Research Article

Human and Climatic Influences on Fire Occurrence in California's North Coast Range, USA

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ABSTRACT

Outside of the immediate coastal environments, little is known of fire history in the North Coast Range of California. Fire scar specimens were collected from ponderosa pine (*Pinus ponderosa* C. Lawson), sugar pine (*Pinus lambertiana* Douglas), incense cedar (*Calocedrus decurrens* [Torr] Florin), and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) for seven plots in mixed-conifer forests from the Mendocino National Forest, California, USA. Five plots were on high ridges immediately adjacent to the Sacramento Valley (DRY plots). The other two plots were on mesic north facing slopes interior in the range (MESIC plots), and were separated from the Sacramento Valley by at least one to several ridge systems. These two plots were selected because they supported populations of rare lady's slipper orchids (*Cypripedium fasciculatum* [Kellogg ex S. Watson] and *C. montanum* [Douglas ex Lindl.]). We found that DRY plots had unusually short fire return intervals (FRI) compared to other areas in northwestern California. The median FRI for these plots ranged from 4.5 yr to 6 yr in comparison with a tenth percentile of 11 yr, grand median of 24 yr, and ninetieth percentile of 66 yr for FRIs from other mixed conifer plots (n = 109) in the region. In northwestern California, most fire scars have been found primarily at ring boundary (68 %) and secondarily in latewood (23 %) with few in earlywood (9 %). In contrast, in the DRY plots 35 % (88) of the fire scars were in earlywood with only 15 % (39) at the ring boundary. Fire occurrence was associated with drought conditions in the year of fire, and with wet conditions three years before the fire year. Before ~1850, fires that scarred at least two trees on a site were quite frequent for the DRY plots while being less frequent and more variable on the MESIC plots. However, the MESIC orchid habitats burned with frequency and seasonality similar to mixed conifer forests in the Klamath Mountains of northern California. Fires were less frequent after ~1850, with fires ceasing on most plots shortly after 1900. We suggest that these unusually low FRIs and high incidence of fire scars in earlywood were due to the adjacency of the DRY plots to the hot, relatively dry Sacramento Valley grasslands that were likely influenced by the burning practices of Native Americans.

Keywords: *Cypripedium,* dendrochronology, fire history, fire scars, lady's slipper orchid, Mendocino National Forest, Native Americans, Sacramento Valley

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INTRODUCTION

Fire regimes vary over space and time in response to climatic variation, local environment, and anthropogenic land use practices (Taylor and Skinner 1998, Heyerdahl *et al.* 2001, Taylor and Skinner 2003, Whitlock *et al.* 2003, Anderson 2006). This variation in fire regimes has been shown to be an important factor contributing to biodiversity (Martin and Sapsis 1992, Agee 1993, Reice 1994, Gill *et al.* 1999). However, the role of fire in ecosystem dynamics changed considerably over the twentieth century with the onset of fire suppression and other intensive management activities (Agee and Skinner 2005). Understanding how fire regimes (seasonal timing, frequency, return interval, severity) varied spatially and temporally is essential for understanding the long-term dynamics of forests (Skinner and Chang 1996). Better information on the range of fire regime attributes in pre-fire suppression forests is important to help managers evaluate the ecological implications of proposed forest management strategies, including those aimed at reducing the risk of high severity fire.

Outside of a narrow geographic band of environments in relatively close proximity to the coast, little is known about pre-1900 fire regimes in the North Coast Range of California (Viers 1980, Rice 1985, Stuart 1987, Finney and Martin 1989, Finney and Martin 1992, Brown and Swetnam 1994, Brown *et al.* 1999, Stuart and Salazar 2000, Brown and Baxter 2003). Most of the existing studies were focused on fire regimes of redwood (*Sequoia sempervirens* [Lamb. ex D. Don] Endl.) forests that are associated with the coastal fog belt (Stuart and Stephens 2006). The fire regimes of more inland conifer forests of the North Coast Range have not been well studied (Stephens *et al.* 2007).

Limited knowledge of fire regimes and their variations can lead to competing resource concerns that make fire and resource management problematic (Agee 1999, Stephens and Ruth 2005). An example is the presence of endangered or rare species in many forests. Their presence often leads to adoption of single-species, fine-filter approaches to management (Stephens and Ruth 2005); whereas fire operates more broadly as a coarse filter (Agee 1999).

Rare lady's slipper orchid species (*Cypripedium fasciculatum* [Kellogg ex S. Watson] and *C. montanum* [Douglas ex Lindl.]) are present in the mixed conifer forests of the North Coast Range, and because they are rhizomatous perennials with short, shallow rootstocks and are considered fire intolerant (Harrod *et al*. 1997), the lack of information on their prehistoric fire regimes has restricted management options. In the North Coast Range, these orchids undoubtedly experienced the same fire regimes as the forests that they were found in. They also experienced the same fire regime changes resulting from the policy of suppression implemented early in the twentieth century. Information on prehistoric fire frequency and seasonality would help land managers develop management plans for landscapes that include these species.

The North Coast Range has strong climatic gradients of temperature and precipitation controlled primarily by distance to the coast and elevation, and secondarily by complex topography (Stuart and Stephens 2006). Variation of fire regimes in the Klamath Mountains to the north and the Cascade Range to the east has been found to be associated with similar gradients (Skinner and Taylor 2006, Skinner *et al.* 2006). It is likely that historical fire frequency increased as one moved along the precipitation/temperature gradient from west to east. Thus, it is unlikely that the available fire history studies would provide satisfactory descriptions of fire regime characteristics for the drier forested areas characteristic of much of the North Coast Range.

Fire occurrence in inland forests of northern California has been found to be strongly synchronous and largely associated with drought (Taylor *et al.* 2008). Describing conditions that set up the droughts that synchronize fire activity would help managers to better plan fire management activities and resources needed for fire suppression and prescribed fire programs (Corringham *et al.* 2008). Along the Pacific coast, inter-annual climatic variation has been associated with variation in sea surface temperature (SST) in the tropical Pacific Ocean (El Niño–Southern Oscillation [ENSO]) (Diaz and Markgraf 2000) and in the northern Pacific (Pacific Decadal Oscillation [PDO]) (Dettinger *et al.* 2000). However, these associations are strongest for the Pacific northwest (Hessl *et al,* 2004) and the American southwest (Swetnam and Betancourt 1990), though in opposite directions. Warm phases of the ENSO and PDO are associated with wet conditions in the southwest and dry conditions in the Pacific northwest, and the opposite during cool phases (Kitzberger *et al.* 2007). Additionally, when the two indices are in phase, they tend to enhance the effects of each other and moderate their effects when out of phase (Gershunov *et al.* 1999; Biondi *et al.* 2001).

The North Coast Range is in the vicinity of the pivot zone of the ENSO-PDO precipitation dipole that is located at approximately 40° to 45° N and that shifts north or south on inter-annual and decadal time scales (Dettinger *et al*. 1998). Thus, inter-annual and inter-decadal fire-climate associations in this area may vary at different periods of time from being similar to those in the Pacific northwest to being similar to those in the southwest (Westerling and Swetnam 2003, Taylor and Beaty 2005), and to being totally lacking in other periods (Fry and Stephens 2006, Taylor *et al.* 2008). No significant fire-SST associations have been found in the Klamath Mountains immediately north of the study area, thus none have been reported in previous studies such as Taylor and Skinner (2003) and Fry and Stephens (2006).

