FIRE HISTORY AND CLIMATE INFLUENCES FROM FORESTS IN THE NORTHERN SIERRA NEVADA, USA

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ABSTRACT

Fire chronologies were developed for four regions representing two general forest types in the Plumas National Forest, Northern Sierra Nevada, California. Chronologies were developed using dendrochronological techniques largely from remnant woody materials, since past logging has left few live trees with long fire scar records. Over the period from 1454 to 2001, 113 fire years were identified in the four regions. Individual sample sites were 0.3-2.0 ha in size. Mean composite fire return intervals (CFI) for the sites ranged from 8 to 22 years when examining fires scarring more than 10% of samples. These values are consistent with fire return intervals derived from similar forests in the Southern Cascades and Northern Sierra Nevada. Differences in CFI were not significantly different between most sites or forest types, or between two management eras. Fire scar formation was predominantly recorded in the latewood and at the ring boundary, suggesting that most fires for this region occurred in the late summer or fall. Fire years in each of four regions were found to correspond significantly to drought conditions when compared to the Palmer Drought Severity Index and to salinity levels in the San Francisco Bay. Fire years also corresponded significantly to transitions from warm to cool phases of the Pacific Decadal Oscillation and the El Niño-Southern Oscillation, which are climate forcing atmospheric processes operating on decadal time scales.

Keywords: fire intervals, dendrochronology, fire climate interactions, mixed conifer, ponderosa pine, Jeffrey pine forests

INTRODUCTION

Fire has played a vital role in the development of the flora and fauna of the Western United States (Skinner and Chang 1996). Prior to Euro-American settlement, fires occurred frequently in many forest types. Whether naturally ignited or anthropogenic, fire served as a regular ecosystem process, influencing vegetation patterns, wildlife distributions, nutrient cycling, and many other ecosystem elements (Kilgore, 1973;

Weatherspoon et al., 1992; Agee, 1993; Skinner and Chang, 1996).

Mid-elevation forest types in the Sierra Nevada, such as ponderosa pine (*Pinus ponderosa* Laws.) and Sierran mixed conifer, burned many times per century. These low to moderate intensity fires often burned for months at a time, and collectively covered very large areas (Skinner and Chang, 1996). In the late 19th and early 20th centuries, policies of comprehensive fire exclusion, introduction of livestock grazing and logging, and elimination of Native American ignitions greatly reduced fire frequencies in these forests (Vankat, 1977; Kilgore and Taylor, 1979; Stephens and Sugihara, 2005). The effects of such policies are complex and varied, but it is generally agreed that they have resulted in significant changes in the structure and function of many forest types (Biswell, 1989).

Dendrochronology- (tree ring-) based fire history investigations can shed light on the spatial and temporal patterns of fire for a given landscape, provide evidence for fire's historical and pre-settlement role in these ecosystems, and provide information that managers can use when defining desired conditions (Dieterich, 1980; Stokes, 1980; McBride, 1983; Swetnam et al., 1985; Grissino-Mayer, 1995; Stephens and Fule, 2005). The majority of tree ring-based fire history studies performed in the Sierra Nevada are from the southern region such as Yosemite, Sequoia, and Kings Canyon National Parks (Skinner and Chang, 1996). Very little fire history information exists for northern or eastern Sierra Nevada forests, which can differ significantly from the southern Sierra Nevada (Stephens and Collins, 2004). Several fire history studies have been performed in the southern Cascades and Klamath Mountains of northern California (Taylor and Halpern, 1991; Taylor, 1993; Taylor and Skinner, 1998; Taylor, 2000; Fry and Stephens, 2006), which are similar floristically to the northern Sierra Nevada, and thus discussions of fire history for northern Sierra Nevada forests often draw on these studies (Skinner and Chang, 1996).

One published study by Stephens (2001) compared fire history in adjacent Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) and red fir (*Abies magnifica* Andr. Murray) forest types near Mammoth Lakes in the eastern Sierra Nevada. Recent work by Taylor and Beaty in the Lake Tahoe area (2005) and by Stephens and Collins near Georgetown, CA. (2004) represent the closest crossdated fire history studies to this work. Fire frequency was estimated early in the twentieth century for one area of the Plumas National Forest by Boyce (1921) and Show and Kotok (1924), and later evaluated by Wagener (1961), but these estimates were derived from ring counts in the field, a method far less accurate and informative than crossdating. These early studies also did not report how their samples were spatially distributed. No other fire history work has been published for the northern Sierra Nevada.

The concern over forest structural and process changes caused by disruption of pre-settlement fire regimes in the late 19th and early 20th centuries has driven research efforts aimed at establishing pre-settlement conditions, including fire regime characteristics. Fire regimes (frequency, extent, severity, seasonality, and synergy) in western forests are influenced by a host of factors, including local weather, fuels, vegetation type and condition, topography, and ignition sources (natural and anthropogenic). However, recent studies in the Southwest and Northwest United States have shown temporal patterns of fire to be linked to both inter-annual climate variability (e.g. drought) and inter-decadal climate patterns such as the El Niño-Southern Oscillation (ENSO) (Swetnam and Betancourt, 1990; Swetnam and Betancourt, 1998; Brown et al., 2001; Heyerdahl et al., 2002; Taylor and Beaty, 2005). Inter-decadal atmospheric processes such as ENSO and the Pacific Decadal Oscillation (PDO) are understood to have significant influence on annual-scale climate in California and the western states (Swetnam and Betancourt, 1998; Dettinger et al., 2001). Proxy indices for these processes have been reconstructed beyond historical instrumental data, providing a reference of past variation. Comparing these indices to temporal patterns of fire occurrence may provide information on past interactions of fire and climate.

The primary objective of this study was to establish a record of fire for several forested sites within the northern Sierra Nevada. Comparison of fire regime characteristics between sites within this study could yield important information regarding local differences. Comparison of temporal fire records to independent climate indices could determine if they are significantly correlated. We anticipated slight differences in fire frequencies between different forest types within the study, with more xeric eastern Sierra forest types dominated by Jeffrey pine and ponderosa pine yielding shorter fire intervals than mixed conifer sites. We further expected inter-annual and inter-decadal patterns of climate to have a strong influence on past fire occurrence, with antecedent conditions playing a stronger role in the more xeric, pine dominated sites.

