of large-scale climate patterns on the occurrence of 25 regional-fire years (≥20% of 18 sites recording fires from 1700 to 1900) for all four combinations of NINO3 and PDO phases (negative/positive)

All combinations were not significant ($P = 0.0581$). Expected numbers are from the proportion of years occurring during each phase combination, regardless of fire activity

Number of years	NINO3/PDO			
	Positive/positive	Positive/negative	Negative/positive	Negative/negative
Observed	4	5	3	13
Expected	7.1	8.1	2.7	7.1
Percentage of expected	56%	62%	110%	183%

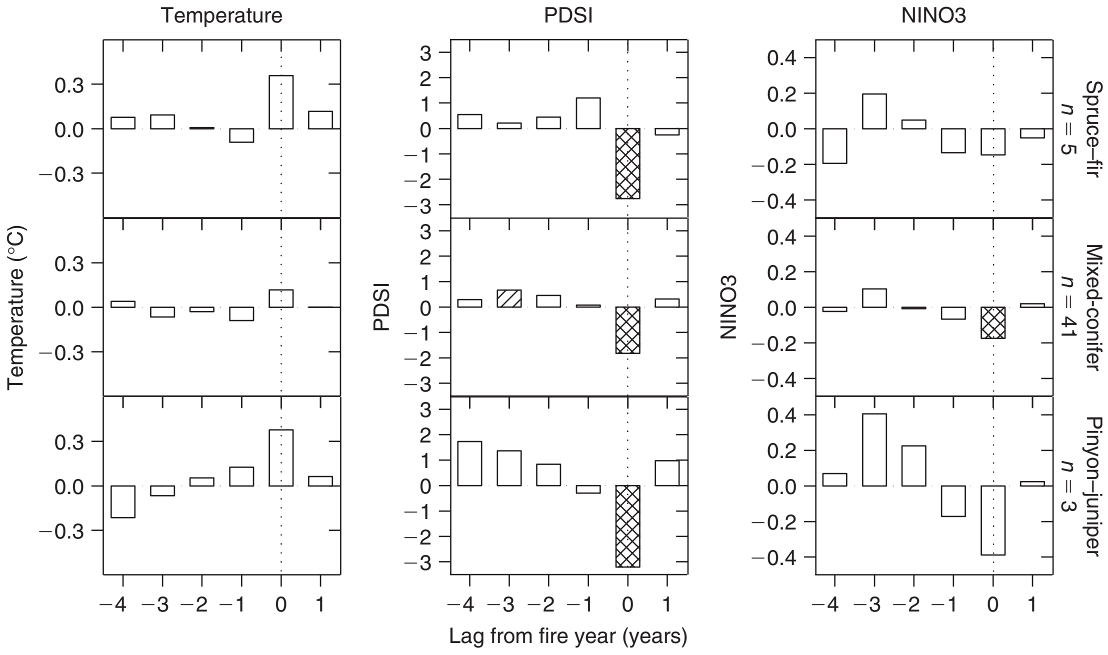

Fig. 6. Superposed epoch analysis of average climate departures during fire years at the southern sites by forest type. N is the number of years with ≥2 fire-scarred trees in spruce–fir, mixed-conifer (mixed-conifer plus ponderosa pine), and pinyon–juniper biophysical settings plots (Table 1). Departures exceeding 95% confidence intervals are hatched and those exceeding 99% confidence intervals are crosshatched. Climate time series were prewhitened before analysis.

active period of fire in our southern sites (Fig. 2). It is likely that the spatial signature of the late 1700s–early 1800s fire quiescent period across the region is related to large-scale climate patterns and may be related to the pivot point ~40°N latitude.

Varying strength of NINO3 in individual sites provides support for the hypothesis of a strong spatial component to ENSO effects on fires in the central western US, and that a northern geographic limit in ENSO effects may indeed occur ~40°N (Fig. 7; Dettinger *et al.* 1998; Hessl *et al.* 2004). Low PDSI was related to fire occurrences across the gradient, suggesting that climate factors other than La Niñas affected droughts (and hence fire occurrences) at our northern and western sites.

The climate effects on regional fires that we identified more likely represent conditions in the southern than the northern part of our study area (defined as sites north and south of 40°N; Fig. 1) because fires were not frequent at sites in the north (an average of 9 regional-fire years at northern sites *v.* 25 regional-fire years at southern sites from 1630 to 1900). This low frequency of fire resulted in only 3 regional-fire years in at least two sites (1707, 1709, and 1735) among our northern sites (Fig. 2). Analysis of our network from Utah with other sites from across the western US may help to illuminate stronger spatial and temporal patterns of climate teleconnections in the northern portion of our study area.