The Pacific-North American Pattern (PNA) of atmospheric high pressure ridges and low pressure troughs (Wallace and Gutzler 1981) has been found to influence inter-annual variability of precipitation in the Pacific northwest (Sheridan 2003) and the area of the ENSO-PDO precipitation dipole (Trouet and Taylor 2009). A strong winter high pressure ridge that blocks precipitation into the area is characteristic of a positive PNA (pPNA), while wet winters are characteristic of reverse conditions (rPNA) (Leathers *et al.* 1992, Sheridan 2003). In northern California, inter-annual variability in area burned over the twentieth century (Trouet *et al.* 2006), as well as two fire danger rating indices—the Haines Index (Haines 1988, Werth and Werth 1998) and the energy release component of the National Fire Danger Rating System (Bradshaw *et al.* 1983)—have been found to be associated with positive phases of the PNA (Trouet and Taylor 2009). Thus, the condition of the PNA may contribute to our understanding of climatic mechanisms that contribute to drought and associated fire activity.

Changes in the cultural uses of fire may also influence fire occurrence patterns. Before the late 1800s, the Native Americans of California commonly used fire to manage many resources including the grasslands and oak woodlands of the Sacramento Valley (Lewis 1993, Anderson 2006). Changes in fire regimes have been noted elsewhere that are coincident with Euro-American settlement and the associated disruption of native cultures (Savage and Swetnam 1990, Stephens *et al.* 2003, Norman and Taylor 2005). In the Klamath Mountains adjacent to the north end of the Sacramento Valley, Fry and Stephens (2006) found that fire became less frequent but more extensive after about 1850 before ceasing with the initiation of fire suppression early in the twentieth century. They noted that the change coincided with the influx of non-native people during the gold rush. However, to confidently identify driving factors that generated changes in past fire regimes, it is important to distinguish the possible influences of climate from the influences of cultural practices.

The primary goal of this paper was to remedy the lack of fire history information for the mixed conifer forests of the North Coast Range. Additionally, we wanted to answer the following questions: 1) How did fire occurrence on drier sites farthest from the coast adjacent to the Sacramento Valley (DRY plots) differ from more mesic sites interior to the range between the coast and the valley (MESIC plots)? 2) Were there years when widespread fire activity was recorded across the plots? 3) If so, were these years of widespread fire activity associated with drought and specific conditions of ENSO, PDO, or PNA? And 4) How did patterns of fire activity change with Euro-American settlement?

METHODS

Study Area

The data were collected in the Mendocino National Forest in California's North Coast Range that includes the Northern California Coast Ranges ecological sections M261B and the Northern California Interior Coast Ranges M261C of Miles and Goudey (1997). The climate is Mediterranean with cool, wet winters, and warm, dry summers with over 90 % of the precipitation falling between October and April. Strong climatic gradients characterize the precipitation and temperature patterns of the North Coast Range: 1) precipitation increases and temperature decreases with altitude, 2) summer temperatures increase from west to east (Stuart and Stephens 2006), and 3) because most precipitation is from frontal systems moving in from the Pacific Ocean, there is a dramatic decline in precipitation on the eastern edge of the range where it drops into the Sacramento Valley due to a rain-shadow effect. Average temperatures at Covelo (436 m), in the west, range from 5.2 °C in January to 22.6 °C in July, while in the east at Stony Gorge Reservoir (244 m), these same monthly temperatures range from 6.6 °C to 25.9 °C, respectively. Annual precipitation averages 105.7 cm at Covelo and 51.5 cm at Stony Gorge Reservoir (WRCC 2009).

Forests are of the mixed-conifer type and are comprised of various combinations of the conifers Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), ponderosa pine (*Pinus ponderosa* C. Lawson), sugar pine (*P. lambertiana* Douglas), white fir (*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.), and incense cedar (*Calocedrus decurrens* [Torr.] Florin), along with the hardwoods California black oak (*Quercus kelloggii* Newberry) and canyon live oak (*Q. chrysolepis* Liebm.). Although the arboreal vegetation is similar across sites, ponderosa pine plays a more dominant role in the

DRY plots, whereas Douglas-fir and sugar pine are more prominent on the MESIC plots.

Three Native American cultural groups occupied portions of the study area in the early 1800s: Yuki, Nomlaki, and Patwin (Heizer and Whipple 1971, Anderson 2005). The MESIC plots were in the cultural area of the Yuki. The DRY plots were in the cultural area of the Nomlaki and transitional to the Patwin, which were both of the Wintun language group (Heizer and Whipple 1971). All three cultural groups are known to have commonly used fire for a variety of purposes: for example, to maintain grasslands for better grain crops, improve bulb crops, and for collection of grasshoppers (Stewart 2002, Anderson 2005).

Data Collection

The fire scar samples used here were collected from mixed conifer forest stands on a total of seven plots that each covered about 2 ha on the Mendocino National Forest (Figure 1, Table 1). These data were originally collected for two separate studies with different purposes. One study was focused on the fire history of two mesic plots supporting populations of the two rare orchids. The lady's slipper orchids (Figure 2) are rare plants associated with mesic sites. The local ranger district had a particular interest in understanding their long-term relationships to fire. The other five plots were drier and part of a larger study to better understand fire-climate relationships