METHODS

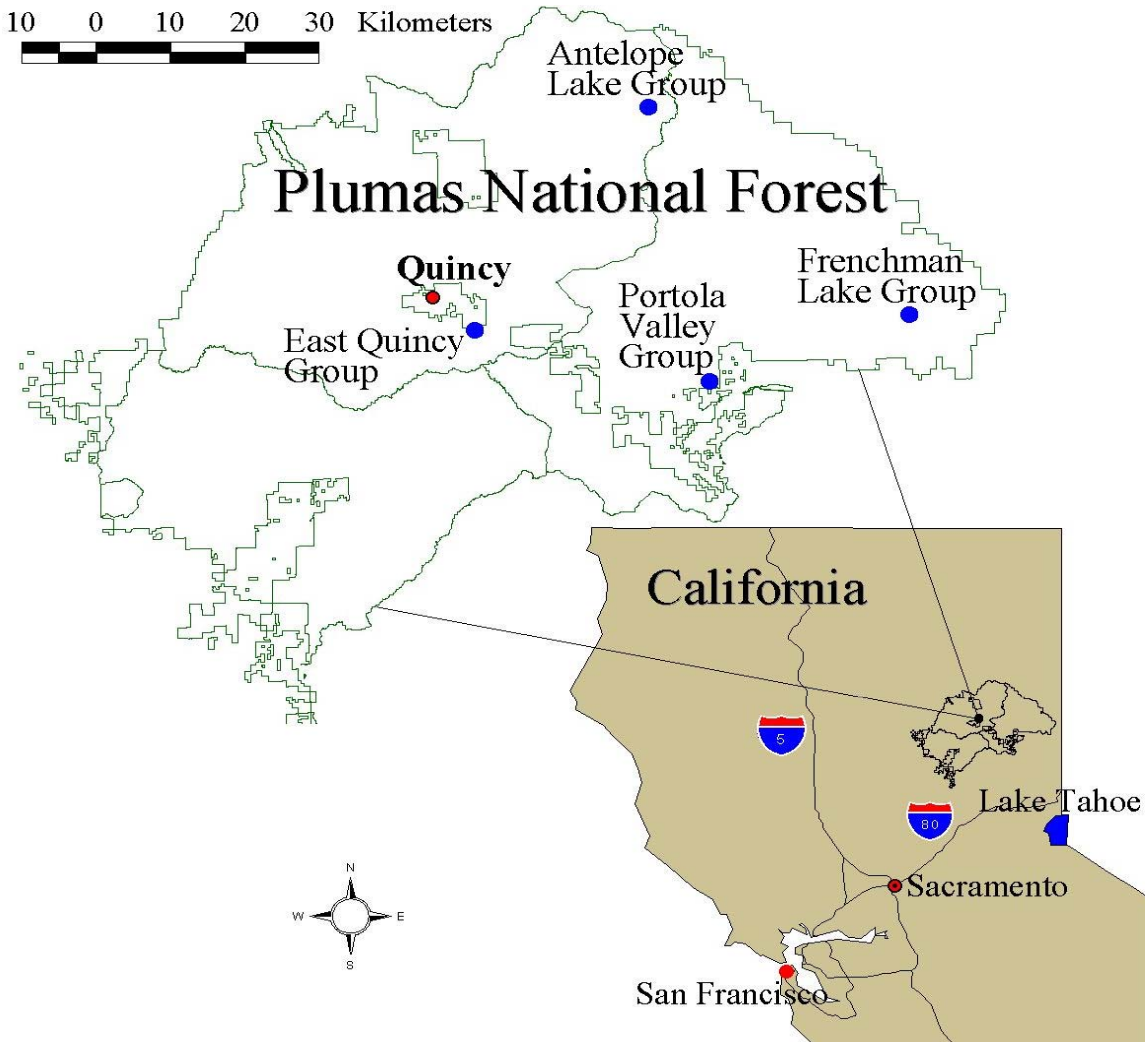
Study Area

The Plumas National Forest (PNF) spans the northern extent of the Sierra Nevada (Figure 1). It is bounded by the Sacramento Valley to the west, the Honey Lake Valley to the east, and to the north by the Cascade and Klamath Mountains (geologically different ranges). The crest of the Sierra Nevada in the PNF rises to over 2400 m. Quincy, the seat of Plumas County, lies in the center of the PNF, at the junction of State Highways 70 and 89.

The watershed of the Feather River, and its main forks and tributaries, comprise the majority of the PNF. Climate of the PNF is largely Mediterranean in character, with cool, wet winters and warm, dry summers. Annual precipitation ranges from 38 cm on the eastside to over 229 cm on the westside (USDA, 1986). Snow pack of 1.5-3 meters is typical over elevations of 1500-1800 meters in the winter months (USDA, 1986). The PNF exhibits the geologic complexity typical of the Sierra Nevada (underlain by older metamorphics, granitic intrusions, and younger volcanics on the eastside). The climate and geology has contributed to diverse soils across the PNF, with warmer, wetter westside areas yielding generally deeper more productive soils (USDA, 1986).

Major forest types of the PNF can by generally characterized as westside mixed conifer – which includes the species ponderosa pine, sugar pine (*P. lambertiana* Douglas), Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco var. *menziesii*), white fir (*Abies concolor* (Gordon & Glend.) Lindley), incense-cedar (*Calocedrus decurrens* (Torrey) Florin), and California black oak (*Quercus kelloggii* Newb.); eastside mixed conifer – which includes ponderosa pine, Jeffrey pine, and white fir; and eastside pine – consisting of ponderosa and Jeffrey pines. The westside mixed conifer forest types comprise the majority (57%) of the Plumas, and transition into eastside mixed conifer and eastside pine forest types, which are more rare (8% and 13%, respectively) (USDA, 1986). Logging across the forest has left many stumps of various species with visible fire scars.

Figure 1: Plumas National Forest location and fire history sample group locations.



Land Use History

Prior to Euro-American settlement, the Maidu inhabited the land currently designated as the PNF, west to present day Oroville and south to present day Marysville. The Maidu were composed of three bands known as the Konkow Maidu, the Nisenan Maidu, and the Mountain Maidu (Young, 2003). Today's Plumas County was the territory of the Mountain Maidu who established permanent villages and seasonal camps throughout a series of mountain valleys, including the American Valley (Quincy), Indian Valley (Taylorsville), Genesee Valley, Sierra Valley (Portola) and the Susanville area, among others. They numbered between 2000-3000 dispersed across the various settlements (Young, 2003). The Maidu were primarily a hunting, fishing, and gathering society, and used fire as a means to enhance young shoot growth for basket weaving (Young, 2003), to clear out shrubs for hunting (Dixon, 1905), and to reduce natural fire hazard (Potts, 1977).

Euro-American settlement of Plumas County largely coincided with the California Gold Rush. In 1849 prospectors began moving up from the foothills east of Oroville toward the present day Plumas County line upon hearing of gold in the high country. A series of subsequent discoveries would draw thousands more in the next few years. By 1860, bustling communities existed in the American, Indian, and Sierra Valleys, and in the Big Meadows area. A logging industry quickly developed to support mining and the fast growing towns. Agriculture and livestock grazing became the way of life for many residents of the fertile valleys. Railroads became an integral form of transportation for Plumas County residents, and would later play an important role in the timber industry (Young, 2003).

In 1905 the United States Forest Service was given responsibility for administering and managing the vast majority of timberland in the county (Husari and McKelvey, 1996). A federal policy of suppressing all wildland fires began, strengthened by the great firestorms of 1910 in the northern Rocky Mountains. Grazing occurred throughout the century and continues today. Mining activities waned over the first half of the twentieth century, but logging continued in earnest until cultural and policy changes in the 1980s reduced timber production and eliminated many saw mills. By the early 1990's, Plumas County was in the midst of an economic depression and facing growing fire hazard from three quarters of a century of fire suppression and past harvesting. The Herger Feinstein Quincy Library Group Forest Recovery Act of 1997 (H.R. 858 and S. 1028) was aimed at reducing fire hazard by implementing defensive fuel profile zones (DFPZs), the creation of which would ideally result in a steady supply timber to mills, more jobs, and increased revenues to the local community. Today the PNF remains at the center of debate over issues such as costs of fuel hazard reduction, merits of structural versus process-oriented restoration, and effectiveness of fuel treatments (Stephens and Ruth, 2005).

Fire Scar Sampling and Preparation

Over 100 cross sections with apparent fire scars (fire scar samples) were cut from stumps, snags, and downed logs of various species in the PNF from 1997-1999 by US Forest Service employees. Sites for potential sampling were chosen to represent a variety of aspects, topographic positions, forest types, and precipitation zones. Samples were taken from sites near Antelope Lake, near La Porte Road east of the town of Quincy, near Frenchman Lake, and surrounding the town of Portola (Moody, 2005). Clusters of fire scars were located, existing vegetation was noted, and samples were then chosen and collected to maximize the completeness of fire dates within the area in question (Swetnam and Baisan, 2003).

Several recent studies have investigated the merits of systematic sampling strategies vs. targeted methods used here and in many prior studies (Heyerdahl et al. 2001, Everett 2003). However, the goal of targeted sampling techniques is to determine the majority of fire events that occurred in a particular sample area, and taken as such, should not be invalidated by arguments for systematic sampling in fire history studies. Proper interpretation of target-sampled and composite-based fire histories is important.