Interacting phases of large-scale climate patterns weakly synchronised fires across the study area. Droughts over the SW tend to be enhanced when La Niñas occur during cool phases of the PDO, and wetter conditions prevail in the SW when El Niños occur during warm PDO phases (e.g. Westerling and Swetnam 2003; Schoennagel *et al.* 2005). Moreover, many of our regional-fire dates occurred during a period when AMO was in a relatively moderate phase during the 1700s (Fig. 5*e*). Longer fire chronologies that contain more fire dates in the high and low phases of AMO do show significant contingencies with both PDO and

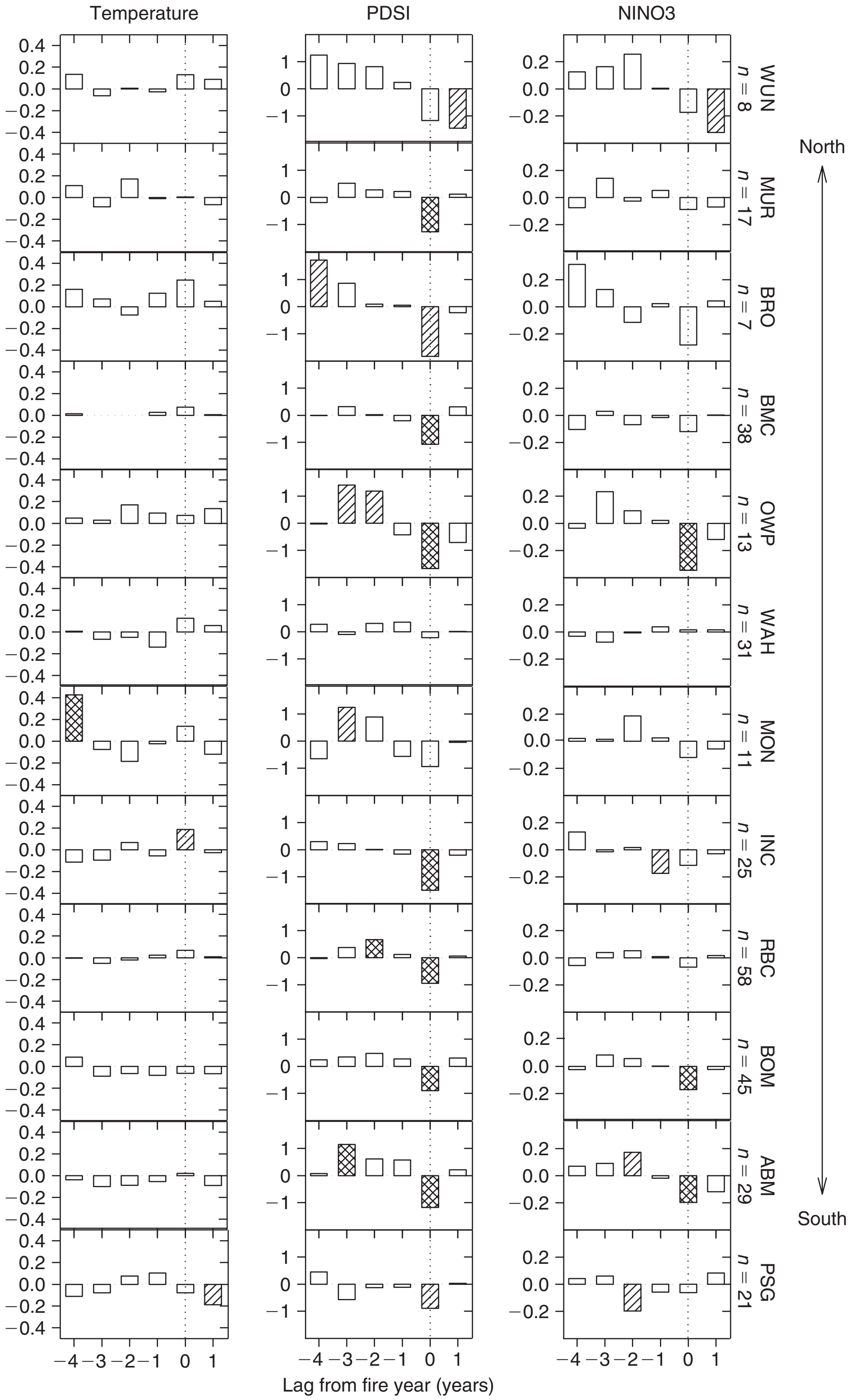

Fig. 7. Superposed epoch analysis of average climate departures during fire years in mixed conifer or ponderosa pine forest types at individual sites. N is the number of years with ≥2 fire-scarred trees. Departures exceeding 95% confidence intervals are hatched and those exceeding 99% confidence intervals are crosshatched. Climate time series were prewhitened before analysis.

ENSO (Brown 2006; Sibold and Veblen 2006; Kitzberger *et al.* 2007).

Results from the current study support findings from previous studies on the importance of droughts and Pacific basin teleconnections on fire occurrence across the western US. Fire–climate relations, including the strength of Pacific effects, varied both by forest type and location across the region. Data from both frequent-fire mixed-conifer and ponderosa pine forests and infrequent spruce–fir and pinyon–juniper stands highlight varying importance of antecedent wet conditions to widespread fire occurrence. Increased annual droughts over larger regions that may occur in the future (e.g. Cook *et al.* 2004) also may lead to more years when fuels will be dry enough for regional fires to occur across all forest types.

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