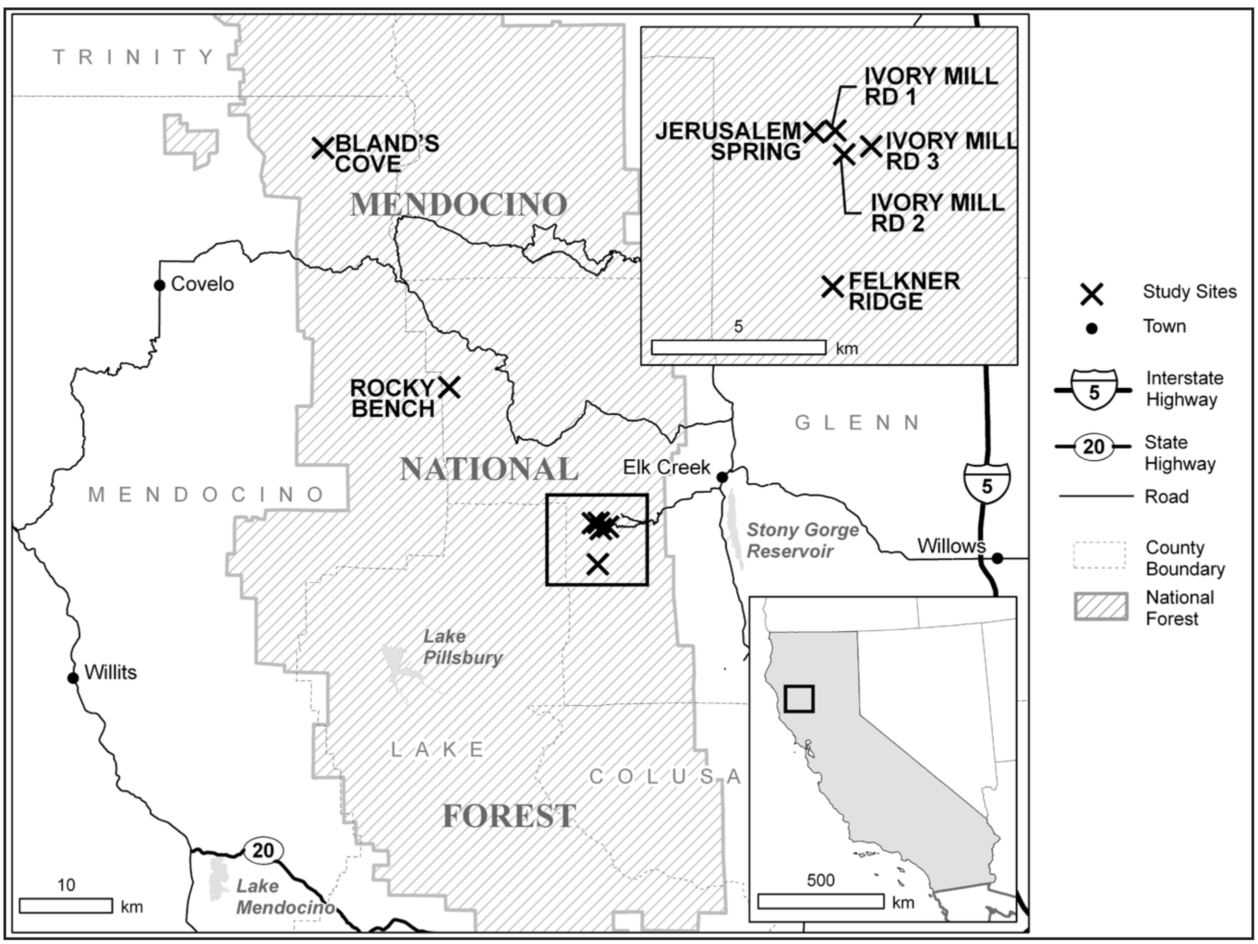

Figure 1. Vicinity map showing approximate locations of the sample plots on the Mendocino National Forest within the North Coast Range of California.

Table 1. Type of site (MESIC or DRY) and location for each sampling location.

Site	Site type	Elevation (m)	Latitude	Longitude
Bland's Cove	MESIC	1295	39.9276	-123.042
Rocky Bench	MESIC	1218	39.6943	-122.883
Felkner Ridge	DRY	1630	39.5214	-122.696
Ivory Mill Rd 1	DRY	1290	39.5618	-122.695
Ivory Mill Rd 2	DRY	1362	39.5556	-122.692
Ivory Mill Rd 3	DRY	1205	39.5577	-122.683
Jerusalem Spring	DRY	1416	39.5614	-122.702

Figure 2. Photo showing *Cypripedium fasciculatum* in the Rocky Bench MESIC sampling site in the North Coast Range study area. Photo by David Isle.

along the latitudinal range of the Pacific Coast Mediterranean climate area. The five DRY plots were located on ridge tops or the upper one third of east facing slopes adjacent to the Sacramento Valley. Distances between these plots range from 0.7 km to 3.7 km. The two MESIC plots were located northwest of the DRY plots in the interior of the North Coast Range on north facing slopes at mid- to lower slope positions. The distance between the closest MESIC and DRY site was 21 km. The two mesic plots were 29 km apart with a river in between.

The DRY plots were chosen in upper slope positions on the eastern edge of the North Coast Range because we expected this area to be sensitive to climatic variation due to its location on the precipitation-temperature gradient and its topographic position. We subjectively selected the DRY plots after conducting an extensive reconnaissance of the area to locate sites with adequate remnant fire-scarred wood to reconstruct fire history. This was necessary because the Mendocino National Forest records indicated that most of the older trees had been logged many decades earlier and the evidence in this part of the forest had burned away in subsequent fires, or was badly decomposed and unusable (Figure 3).

Sampling was designed to acquire a continuous record of fire over as long a time period as possible on each site. We systematically located fire-scarred specimens, examining each live tree, stump, log, and snag observed to contain fire scars. We then collected samples from specimens with the greatest numbers of well-preserved fire scars distributed as broadly as possible across each site (Swetnam and Baisan 2003, Van Horne and Fulé 2006). Although all fires on a site may not have created scars, the sampling pattern allowed us to distinguish years of little or no fire activity from those of more extensive fire activity (Taylor and Skinner 2003, Taylor and Beaty 2005, Van Horne and Fulé 2006).

Each wedge or cross-section with fire scars was sanded to a high polish and then cross-dated with a local tree-ring chronology (White 1994) obtained from the International Tree-Ring Data Bank (Grissino-Mayer and Fritts 1997) using standard dendrochronological

Figure 3. Photos showing typical condition of the fire scarred material. Left photo shows Alan Taylor assessing a scarred stump. Right photo shows nature of material after being cut for removal. Photos by C. Skinner.

techniques (Stokes and Smiley 1968, Swetnam *et al*. 1985). Specimens were visually cross-dated after using the program COFECHA to suggest ring dates from statistically evaluating the time series from measured annual rings (Grissino-Mayer 2001*a*). Only cross-dated samples were used to identify fire scar dates.

Data Analysis

The FHX2 software was used to analyze fire-scar data (Grissino-Mayer 2001*b*). To investigate the extent of annual fire activity, we determined the year and number of fires that burned in ≥1 plot and ≥2 plots for fires scarring at least one tree per site and for fires scarring ≥2 two trees per site. We grouped plots by whether they were MESIC plots or DRY plots and then compared FRIs between the groups using the distribution-free Mann-Whitney test (Sprent 1993).

To evaluate widespread versus localized fire activity, we compared synchrony of fire scars among the plots. For this purpose, four of the five DRY plots were grouped into a single group since they were located in a landscape context in which fires could spread between them. This gave us two MESIC plots and two DRY groups for comparison. Fire activity was considered synchronous within groups and across the study area if the following criteria were met: 1) synchrony in MESIC plots occurred when both MESIC plots had fire scars in the same year, 2) synchrony in DRY plots occurred when both DRY groups had fire scars in the same year, and 3) synchrony across the study occurred when one of the DRY groups and one of the MESIC plots had fire scars in the same year.

The season of occurrence for each fire was estimated from the intra-ring position of each scar, noted as EE (early earlywood), ME (middle earlywood), LE (late earlywood), LW (latewood), D (dormant or ring boundary), or U (undetermined) (Caprio and Swetnam 1995). At this latitude in the North American Mediterranean climate region, earlywood scars are usually classified as fires burning in spring and early summer, latewood scars are classified as fires burning in mid- to late summer, while ring boundary scars are logically classified as fires burning in the late summer or fall after tree growth had ceased for the year (Beaty and Taylor 2001, Skinner 2002, Stephens and Collins 2004). However, there are no specific published data relating ring position to phenology for the species used in this study in this geographical region. We are relying on phenological data on growth of trees in the Sierra Nevada (Fowells 1941, Royce and Barbour 2001).

Superposed epoch analysis (SEA) was used to examine the association between fire occurrence and each of four proxy climate indices (Baisan and Swetnam 1995, Grissino-Mayer and Swetnam 2000): NINO3 as an index of ENSO (Cook 2000), an index of the Pacific Decadal Oscillation (PDO) (D'Arrigo *et al.* 2001), a reconstruction of the Palmer Drought Severity Index (PDSI) (Grid point 35; Cook and Krusic 2004), and an index of the Pacific-North American Pattern (PNA) (Trouet and Taylor 2009). For these analyses, we used years in which fires scarred trees on at least one DRY site and one MESIC site.

To assess the potential combined influence of PDO and ENSO on the fire regime, we normalized the values of PDO and NINO3 around zero and then added the resulting annual values together (PDO + NINO3). When these indices are combined in this way, the higher and lower absolute values are higher and lower during constructive and destructive interference between PDO and ENSO, respectively (Biondi *et al.* 2001, Mote *et al.* 2003, Yu and Zwiers 2007).

The climate indices were not white noise and had to be whitened before use in SEA. Pre-whitening was accomplished using the ARIMA procedure in MINITAB Release 13.32 (Minitab, State College, Pennsylvania, USA). Significant climate departures associated with fire and non-fire years ($P \leq 0.05$) were identified by bootstrapping (1000 trials) using the software FHEVENT.EXE (version 1993-1.08) (Grissino-Mayer 2001*b*).