Each fire scar sample was cut, sanded, and polished to a high sheen (400 grit) so that tree rings and fire scars could be readily distinguished under a microscope. Fire scars were identified by the characteristic disruption of growth and subsequent healing patterns after injury of radial tree ring growth (Figure 2) (McBride, 1983; Dieterich and Swetnam, 1984). Dates were assigned to tree rings using standard dendrochronological techniques of skeleton plotting or visually graphing tree ring patterns (Stokes and Smiley, 1977; Swetnam et al. 1985). Patterns of fire scar samples were compared to each other and to published master tree ring chronologies from nearby sites at Antelope Lake (Holmes and Adams, 1980) and Susanville (Fritts, 1963).

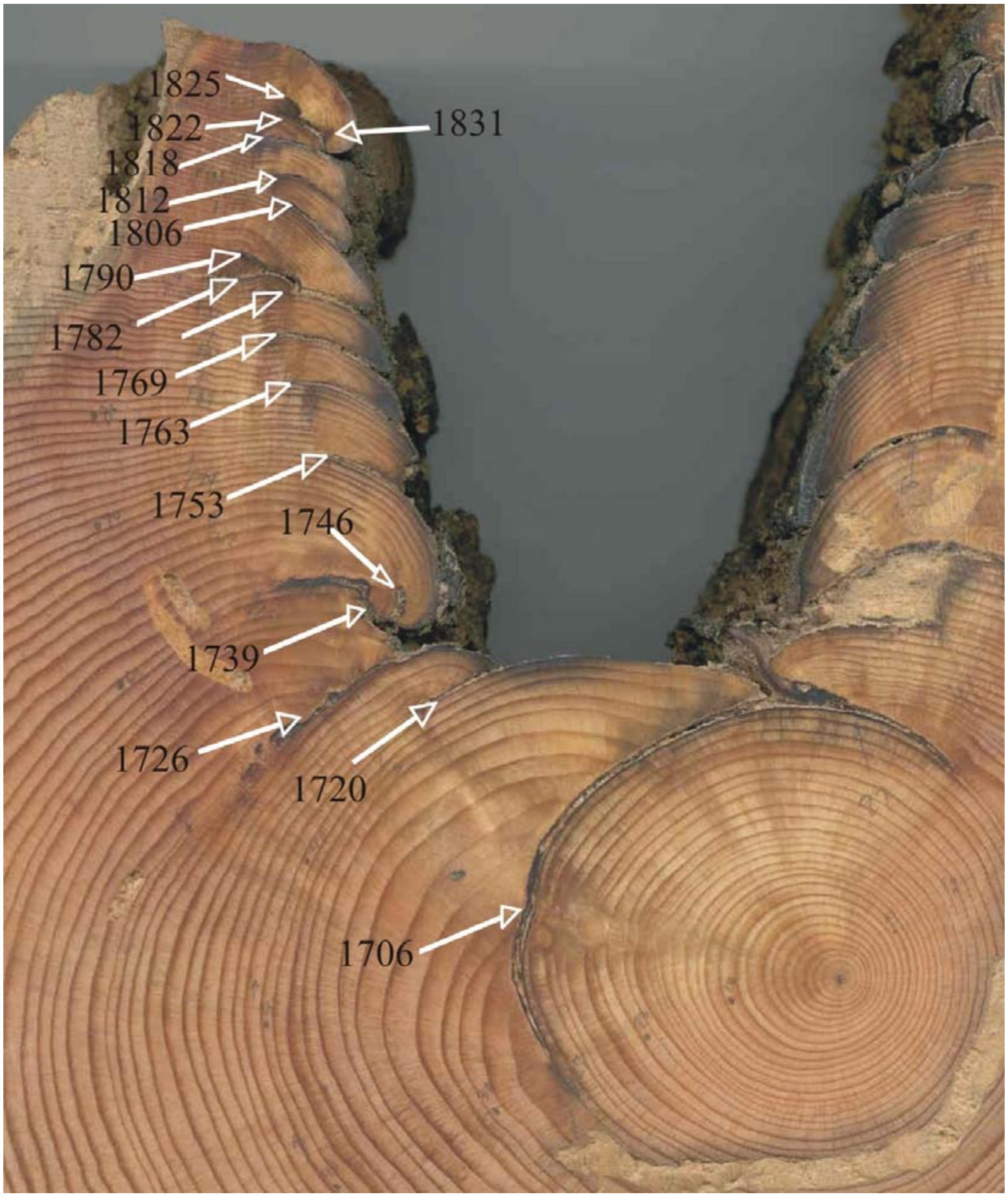
Incense-cedar has yet to be proven to crossdate with other species over large ranges, though at least two fire history studies have used it over limited areas with some success (Everett, 2003; Stephens and Collins, 2004). Many of the samples initially taken in this collection (47%) were incense-cedar due to their availability, their ability to hold a fire scar, and their slow decay. However, this species proved difficult to date accurately against the pine-derived chronologies, so a master tree ring chronology was developed using 18 incense-cedar cores taken from 9 live trees near the Beckworth Ranger Station. A sliding stage micrometer was used to record ring widths, and the program COFECHA was used to crossdate the cores. The program ARSTAN was used to remove long-term trends and create the master tree ring chronology.

Years were assigned to tree rings and fire scars (e.g. Figure 2) by matching tree ring patterns to published chronologies or our incense-cedar chronology, using skeleton plots. In some instances, fire return intervals and dates of known fires or harvesting were used to establish preliminary tree ring dates, especially since tree ring series varied between species. Dating was later validated by crossdating. In order to estimate season of past fire occurrence, each dated scar was noted as forming either in the early-earlywood (EE), middle earlywood (ME), late-earlywood (LE), or latewood (L) portions of the annual rings, at the ring boundary (dormant season – D), or marked as unknown (U) (Caprio and Swetnam, 1995).

Fire Interval Analysis

The FHX2 software package was used to analyze all dated fire scars (Grissino-Mayer, 2001). For the period of record, beginning with the earliest scar recorded on an available recording tree and ending with the last scar recorded for the site (Skinner and Chang, 1996), we first developed fire chronologies for each tree as a point in the landscape (Taylor, 2000), and calculated the point fire interval (PFI) for each tree (the mean number of years between successive fires). We then calculated the individual tree-based site fire interval (SFI) for each site, which is the mean of all tree PFIs for a site, weighted by their corresponding number of intervals (Baker and Ehle, 2001). However, composite fire chronologies, which are created using fire dates from multiple trees in a given site, have been found to provide a more comprehensive record of past fires for the site in question (Dieterich, 1980; Agee, 1993).

Figure 2: Fire history sample (ID# 51-27-04) from a Jeffrey pine stump, taken near the town of Portola in the Plumas National Forest. Arrows denote crossdated fire scars.



We used composite fire chronologies to calculate composite fire interval (CFI) statistics for each site. In some instances the sample material between consecutive fire scars had either deteriorated or burned away such that it was impossible to determine if scars had been created in between. In these instances, the intervening years were not used in fire interval calculations. The last incomplete interval (between the last scar and the last ring formed) was also not used in fire interval analyses.

Composite fire chronologies can be filtered to reflect fires scarring any proportion of trees at a site for a given year (e.g. fires scarring >10%, 25%, or >50% of trees in study area in the same year), allowing for an implicit analysis of fires at different spatial scales. A fire that scars only 5% of trees in the study area may be considered of small extent or of low severity, while a fire that scars >50% of trees in the area may be considered of larger extent or higher severity. Composite fire chronologies were developed for each site based on: 1) all fires recorded on available recording trees (hereafter referred to as no filter), 2) fires that scarred at least 10 percent of available recording trees and a minimum of two trees (10% filter), and 3) fires that scarred at least 25 percent of available recording trees and a minimum of three trees (25% filter). Trees were considered to be available recording trees if they had been scarred at least once and the scarred area (catface) remained exposed to future fires.

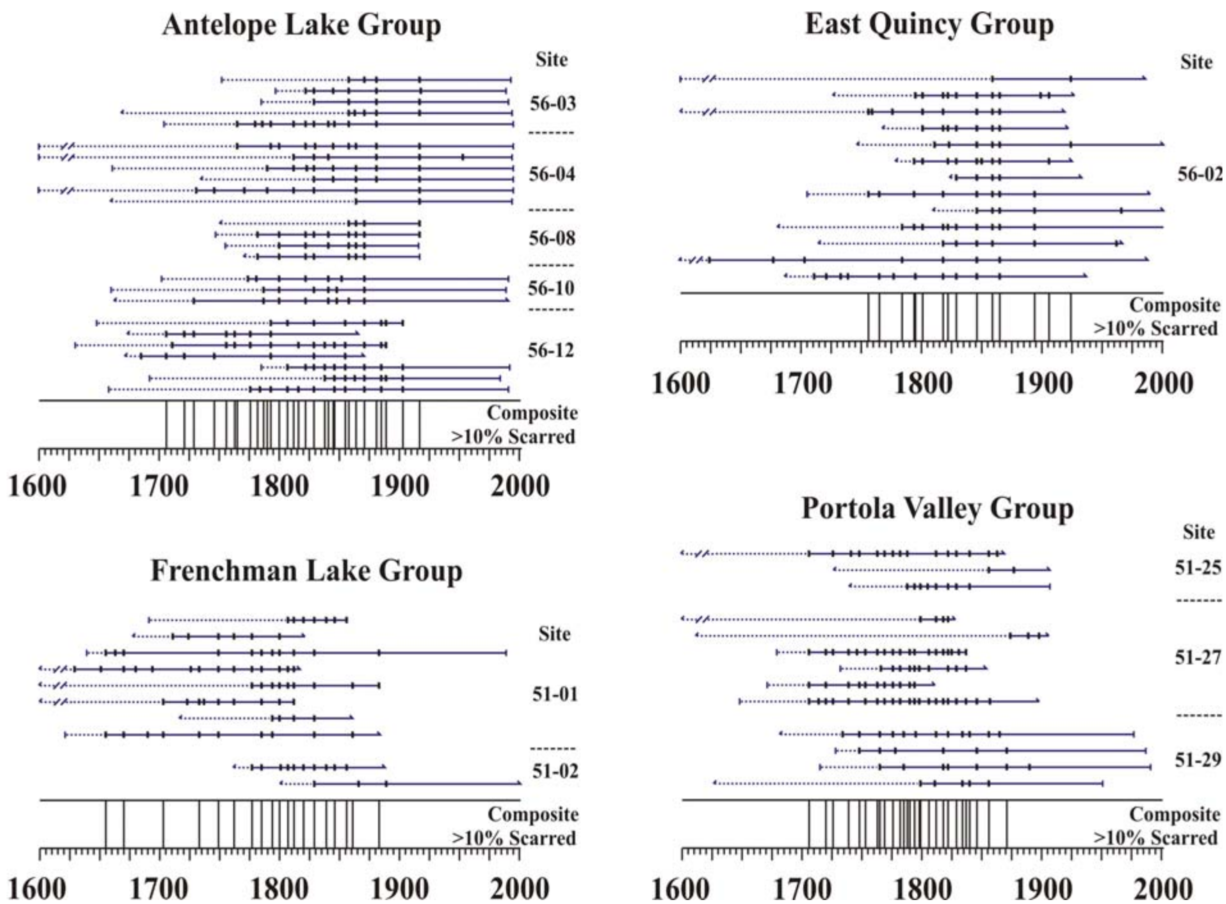
For each level of filtering, we determined the mean, median, minimum, and maximum CFIs for each sample site for the period of record. Additionally, we examined two specific eras within the period of record for each site, in order to maximize sample depths and examine different periods of human activity: pre-settlement (1775 to 1849), and post-settlement (1849 to 1904). The year 1775 was chosen from visual inspection of Figure 3 as the point at which all sample groups had an adequate sample depth. The year 1850 was chosen as the start of Euro-American settlement, as this year signaled the start of the Gold Rush in the Plumas region (Young, 2003). The year 1905 was chosen to represent the start of fire suppression policies implemented by the US Forest Service (Husari and McKelvey, 1996). Limited sample depth and the general absence of fire scars after 1905 precluded CFI analysis of this time period.

To determine if fire frequency was significantly different between sites, we performed a Kruskal-Wallis test (a non-parametric analysis of variance) on the 11 sites for the period of record, the pre-settlement era, and the post-settlement era, at each level of filtering (Zar, 1999). When CFIs among the sites were found to be significantly different, we used the Nemenyi test (a non-parametric Tukey-type multiple comparison) to determine how each group did or did not differ from the other groups (Zar, 1999).

To determine if fire frequency had changed between the two management eras, we performed a Mann-Whitney test (a non parametric two-sample rank test) for each site at each filtering level (Zar, 1999). Non-parametric methods were chosen because some of the fire interval distributions examined here violated the basic assumption of normality.

Recent debate surrounding fire history methodology has been initiated by Baker and Ehle (2001), who caution against misinterpretation of and over-reliance on the CFI as an estimate of the true population fire mean. They contend that mean CFI may overestimate fire frequency if unrecorded fires in a site are rare, and that varying applications of the CFI among studies make its interpretation difficult. Additionally, composite fire intervals are sensitive to both the size of the sampling area (Agee, 1993) and the choice of composite filters.

Figure 3: Fire chronologies for fire history sites in the Plumas National Forest. Horizontal lines represent individual tree samples. Vertical tick marks are dated fire scars. Composite fire chronologies at bottom show only fires scarring >10 percent of samples in each group (minimum of two scars).



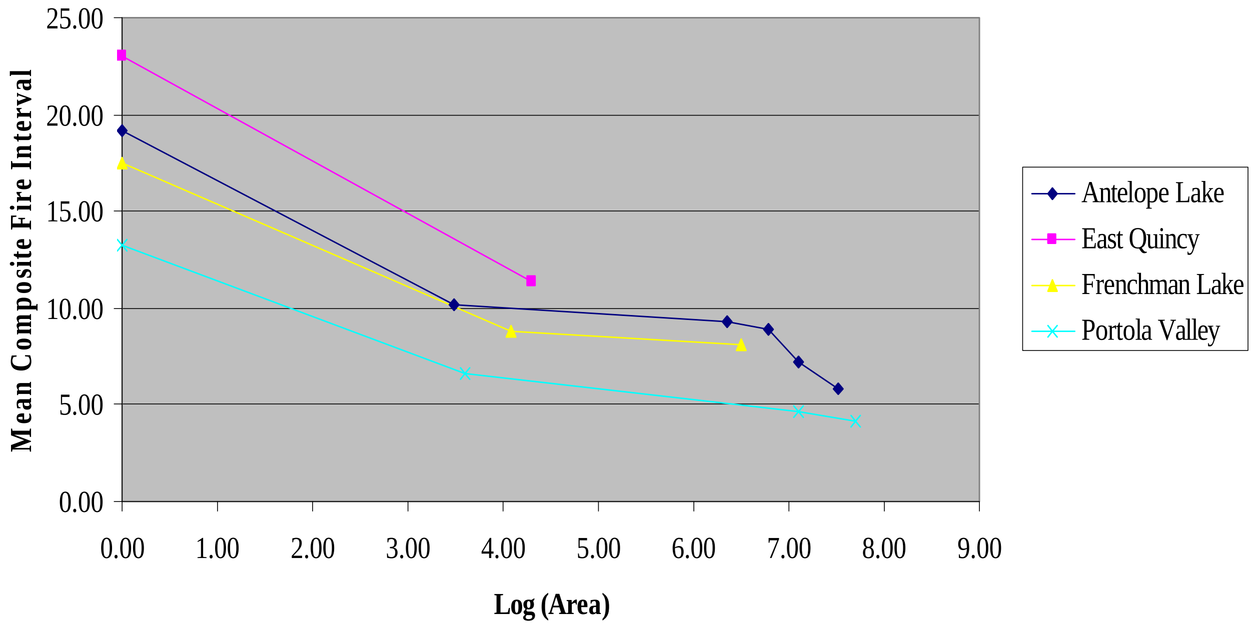
In theory, as sample area increases for a particular site, more fires may be captured in the master chronology, shortening the mean CFI for that area (Figure 4). A researcher may also choose to filter out fires scarring only a few trees, potentially lengthening the mean CFI. Composite fire chronologies must be considered in conjunction with both the size of the associated sampling area and level of filtering. CFI should be considered an estimate of the frequency of fire occurrence within a given sample area (e.g. a mean CFI of 10 years means that on average, a fire occurs somewhere in the study area every 10 years). Baker and Ehle (2001) suggest bracketing estimates of fire frequency using SFI as a “minimum fire” statistic, and CFI (filtered at 10%) as a “maximum fire” statistic for a sample site. We report both statistics here.