RESULTS

Fire Frequency and Occurrence

We collected fire-scarred specimens from 76 trees (37 ponderosa pine, 21 incense cedar, 10 Douglas-fir, 8 sugar pine). Specimens from 68 trees (31 ponderosa pine, 20 incense cedar, 9 Douglas-fir, 8 sugar pine) were cross-dated and yielded 521 dated fire scars. Trees that could not be cross-dated were primarily trees with very tight ring series containing numerous missing rings, or segments from remnants with too few rings (generally <100 rings) to be confident of cross-dating with the master chronology. The earliest recorded fire date was 1374 on Felkner Ridge, and the latest scar date was 1973 at Jerusalem Spring (Table 2). Because the number of samples and records of fires declines rapidly before 1700, and fires ceased to be common in the twentieth century, we focused our analyses of the fire regime to the period from 1700 to 1900 (Figure 4).

Fires were found to have been frequent on all sites in the 1700 to 1900 period, although there appears to be a change in fire occurrence pattern after around 1850. After 1850, fires became somewhat less frequent but remained synchronous on the DRY plots (Figure 4).

Table 2. Fire scar characteristics for the seven collection plots on the Mendocino National Forest. Intervals are for the fires during the period of 1700 to 1900.

				Intervals for all scars				Intervals for ≥ 2 scars for site			
Site	Samples	Earliest scar	Last scar	Median	Mean	Min	Max	Median	Mean	Min	Max
MESIC Bland's Cove	7	1664	1929	8	11.0	2	56	12	17.5	5	38
MESIC Rocky Bench	14	1510	1949	5.5	11.9	2	65	10	13.8	3	33
DRY Felkner Ridge	13	1374	1901	4	8.9	1	15	7	8.3	3	49
DRY Ivory Mill Rd 1*	9	1716	1918	4	5.5	1	16	4.5	5.3	2	12
DRY Ivory Mill Rd 2*	3	1590	1856	6	12.1	3	16	6	6.5	4	11
DRY Ivory Mill Rd 3*	5	1748	1892	4	7.2	2	36	5	10.5	3	36
DRY Jerusalem Spring	18	1539	1973	4	7.4	1	18	6	9.0	1	19

*When the site's record did not span the entire 1700 to 1900 period, all intervals within the period were used.

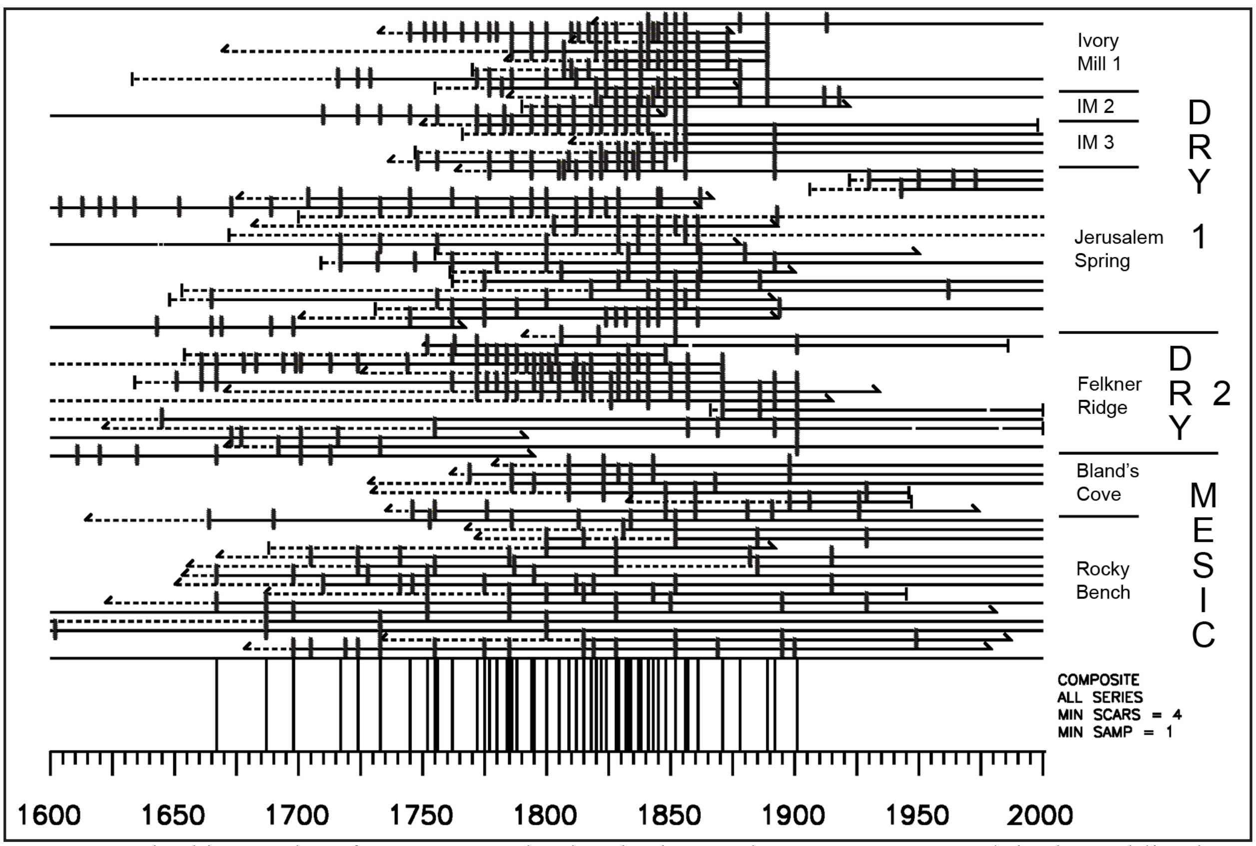

Figure 4. Fire history chart for our 7 sample plots in the North Coast Range. Each horizontal line is an individual tree. Solid horizontal lines are shown after the tree has been scarred at least once. Dotted lines are shown before the first scar. Each vertical tick is a dated fire scar. Chart indicates MESIC and DRY plots as well as grouping of the DRY plots for climate analysis. The composite at the bottom of the chart shows the occurrence of fires that scarred at least 4 trees.

There was no obvious change on the MESIC plots. For fires that scarred ≥2 trees on a site, the median fire return intervals of the MESIC plots (11 yr) were approximately double that of the DRY plots (6 yr) (P = 0.0001, Mann-Whitney, 1700 to 1900) (Figure 5, Table 2).

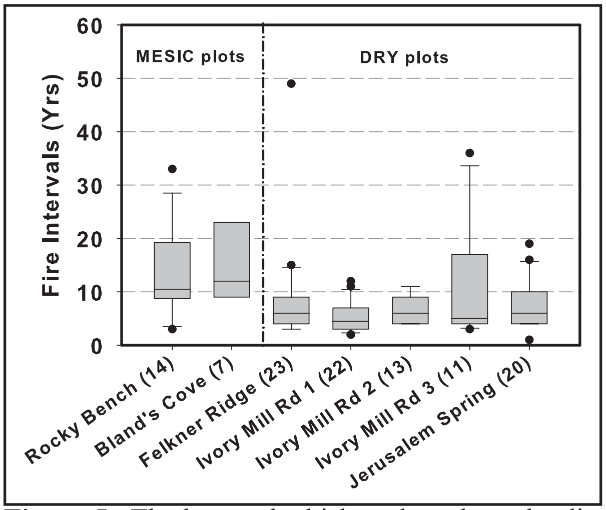

Figure 5. The box and whisker plots show the distribution of fire return intervals for each sample plot for fires that scarred at least two trees on a plot. The medians and the second and third quartiles are shown within the shaded box. The whiskers extend to the fifth and ninety-fifth percentiles. The dots indicate FRI values at the extremes of the distributions.