Fire Climate Analysis

Individual sample sites were combined into four regional groups for climate analysis: Antelope Lake Group, East Quincy Group, Frenchman Lake Group, and Portola Valley Group (Figures 1 and 3). Sample sites were grouped based on proximity and general forest type. Lists of fire events for each regional group derived without a filter, and with the 10 % and 25% composite filters were compared to several proxy indices of climate using superposed epoch analysis (SEA). In SEA, we superpose a window of time over an event (we examined the event year, six years prior, and four years after) and average corresponding climate indices for the years in question. Applying the list of fire intervals and the superposed windows randomly to the series of climate values many times (1000), it is possible to estimate confidence intervals via bootstrapping and compare them to mean values at and around the actual fire events (Baisan and Swetnam, 1995, Grissino-Mayer and Swetnam, 2000). The Palmer Drought Severity Index (PDSI) is an index for drought severity based on summer (June, July, and August) values of precipitation, air temperature, and soil moisture, and is the most commonly used index of drought in the United States (NOAA, 2005). Cook et al. (1999) used correlations between instrumental climate data and tree ring data to reconstruct PDSI across North America back several centuries. PDSI values generally range between –6.0 and +6.0, with negative values indicating dry periods and positive values indicating wet periods. Fire event lists for the PNF were compared to the nearest two PDSI grid points: point 6 (located at 39 degrees N latitude, 122.5 degrees W longitude, near Clear Lake, CA) and point 13 (located at 39 degrees N Latitude, 119.5 degrees W longitude, near Carson City, NV) which were chosen to represent inter-annual patterns of drought on the western and eastern slopes of the northern Sierra Nevada, respectively.

The San Francisco Bay Salinity Index (SFBSI) is a measure of salinity levels in the San Francisco Bay waters, reconstructed beyond instrumental data back to 1605 using the mean of five blue oak (*Quercus douglasii* Hook. and Arn.) tree ring chronologies located along the western edge of the San Joaquin Valley (Stahle et al., 2001). Salinity in San Francisco Bay is correlated with drought, with high levels of salinity corresponding with dry years. Reconstructed values of SFBSI are in parts per million x 10 and range from approximately 225 to 325. Years of fire occurrence in the PNF were compared to SFBSI as an additional measure of inter-annual drought.

Figure 4: Effect of sample area (m^2) on mean composite fire interval (years - no filter) for fire history groups in the Plumas National Forest. Area of groups was approximated as the area of the smallest circle encompassing sites in question. Data at 0 area is the average point fire interval (PFI) for all sites in the group.



The El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are atmospheric processes related to variations in sea surface temperature. They fluctuate between warm and cool phases on decadal time scales (approximately 3-6 years for ENSO, 10-50 years for PDO) and are thought to be an underlying driver of inter-annual climate (Biondi et al., 2001; Dettinger et al., 2001). In the cool phases of ENSO (La Niña), drier than average conditions usually prevail in the southwestern United States. In the warm phases of PDO, dry conditions usually prevail in the Northwest. These inter-decadal processes have been linked to fire occurrence in both the northwestern Mexico (Stephens et al., 2003) and the Sierra Nevada (Taylor and Beaty, 2005). For this study, fire event dates were compared to an index of ENSO intensity (Stahle et al., 1998) and an index of PDO intensity (Biondi et al., 2001), both reconstructed back several centuries based on tree ring indices. For the El Niño Southern Oscillation Index (SOI), positive values indicate cool phase (La Niña) conditions, which are dry in the Southwest. For the Pacific Decadal Oscillation Index (PDOI), positive values indicate warm phase conditions, which correlate to dry conditions in the Northwest. Years of fire occurrence were compared to both SOI and PDOI as measures of inter-decadal modes of climate variation.

RESULTS

Sampling and Crossdating

Individual sample sites ranged from 0.3 to 2.0 ha in size (Table 1). Maximum distances between regionally grouped sites ranged from 1.5 to 8.0 km. Of the 144 individual trees, stumps, or logs sampled, 92 (64%) were examined in the laboratory for crossdating. The remaining samples were not useful due to their condition (excessive rot) or lack of fire scars. Of the samples examined, a total of 61 samples (66%) were reliably crossdated. 68% of dated samples were Jeffrey or ponderosa pine, while 20% were incense-cedar. The remaining dated samples were either sugar pine or Douglas-fir.

For all sites over the 548-year period from 1454 to 2001 A.D. (the earliest and latest dated tree rings, respectively) a total of 478 individual fire scars were dated to their year of formation. These scars corresponded to 113 years with fire in one or more of the sites. Recording trees was rare before 1729 in the Antelope Lake region, before 1750 for East Quincy, before 1655 for Frenchman Lake, and before 1706 for Portola Valley.

Suppression era fires (1905 onward) are absent in both the Portola Valley and Frenchman Lake regions, although sample sizes are small during that time period. Four fire events are recorded after 1905 in the East Quincy region, which might have been human ignited fires for sheep grazing, or slash fires from logging (Skinner and Chang, 1996). Over 50% of the Antelope Lake samples recorded a long fire-free interval after 1881, followed by a significant fire event in 1917.

Fire Chronologies and Fire Return Intervals

Fire occurrence was found to be frequent in the period of record for all sites (Figure 3, Tables 1 and 2). Mean point fire return intervals (PFI) for trees ranged from 9 to 28 years (Table 1). Individual tree-based site fire intervals (SFI) ranged from 8 to 23 years (Table 1). The mean composite fire return interval (CFI) for the 11 sites over the period of record ranged from 7 to 20 years with no filter, 8 to 22 years with a 10% filter, and 9 to 29 years with a 25% filter (Table 2).

Table 1: Site characteristics, point fire interval (PFI), and individual tree-based site fire interval (SFI) data for fire history sites in the Plumas National Forest, northern Sierra Nevada, California. PFI and SFI are calculated for the period of record. * Forest Type: MC = Sierran mixed conifer, EP = eastside pine.

Site	Number Samples	Approx. Area	Elevation	Aspect	Forest Type*	Period of Record	Mean PFI	SFI
Antelope Lake Group								
56-03	8	0.3 ha	5200	W	MC	1765-1995	18.9	16.7
56-04	6	0.3 ha	5500	NE	MC	1731-1995	27.5	22.6
56-08	4	0.8 ha	6000	NE	MC	1782-1917	16.4	16.1
56-10	3	0.3 ha	6100	SSW	MC	1729-1991	17.8	18.0
56-12	7	0.6 ha	5000	SE	MC	1685-1992	15.3	14.9
East Quincy Group								
56-02	13	2.0 ha	4480	W	MC	1624-2001	23.0	19.0
Frenchman Lake Group								
51-01	8	1.2 ha	5900	NW	EP	1629-1989	15.5	16.2
51-02	2	1.2 ha	6100	E	EP	1777-2001	19.4	12.7
Portola Valley Group								
51-25	3	0.4 ha	5000	E	EP	1706-1907	13.2	10.4
51-27	6	0.4 ha	5200	N	EP	1706-1906	8.5	7.9
51-29	4	0.4 ha	5900	E	EP	1734-1991	17.9	16.8

Table 2: Composite fire interval (CFI) data for the period of record from fire history sites in the Plumas National Forest, northern Sierra Nevada, California. "–" indicates instances where too few intervals remained after filtering to calculate interval statistics.

		No Filter				**10% Filter**				**25% Filter**			
Site	**Period**	**Inter-vals**	**Mean (**	**Med years**	**Range)**	**Inter-vals**	**Mean (**	**Med years**	**Range)**	**Inter-vals**	**Mean (**	**Med years**	**Range)**
Antelope Lake Group													
56-03	1765-1995	15	10.2	8.0	1-36	5	19.0	13.0	7-36	3	29.3	29.0	23-36
56-04	1731-1995	18	12.3	10.5	1-36	6	21.7	18.0	16-36	5	21.0	17.0	16-36
56-08	1782-1917	8	16.9	14.5	6-46	8	16.9	14.5	6-46	4	17.8	14.5	6-36
56-10	1729-1991	11	12.9	7.0	4-45	5	16.8	19.0	7-23	2	35.5	35.5	30-41
56-12	1685-1992	22	9.9	9.0	4-21	15	13.1	13.0	4-35	10	12.7	14.0	4-22
East Quincy Group													
56-02	1624-2001	30	11.4	7.0	1-53	14	12.0	11.0	1-29	8	12.5	10.0	4-29
Frenchman Lake Group													
51-01	1629-1989	29	8.8	8.0	1-22	14	16.3	15.0	5-33	10	15.9	11.0	5-63
51-02	1777-2001	11	10.2	9.0	5-23	0	-	-	-	0	-	-	-
Portola Valley Group													
51-25	1706-1907	18	9.5	7.0	5-20	5	13.6	11.0	7-24	0	-	-	-
51-27	1706-1906	29	6.6	6.0	1-17	17	7.7	7.0	4-14	14	9.4	7.5	4-19
51-29	1734-1991	18	8.7	8.0	1-19	9	13.7	12.0	4-33	0	-	-	-

Table 3: Composite fire interval (CFI) data for the pre-settlement era (1775-1849) from fire history sites in the Plumas National Forest, northern Sierra Nevada, California. "–" indicates instances where too few intervals remained after filtering to calculate interval statistics.

		No Filter				10% Filter				25% Filter			
Site	**Period**	**Inter-vals**	**Mean (**	**Med years**	**Range)**	**Inter-vals**	**Mean (**	**Med years**	**Range)**	**Inter-vals**	**Mean (**	**Med years**	**Range)**
Antelope Lake Group													
56-03	1775-1849	8	8.3	7.0	1-19	1	7.0	-	-	0	-	-	-
56-04	1775-1849	9	6.1	6.0	1-12	3	18.3	17.0	16-22	2	16.5	16.5	16-17
56-08	1775-1849	4	14.8	15.0	7-22	4	14.8	15.0	7-22	1	22.0	-	-
56-10	1775-1849	6	11.2	9.5	6-22	4	15.3	16.0	7-22	1	41.0	-	-
56-12	1775-1849	8	8.8	8.5	6-14	6	11.7	11.0	8-17	5	14.0	14.0	8-22
East Quincy Group													
56-02	1775-1849	11	6.4	6.0	1-17	7	8.9	7.0	1-17	5	10.4	7.0	4-17
Frenchman Lake Group													
51-01	1775-1849	9	7.7	8.0	5-10	6	8.7	7.5	5-17	6	8.7	7.5	5-17
51-02	1775-1849	8	8.6	8.0	5-16	0	-	-	-	0	-	-	-
Portola Valley Group													
51-25	1775-1849	9	7.1	6.0	5-11	4	13.0	10.5	7-24	0	-	-	-
51-27	1775-1849	14	5.0	5.0	1-9	10	6.1	6.0	4-8	8	7.6	6.0	4-15
51-29	1775-1849	11	6.4	6.0	1-12	5	12.2	6.0	4-33	0	-	-	-

Table 4: Composite fire interval (CFI) data for the post-settlement era (1850-1904) from fire history sites in the Plumas National Forest, northern Sierra Nevada, California. "–" indicates instances where too few intervals remained after filtering to calculate interval statistics.

		No Filter				10% Filter				25% Filter			
Site	**Period**	**Inter-vals**	**Mean (**	**Med years**	**Range)**	**Inter-vals**	**Mean (**	**Med years**	**Range)**	**Inter-vals**	**Mean (**	**Med years**	**Range)**
Antelope Lake Group													
56-03	1850-1904	3	7.7	8.0	5-10	2	11.5	11.5	10-13	1	23.0	-	-
56-04	1850-1904	2	11.5	11.5	6-17	1	17.0	-	-	1	17.0	-	-
56-08	1850-1904	2	6.5	6.5	6-7	2	6.5	6.5	6-7	2	6.5	6.5	6-7
56-10	1850-1904	2	9.5	9.5	6-13	0	-	-	-	0	-	-	-
56-12	1850-1904	5	9.6	8.0	4-14	4	12.0	14.0	4-16	4	12.0	14.0	4-16
East Quincy Group													
56-02	1850-1904	4	12.3	7.5	5-29	2	17.5	17.5	6-29	2	17.5	17.5	6-29
Frenchman Lake Group													
51-01	1850-1904	2	13.5	13.5	5-22	1	22.0	-	-	0	-	-	-
51-02	1850-1904	2	16.5	16.5	10-23	0	-	-	-	0	-	-	-
Portola Valley Group													
51-25	1850-1904	2	10.5	10.5	7-14	0	-	-	-	0	-	-	-
51-27	1850-1904	3	13.7	15.0	9-17	0	-	-	-	0	-	-	-
51-29	1850-1904	3	11.3	9.0	6-19	1	15.0	-	-	0	-	-	-

Mean CFI during the pre-settlement era, which had the best sample depth for all sites, ranged from 5-15 years with no filter, 6-18 years with a 10% filter, and 8-22 years with a 25% filter (Table 3). Mean CFI during the post-settlement era ranged from 7-17 years without a filter, 7-22 years with a 10% filter, and 7-23 years with a 25% filter (Table 4), though several site chronologies had few intervals in this period after the filtering process. CFI generally lengthened with higher percentages of filtering, suggesting that widespread or more severe fires were less frequent. For each site, CFI calculated for the pre- and post-settlement eras were generally shorter than when calculated over the entire period of record. This could have been due to shallow sample depth in the early and late parts of the fire record.

ANOVA and multiple comparison testing for CFIs calculated without filters over the period of record indicated that site 51-27 (Portola Valley - eastside pine) had a significantly shorter fire interval than sites 56-8 and 56-12 (Antelope Lake – mixed conifer), with the rest of the sites falling in between, but not belonging to either group statistically. When fires were filtered at 10%, site 51-27 was significantly shorter than site 56-04 (Antelope Lake – mixed conifer), with the rest of the sites falling in between. When filtered at 25%, there was no significant difference between the sites. Two sample tests performed on site CFIs without filtering detected a significant difference between the pre-settlement and post-settlement periods at only one site (51-27, Portola Valley, eastside pine). At other filtering levels, most sites lacked enough intervals in the post-settlement period to test for temporal differences.

Seasonality

The intra-annual position of the fire scar within the growth ring was determined for 89.3% of the scars dated (427 of 478). Of these, 52.5% (224) were formed at the ring boundary (dormant season), 31.1% were formed in the latewood ring growth, 15.0% (64) were formed in the late earlywood, with the remainder (1.4%) forming in middle earlywood, suggesting that most fires occurred in late summer (during latewood formation) or fall (after cessation of growth) (Figure 5). Eleven samples in the Antelope Lake group showed a scar on the ring boundary between 1917 and 1918, which could have corresponded to a fire recorded in the PNF fire atlas as occurring on that site in 1918. One tree in the same group showed an earlywood scar in 1918. However, since it is generally accepted that ring boundary scars in the Sierra Nevada are associated with late season (fall) fires, these ring boundary scars were dated as 1917.