Occasionally, fires were synchronous within each type of plot. Fires were found to have occurred simultaneously in both MESIC plots in five years, whereas both DRY groups burned in the same year 19 times. Scars were found in the same year on at least one MESIC site and one DRY site 21 times. Fires occurred synchronously on the two MESIC plots and two DRY groups in only one year (1755). Given the number of fires found in this study, a Monte Carlo simulation indicated that there was approximately a 10% probability that the one year of synchrony between the MESIC plots and DRY groups would have occurred by chance in the 1700 to 1900 analysis window.

Fire Seasonality

It was possible to determine the season of burn for 66% of the MESIC site scars and 72% of the DRY site scars (Table 3). For the remainder of scars, although the year of the fire could be readily determined, rot or other physical damage in the immediate vicinity of the scar juncture obscured the intra-ring position of the scars. On MESIC plots, only 40% of scars occurred within the growing season, while 60% were at the ring boundary. Conversely, on DRY plots, 82% of scars formed in the growing season, with only 18% of scars found at the ring boundary. Further, there was a shift from the large proportion of scars in earlywood before 1850, to latewood, and especially more ring-boundary scars, after 1850 (Figure 6).

Fire and Climate

The superposed epoch analysis (SEA) showed significant association between fire years and negative PDSI (dry conditions) in the fire year, and a positive PDSI and negative PNA (rPNA) (wet conditions) three years before the fire year. Years without any fire scars were found to be associated with a negative PDSI in the year before the year with no fire scars (Figure 7). No PNA association was found with non-fire years (Figure 7). There were no significant associations ($P > 0.05$) between fire occurrence and the NINO3, PDO, or the combined NINO3+PDO (data not shown).

DISCUSSION

Fire Frequency and Seasonality

Though fires were frequent on all sampled plots in this study, there were important differences in fire regime characteristics between the drier forest plots and the mesic plots. The DRY plots burned more frequently than the

Table 3. Intra-ring position of fire scars. EE = Early Earlywood, ME = Middle Earlywood, LE = Late Earlywood, LW = Latewood, D = Dormant or ring boundary.

			Intra-ring scar position				
Site	Fire scars	Scars w/ position	% EE	% ME	% LE	% LW	% D
MESIC Bland's Cove	41	26	0	0	11.5	38.5	50.0
MESIC Rocky Bench	75	51	0	2.0	7.8	25.5	64.7
DRY Felkner Ridge	114	76	2.6	7.9	17.1	50.0	22.4
DRY Ivory Mill Rd 1	104	83	2.4	18.1	20.5	45.8	13.3
DRY Ivory Mill Rd 2	39	30	0	3.3	30.0	56.7	10.0
DRY Ivory Mill Rd 3	37	28	3.6	25.0	7.1	57.1	7.1
DRY Jerusalem Spr.	111	73	1.4	16.4	17.8	38.4	26.0
Total	521	367	1.6	11.4	16.6	43.6	26.7

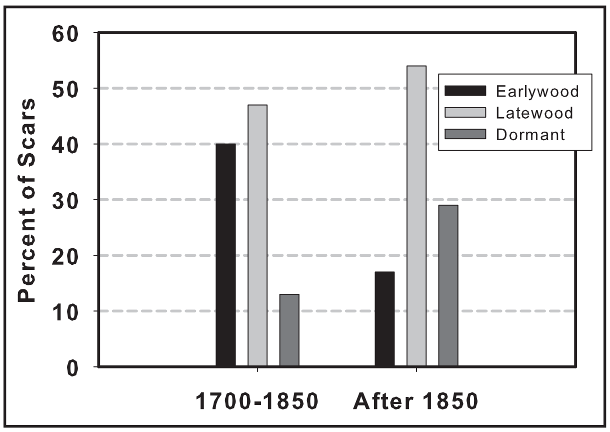

Figure 6. Bar chart depicting the differences in proportion of scars formed in the growing season (earlywood and latewood) and in the dormant season (ring boundary) between the two periods (1700 to 1850, 1951 to 1900) in the North Coast Range.

MESIC plots. The frequency of fires on the MESIC plots was similar to the frequency of fires on mixed conifer plots in the Klamath Mountains to the north (Wills and Stuart 1994; Taylor and Skinner 1998, 2003; Fry and Stephens 2006). However, fires on the DRY plots were more frequent compared to other mixed conifer plots in northwestern California (Figure 8). We suggest that this may be due to the proximity of the DRY plots to the expansive grass and oak woodlands of the Sacramento Valley. These grass-dominated fuel beds would have allowed fires that started long distances away to augment the record of more localized fires. Furthermore, the grass fuels would quickly re-grow and allow for repeat burns more frequently than in areas where fires were supported more by conifer needles and woody litter.

Interestingly, Figure 4 shows a change in fire activity in the mid-1800s similar to that found by Fry and Stephens (2006). There appears to be a lot of fire activity, especially on the DRY plots before about 1860. After that, fire occurrence drops rapidly and there is almost no fire in the twentieth century, similar to that found by Caprio and Swetnam (1995) in the Sierra Nevada. This coincides with the mid-1800s settlement that brought heavy cattle grazing to the Sacramento Valley, along with farming to help feed the mining districts (Dasmann 1973). Both activities would likely break up the continuity of the grass and herbaceous fuels and reduce the ability of fire to sweep easily through the valley. Elsewhere, others have found changes in fire regimes to have occurred coincident with the introduction of grazing (Savage and Swetnam 1990, Stephens *et al.* 2003, Norman and Taylor 2005). Additionally, Nomlaki and Patwin cultures are known to have used fire to manage resources (Stewart 2002, Anderson 2005), and the timing of this change in the fire regime coincides with the dramatic reduction in Native American