Fire-Climate Relationships

Fire was found to have significant relationships to climate on both inter-annual and inter-decadal time scales (Figure 6). When compared to PDSI at grid point 13 (eastern Sierra), fire years from composite chronologies were found to be significantly dry ($p < 0.05$) in all regional groups at one or more of the filtering levels. When a single composite fire chronology from all regional groups (25% filter) was compared to PDSI grid point 13, fire years were found to be significantly dry ($p < 0.05$, Figure 6). When compared to PDSI at grid point 6 (western Sierra), fire years were significantly dry ($p < 0.05$) for all groups except Portola Valley at one or more filtering level.

For a single composite fire chronology created from all regional groups (25% filter), fire years were found to be significantly dry ($p < 0.05$) when compared to PDSI grid point 6. Significantly wet years were noted 1-4 years prior to fire years in some groups, but no consistent pattern was noted.

Fire years were also found to coincide with years of significantly high levels of salinity in the San Francisco Bay (Figure 6). For all sample groups at all filtering levels, salinity was found to be significantly higher than mean conditions ($p < 0.05$) during fire years, suggesting that drought conditions prevailed. Salinity was found to be low (wet conditions) 1-3 years prior to drought in some instances, but not consistently so. Fire years from a single composite of all groups filtered at 25% were found to correspond significantly with high salinity levels or drought conditions ($p < 0.001$, Figure 6).

When compared to the Pacific Decadal Oscillation Index, fires years (25% filter) occurred during the transition between warm and cool phases of the PDO (Figure 6). This was evidenced by a trend in all regional groups of positive (warm phase) values of PDOI at least two years prior to fire years (t-2), decreasing to negative values of PDOI at least one year after fire years (t+1). The t-2 year was significantly high (positive) at Antelope Lake and Portola Valley. The t+1 year was significantly low (negative) for the Antelope Lake, Frenchman Lake, and Portola Valley groups. The t+2 year was also significantly low for Antelope Lake. When a single composite of fire years from all regional groups (25% filter) was compared to PDO, the t-2 year was high (but not significantly so) indicating warm phase conditions, and the t+1 year was significantly low, indicating cool phase conditions (Figure 6). A similar trend was seen when comparing fire years to the Southern Oscillation Index. When all regional groups were combined and fire years filtered at 25%, SOI in the t-2 year was significantly low (negative) indicating warm phase (El Niño) conditions. The t+1 year was high (positive) indicating cool phase (La Niña) conditions, but not significantly so (Figure 6).

DISCUSSION

Fire Chronologies

The relatively frequent occurrence of fire in the PNF (median CFI of 7-19 years for sites when filtered at 10%, Table 2) indicates that fire was an important ecosystem process in these forests. Median fire return intervals for the mixed conifer sites were similar to those reported in Skinner and Chang's (1996) survey of fire history studies in the Sierra Nevada, although they did not report whether statistics were derived with filters. They cite median fire intervals of 8-11 years in southern Sierra ponderosa pine-mixed conifer forests (<2 ha sample areas, composite intervals), 12-17 years in Klamath Mountain Douglas-fir-mixed conifer forests (<2 ha sample areas, composite intervals), and 8-18 years in Southern Cascade and Sierra Nevada mixed conifer forest types (<2 ha sample areas, composite intervals). Stephens and Collins (2004) derived median fire return intervals of 6-14 years for sites larger than ours (3-5 ha, 10% composite filter) in mixed conifer forests of the north-central Sierra Nevada. Fry and Stephens (2006) derived median intervals of 5-15 years (1.6 ha sites, 10% filter, composite intervals) for ponderosa pine-mixed conifer forests in the southeastern Klamath Mountains.

Skinner and Chang (1996) cite median intervals for eastside ponderosa pine and mixed conifer forests of 9-16 years (<10 ha, composite intervals). Median fire intervals for eastside pine sites in the PNF (Frenchman Lake and Portola Valley groups) were generally longer than those reported by Taylor and Beaty (2005), but their statistics were derived on the watershed scale. Stephens (2001) derived similar values to those listed here (median fire interval 9.0 years, 2 ha plots, composite intervals) for an eastside Jeffrey pine stand near Mammoth Lakes, California, based on 14 crossdated fire scar samples.

Figure 5: Fire scar season of formation for grouped fire history sites in the Plumas National Forest, northern Sierra Nevada, California**.**

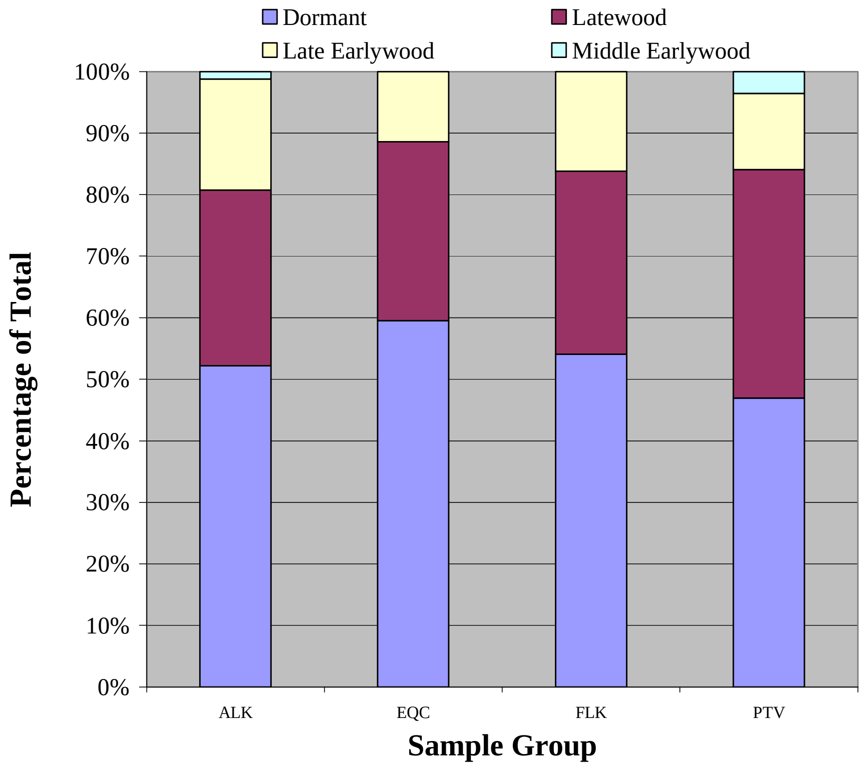
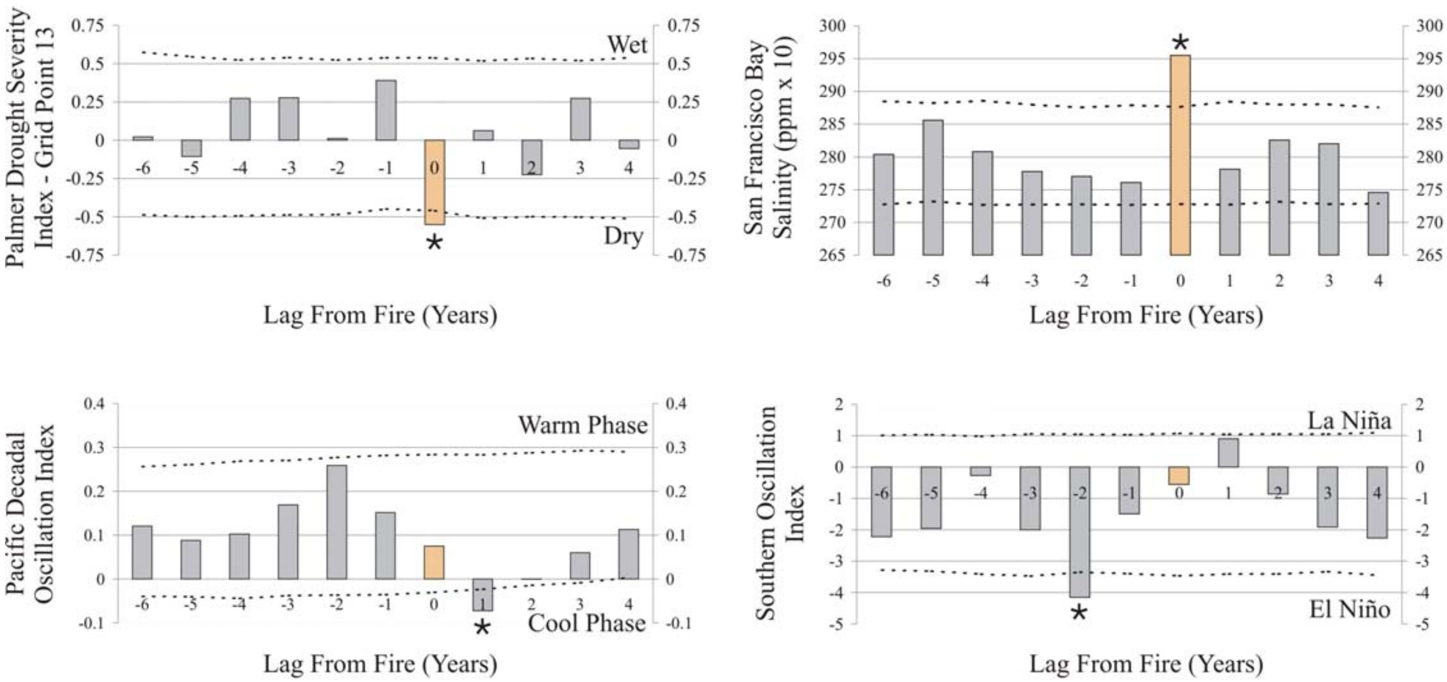


Figure 6: Superposed epoch analysis of climate indices and composite fire chronology of all fire history sites in the Plumas National Forest (filtered at 25% to examine widespread or severe fire events). Vertical bars indicate mean index values at or around fire events. Dashed horizontal lines are bootstrapped 95% confidence intervals. * indicates a significant departure from mean conditions ($p<0.05$).



We were able to show that one of the eastside pine sample sites (Portola Valley) had a shorter composite fire interval over the period of record than at least one of the mixed conifer sites (Antelope Lake) when fire chronologies were either complete or filtered at 10%, lending evidence to our hypothesis that the eastside pine sites are more prone to fire than nearby mixed conifer sites. However eight of the remaining sites could not be statistically associated with either of these two groups (shorter and longer intervals) at any filtering level. It is possible that greater sample depth for the sites could differentiate these groups further. The fact that mean composite fire intervals were statistically equivalent for all groups over the period of record when filtered at 25% could suggest that the frequency of more widespread or severe fires is similar for both forest types.

Although our composite fire histories only allow us to draw implicit conclusions about the spatial patterns of fire, the evidence presented here combined with contemporary records of fire for the 20th century suggest that even when smaller or less severe fires are filtered out (e.g. 25% composite filters), the PNF has experienced much more frequent and widespread burning in the past than it does today. While the extent of fuels management programs are on the rise in the forms of both prescribed burning and mechanical treatments, financial, institutional, social, and political limitations may preclude even the most ambitious of fire managers from restoring fire to the landscape at frequencies and extents experienced before the Euro-American settlement or fire suppression eras. Definitions of desired future conditions will have to take into account both our understanding of fire history for the PNF, as well as our operational limitations.

In terms of methodology, this study highlights both the benefits and the limitations of tree-ring based fire history reconstructions, particularly in areas where fire scarred materials are limited to dead and downed trees. While we were able to develop several reasonably robust composite fire chronologies, sample depth was limited for the entire record at some sites, and in the early and late parts of the record for all sites, especially at Frenchman Lake and Portola Valley. Additionally, the time periods in which sample depth was the greatest varied by site, which made comparison between sites difficult. The pre-settlement period (1775 to 1849) had the best overall sample depth for all sites, and likely the most complete record of fire, which is beneficial as it provides information for fire regime characteristics before Euro-American settlement. However the varying distances between sample sites in each regional group precluded us from making comparisons over larger spatial areas (e.g. between regional groups). Greater sample depth from continuous, similar sized sampling sites would provide stronger evidence for fire regime parameters. As remnant materials naturally decay, fire history information is lost. For regions such as the PNF, where live fire-scarred specimens may be scarce, it is important to preserve as much information as possible through studies such as this one.

Fire Seasonality

The dominance of fire scars formed in the late season (in the latewood and at the ring boundary) in the PNF coincides with a general trend of increasing proportions of early/growing season scars (earlywood) the farther south one goes in the Sierra Nevada (Stephens and Collins, 2004). A similar latitudinal gradient was found in the Blue Mountains of Oregon and Washington by Heyerdahl et al. (2001), although fire seasonality for the PNF may not be definitively attributed to latitude. Taylor (2000) found more early season fires in lower elevations than higher in nearby Lassen National Park, suggesting that elevational gradients may play a role in fire seasonality. Phenology data from Lassen National Park indicate that Jeffrey pine in this region begins growth around mid-May and cease in late August (Taylor, 2000). Thus the fire scar data examined here suggest that the majority of fires in the PNF likely occurred between August and the beginning of the wet season, which in the Sierra Nevada coincides with conditions that favor both fire ignition and fire spread.

Fire Climate Interactions

Fire in this portion of the northern Sierra Nevada is influenced by climatic conditions on both inter-annual and inter-decadal time scales. The strong relationship between fire years and indices of drought suggest that climatic conditions for a given year were a significant driver of fire. The Palmer Drought Severity index values are a function of precipitation, air temperature, and soil moisture. Drought years in this index would thus correspond to highly favorable fire conditions with respect to both fuels and weather. Conditions such as low fuel moistures, high air temperatures, and low relative humidity, all of which favor fire, would be found in PDSI-derived drought years. Comparisons with the San Francisco Bay Salinity Index also highlight this relationship, with fire years strongly correlated to high levels of salinity (drought).

Climate conditions one to four years prior to fires were significantly wet in some instances, but not consistently so across all regions in the study. Wet antecedent conditions have been shown to strongly influence fire in the Southwest US by causing an increase in vegetation and fine fuel production (Swetnam and Betancourt, 1998). Similar relationships were found at Antelope Lake, Frenchman Lake, and East Quincy. However the inconsistency of these relationships suggests that antecedent conditions have less of an influence on fire occurrence in the northern Sierra Nevada when compared to forests in the Southwest US.

Fire in this area is influenced by switches from warm to cool phases of the Pacific Decadal Oscillation (PDO), and from warm (El Niño) to cool (La Niña) phases of the El Niño Southern Oscillation (ENSO) (Figure 6). Warm phases of both PDO and ENSO are characterized by equatorward diversions of low-pressure systems, resulting in dry conditions in the Pacific Northwest US, and wet conditions in the Southwest US. Shifts to cool phases bring the reverse conditions. As dry conditions shift from the Pacific Northwest to the Southwest (warm to cool phase PDO, or El Niño to La Niña) fire becomes more prevalent in the PNF.

Variations in PDO are most clearly expressed in the climate of the northern Pacific basin, while ENSO variations have their most profound effect in the tropics and in southwestern North America (Dettinger et al., 2001). However, the significant relationship between fire years in the PNF and phase changes in these two atmospheric processes suggests that the PNF may be uniquely positioned between the two regions so as to be affected by both. It is interesting to note that both the PDO and the ENSO experienced significant weakening of amplitude during the late eighteenth and early nineteenth centuries, the period in which our fire record is the best (Biondi, 2001, Stephens et al., 2003). A more complete record of fire for the seventeenth century or earlier might elucidate these fire-climate relationships further, although deterioration of fire-scarred remnant wood samples in the PNF would make this a difficult prospect. The interactions between PDO and ENSO on the timing and extent of fire in the PNF needs further study.

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