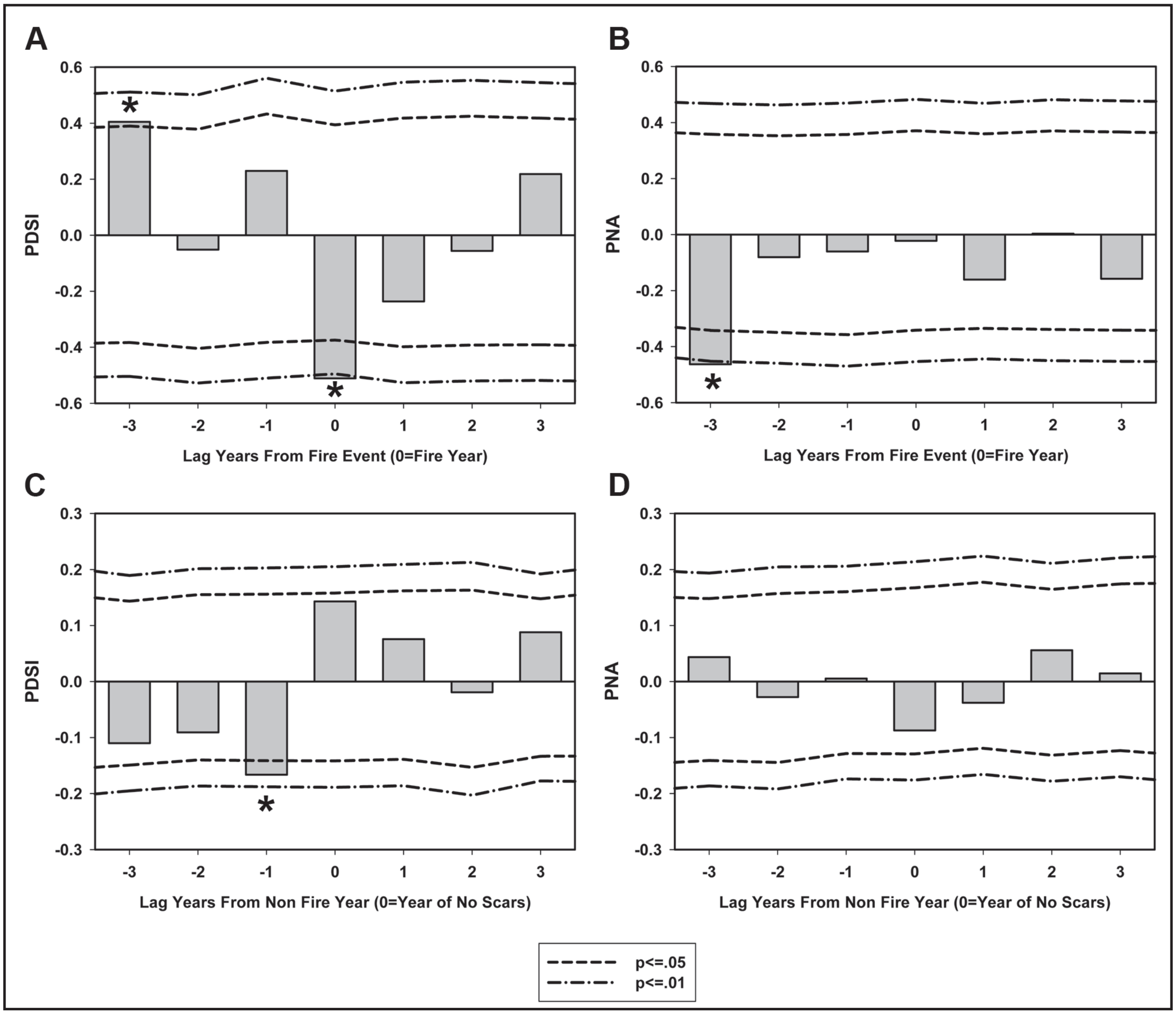

Figure 7. Superposed epoch analysis (SEA) of PDSI (Cook and Krusic 2004) and PNA (Trouet and Taylor 2009) with years when fires scarred trees on both MESIC and DRY plots or on no plots in the same year during the period from 1700 to 1900 across the North Coast Range study area. A) PDSI compared to fire years, B) PNA compared to fire years, C) PDSI compared to years of no scars, and D) PNA compared to years of no scars. Asterisks above or below bars indicate significant association ($P < 0.05$) of index condition in that year with the fire event or non-fire year.

populations and disruption of cultural practices due to introduced disease, relocation, and genocide (Heizer and Elsasser 1980).

DRY Plots

The predominance of growing season fire scars in the DRY plot samples is noteworthy compared to plots elsewhere in northwestern California, where dormant season fire scars were more common (Taylor and Skinner 1998, Taylor and Skinner 2003, Fry and Stephens 2005) (Figure 9). It is possible that differences in species dominance between this study and the previous studies may have contributed to the differences in fire seasonality due to potential differences in phenological conditions at the time of the fires. The current study relied heavily on samples from remnant wood of ponderosa pine (45.6%) and incense cedar (29.4%), whereas ponderosa pine (20.6%) and incense cedar (7.3%) were not so prominent in

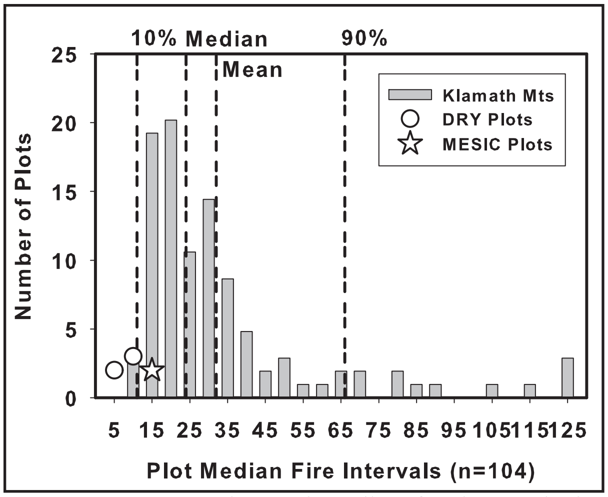

Figure 8. Comparison of median fire intervals for fires that scarred at least 2 trees in the same year on a plot in this study with 104 mixed conifer plots from the Klamath Mountains (Taylor and Skinner, 1998, 2003). Circles depict the DRY plots and the star depicts the MESIC plots. The tenth percentile, grand median, grand mean, and ninetieth percentile of the distribution of Klamath Mountain median fire return intervals are also indicated.

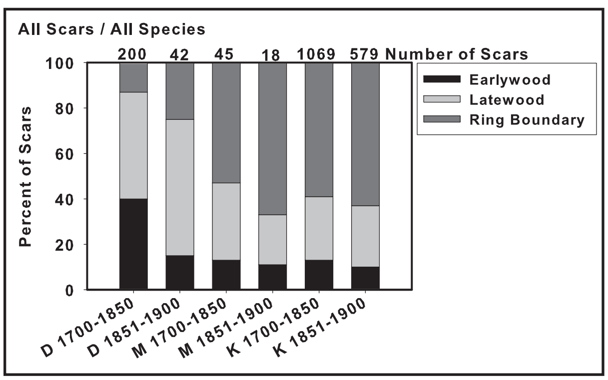

Figure 9. Chart shows the proportion of scars in earlywood, latewood, and ring-boundary (dormant) position before and after 1850 for our DRY (D) and MESIC (M) plots compared to 104 plots in mixed conifer forests of the Klamath Mountains (K) (Taylor and Skinner 1998, 2003).

the Klamath Mountains studies, which were dominated by samples from Douglas-fir (46.3 %). Other species of importance there were sugar pine (17.1 %) and white fir (5.8 %) (Taylor and Skinner 1998, 2003; Fry and Stephens 2006). Yet, even when accounting for species differences, there are still obvious disparities between our DRY plots and the Klamath Mountain studies in the intra-ring position of the fire scars (Figure 10, Table 4).

Season of fire on the DRY plots may have been influenced by continuity of fuels and proximity to the Sacramento Valley, as well as the burning practices of the Nomlaki in the woodlands and grasslands. A common practice in these environments in California was to burn grasslands after seeds were collected, which normally took place in the summer (Lewis 1993, Stewart 2002, Anderson 2005). It is likely that the grasses would grow and set seed earlier in the year in the warmer, drier, lower elevations of the Sacramento Valley compared to our sample plots, as the perennial grasses of the time appear to have followed similar patterns of growth and drying as do the annuals of today (Biswell 1956). Thus, fires that spread from the grasslands into our DRY plots could then potentially be represented as growing season scars. Earlywood scars would

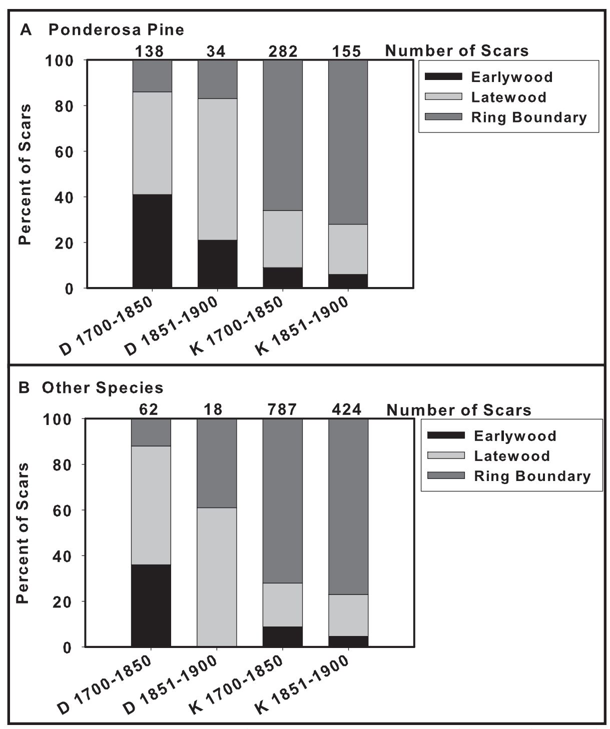

Figure 10. DRY plots (D) compared to Klamath Mountain plots (K) in proportion of scars in earlywood, latewood, and ring-boundary (dormant) position before and after 1850 for (A) ponderosa pine and (B) all other species combined.

Table 4. Intra-ring position of fire scars for ponderosa pine (PIPO) and other species on DRY plots in this study compared to mixed conifer forests of the Klamath Mountains (Taylor and Skinner 1998, 2003). EW = Earlywood, LW = Latewood, D = Dormant or ring boundary.

Site	Fire scars	Intra-ring scar position		
		% EW	% LW	% D
DRY PIPO				
1700 to 1850	138	41	45	14
1851 to 1900	34	21	62	18
DRY Non PIPO				
1700 to 1850	62	35	52	13
1851 to 1900	18	0	61	39
KLAMATH PIPO				
1700 to 1850	282	9	25	66
1851 to 1900	155	6	22	72
KLAMATH Non PIPO				
1700 to 1850	787	8	19	72
1851 to 1900	424	5	18	77

likely have been most frequent in dry years, which also would potentially contribute to early seed set in grasses. This is similar to the finding of Norman and Taylor (2003) in northeastern California where early season fire scars were associated with unusually dry years.

Notably, after 1850, the proportion of earlywood scars dropped from 40 % to only 17 % of the scars, and dormant (ring-boundary) scars more than doubled from 13 % to 29 % (Figure 6) and was accompanied by a reduction in the frequency of fire activity (Figure 4). We surmise that these changes may have been a result of two factors, either individually or in combination: 1) the likely reduction in Native American burning, and 2) reduction in fuel continuity due to grazing. However, the possible influence of variation in climate patterns (effective moisture and temperature) may have also contributed.

To determine the potential influence of climate on differences in the distribution of intra-ring scar position on the DRY plots between the two periods (1700 to 1850 and 1851 to 1900), we tested for differences in PDSI and temperature (grid point 16, Briffa *et al.* 2002) between the two periods. For PDSI (Table 5), we found 43 % of years were dry (PDSI < 0) and 57 % of years wet (PDSI > 0) in the early period with 54 % dry and 46 % wet in the later period. These shifts were not found to be significantly different using a chi squared contingency test ($P = 0.1952$). Interestingly, 85 % of the earlywood scars were found in dry years in the early period but only 50 % in the later period. For latewood scars, 57 % in the early period and 56 % of scars in the later period were in years classified as wet. Ring-boundary scars were 54 % in wet years in the early period, but changed to 77 % in dry years after 1850 (Table 5).

In regard to temperature (Table 6), we found that 53 % of years from 1700 to 1851 and 64 % after 1850 were warm. These values were not found to be significantly different ($P = 0.192$). For intra-ring scar positions, 71 % of earlywood scars were in warm years in the early period, while 63 % were in warm years after 1850. In contrast, 64 % of latewood scars were in cool years from 1700 to 1850, while 65 % were in warm years after 1850. Ring-boundary scars also shifted from 52 % in cool years before 1850 to 92 % in warm years after 1850.

The coincidence of warm-dry years shifted ($P = 0.066$) from only 27 % of years classified as warm-dry compared to 40 % after 1850 (Table 7). When warm-dry or cool-moist conditions were combined, the combinations did not appear to affect fire scar occurrence as the proportion of scars in each combination was proportional to the number of years in each combination. This may be a result of the long, warm, dry summer of the Mediterranean climate creating conditions where fires annually can easily spread where there is available fuel. The main difference was in the shift of ring-boundary scars, especially in the warm-dry

Table 5. Intra-ring position of DRY plot fire scars in dry years (PDSI < 0) and wet years (PDSI > 0) for the period 1700 to 1850 and the period 1851 to 1900. PDSI was normalized with a mean of 0 and a standard deviation of 1 for the analysis years (1700 to 1900). Values shown are percent for each period (number of scars) in each intra-ring position.

	Years for condition % (*n*)	Total scars for period % (*n*)	Earlywood % (*n*)	Latewood % (*n*)	Ring boundary % (*n*)
Dry 1700 to 1850	43 (65)	60 (121)	34 (68)	20 (40)	6 (13)
Wet 1700 to 1850	57 (86)	40 (81)	6 (12)	27 (55)	7 (14)
Total 1700 to 1850	100 (151)	100 (202)	40 (80)	47 (95)	13 (27)
Dry after 1850	54 (27)	53 (28)	8 (4)	26 (14)	19 (10)
Wet after 1850	46 (23)	47 (25)	8 (4)	34 (18)	6 (3)
Total after 1850	100 (50)	100 (53)	16 (8)	60 (32)	25 (13)

Table 6. Intra-ring position of DRY plot fire scars in cool years (temperature < 0) and warm years (temperature > 0) for the period 1700 to 1850 and the period 1851 to 1900. Temperature was normalized with a mean of 0 and a standard deviation of 1 for the analysis period (1700 to 1900). Values shown are percent of total fire scars for each period (number of scars) in each intra-ring position.

	Years for condition % (*n*)	Total scars for period % (*n*)	Earlywood % (*n*)	Latewood % (*n*)	Ring boundary % (*n*)
Cool 1700 to 1850	47 (71)	54 (112)	18 (37)	30 (61)	6 (14)
Warm 1700 to 1850	53 (80)	45 (90)	21 (43)	17 (34)	7 (13)
Total 1700 to 1850	100 (151)	100 (202)	40 (60)	47 (95)	13 (27)
Cool after 1850	36 (18)	28 (15)	6 (3)	21 (11)	2 (1)
Warm after 1850	64 (32)	72 (38)	9 (5)	40 (21)	23 (12)
Total after 1850	100 (50)	100 (53)	16 (8)	60 (32)	25 (13)

years from before 1850 to after 1850 (42 % vs. 91 %, respectively) (Table 7).

We surmise that these changes of intra-ring scar position are not a result of climate variation but are consistent with the reduction in Native American burning and the effects of grazing on fuels, as previously discussed. We would expect that warm and dry conditions would increase growing season scars rather than dormant season scars as the grasses would tend to dry and cure earlier, supporting more early-season fires. However, our results suggest an influence other than climate variation. The results from analyzing PDSI and temperature associations with intra-ring positions of fire scars appear to be consistent with that expected from the reduction in the grassland burning by the Native Americans (Lewis 1993, Stewart 2002, Anderson 2005). Both latewood scars and ring-boundary scars were split fairly evenly between wet and dry years, with the most in wet years from 1700 to 1850 for both types of scars. Latewood scars did not appreciably change their proportion in the later period. However, ring-boundary scars were found predominantly in dry (76 %) (Table 5) and warm (92 %) (Table 6) years after 1850. This would be consistent with reduction in the ability of fire to easily burn across the landscape except in periods of more severe fire conditions, as discussed above, in relation to the heavy grazing of the valley.

It should be noted that for our DRY plots, the material used to reconstruct the historical fire activity was mostly from highly decomposed ponderosa pine (60.4 %), sugar pine

Table 7. Intra-ring position of DRY plot fire scars in cool-moist years (temperature < 0, PDSI>0) and warm-dry years (temperature > 0, PDSI<0) for the period 1700 to 1850 and the period 1851 to 1900. T and PDSI were each normalized with a mean of 0 and a standard deviation of 1 for the analysis years (1700 to 1900). Values shown are percent of total scars for each period (number of scars) in each intra-ring position accounted for by the combination of T and PDSI condition.

	Years in condition % (*n*)	Total scars for period % (*n*)	Earlywood % (*n*)	Latewood % (*n*)	Ring boundary % (*n*)
Cool-Moist 1700 to 1850	31 (46)	23 (47)	3 (6)	16 (33)	4 (8)
Warm-Dry 1700 to 1850	27 (40)	26 (53)	14 (28)	9 (19)	3 (6)
Total 1700 to 1850	58 (86)	49 (100)	17 (34)	25 (52)	7 (14)
Cool-Moist after 1850	22 (11)	21 (8)	2 (1)	11 (6)	8 (1)
Warm-Dry after 1850	40 (20)	40 (21)	8 (4)	13 (7)	19 (10)
Total after 1850	62 (31)	61(29)	10 (5)	24 (13)	27 (11)

(10.4%), and incense cedar (16.7%) stumps of trees cut decades ago. Incense cedar is resistant to decay and the resin that formed around the fire wounds in the pines helped preserve enough of the wood to develop a long term fire history (Figure 3). It is likely that most pine stumps lacking fire scars, along with the Douglas-fir, white fir, and oak stumps, have mostly decomposed. Though nearly all of the fire scarred specimens collected on the DRY plots were ponderosa pine, sugar pine, or incense cedar, the forest on these plots today is largely composed of Douglas-fir, canyon live oak, and California black oak (Figure 11). Given the frequency of fire found in the fire scars for these DRY plots, the original forest structure and composition would have been very different than that shown in Figure 11. It would likely have been much more open with a surface fuel bed composed largely of grasses and other herbaceous material rather than being dominated by tree litter. Thus, it would be extremely difficult, if not impossible, to reconstruct with a high degree of certainty what the original stands looked like for the DRY plots.

MESIC Plots

The frequency and predominance of late-season burns on MESIC plots were similar to mixed conifer plots elsewhere in the Klamath Mountains (Wills and Stuart 1994; Taylor and Skinner 1998, 2003; Fry and Stephens 2006) (Figure 6). Similar to the other mixed conifer studies, with the exception of Fry and Stephens (2006), our MESIC plots did not show a reduction in fire frequency until after implementation of fire suppression in the twentieth century (Wills and Stuart 1994; Taylor and Skinner 1998, 2003). Moreover, there was no change in the seasonality of fire on MESIC plots over time as there was on DRY plots on the edge of the Sacramento Valley. Latewood and ring-boundary scars dominated on MESIC plots both before and after Euro-American settlement.

The fire scar record shows that fire was once very common in the forests surrounding the present orchid populations even though the contemporary MESIC plot stand conditions suggest that these plots were originally different in species composition and structure than the DRY plot conditions (Figure 11). Fire suppression has likely altered these forests analogous to that found in similar forests elsewhere (Taylor and Skinner 2003). Eliminating fire in these orchid sites has likely led to forest densification and buildup of surface fuels that, for lady's slipper orchids and associated understory species, may lead to negative effects on habitat conditions (Brown 2008). Additionally, when forest stands do inevitably burn after

Figure 11. Photos showing typical contemporary A) DRY site and B) MESIC site stand conditions in the North Coast Range study area. Photo A by C. Skinner. Photo B by D. Fry.

an unusually long period without fire, fire intensity and severity can be high (Agee and Skinner 2005), with potential adverse effects to the lady's slipper populations. Careful reintroduction and monitoring of prescribed fire in the orchid habitats is a logical progression based on the evidence collected in this study. In planning prescribed fires, it would likely be important to strive for leaving a heterogeneous burned-unburned pattern that would likely have been common under the original fire regime of frequent, low-moderate intensity fires in order to accommodate the sensitivity of lady's slipper orchids to fire (Brown 2008).

Fire and Climate

Fire occurrence and extent in the Northern Coast Range was strongly influenced by drought conditions. Both small and more widespread fires occurred most commonly in years when conditions were dry. Years without fire scars were associated with drought the year before the non-fire year. It may be that the previous drought year reduced herbaceous growth sufficiently to limit fuel, or that much of the area had burned in the preceding dry year. Moreover, years of widespread burning in the North Coast Range are generally synchronous with those in other forests in northern California. Several of the large fire years (e.g., 1729, 1733, 1762, 1776, 1794, 1812, 1829, 1841, 1886) are identical to years of extensive burns in the northern Sierra Nevada (Stephens and Collins 2004, Beaty and Taylor 2008), southern Cascades (Taylor *et al.* 2008), and Klamath Mountains (Taylor and Skinner 2003). This indicates that climate variation, specifically drought, was an important regional driver of fire occurrence in the North Coast Range as in other parts of northern California.

Variation in ENSO and PDO have been identified as important climatic influences on fire occurrence and extent in some mixed conifer and pine dominated forests in northern California (e.g., Taylor and Beaty 2005, Moody *et al*. 2006) but not others (e.g., Fry and Stephens 2006). The inconsistency in the fire-climate association with ENSO and PDO is likely related to inter-annual and multidecadal variability in the pivot zone of the ENSO-PDO dipole (Dettinger *et al*. 1998). Inter-annual variability in late twentieth century precipitation and temperature in northern California are associated with variation in ENSO and PDO, and the associations are stronger for the PDO (Trouet *et al*. 2008). Yet, ENSO and PDO were not associated with fire activity on our plots in the North Coast Range. The relatively short fire record, the apparent importance of Native American burning in the fire record on the DRY plots, and the geographic position of the plots in the ENSO pivot zone may have masked the ENSO and PDO signal. However, variation in temperature and precipitation in northern California is also strongly correlated with variation in the PNA (Trouet *et al*. 2008), and variation in fire activity in the North Coast Range was indirectly associated with the PNA. The negative or reversed PNA and the positive PDSI are both indicative of wet conditions. That both indices were significantly associated with fire years three years before a fire year occurred (Figure 7) suggests that wet conditions before the fire year may help with setting the area up to better carry fire, similar to that reported in other studies outside of northwestern California (e.g., Baisan and Swetnam 1990, Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2000, Norman and Taylor 2003). Thus, the PNA may be an important climate mechanism that helped to synchronize regional fire activity in northern California.

Variation in North Coast Range Fire Regimes

This study shows that there was considerable variation in fire occurrence and in the timing of fire regime changes since Euro-American settlement in California's North Coast Range. Fire frequency and seasonality were different depending on spatial context. Areas in close proximity to the dry Sacramento Valley had more frequent fires, and fire tended to occur earlier in the growing season than on plots farther west away from the valley. The changes in the fire frequency occurred at different times, with those closer to the Sacramento Valley changing earlier (late 1800s) than those more distant from the Sacramento Valley (1900s). The initial changes in the DRY eastern plots appear to coincide with the disruption of Native American cultures and the introduction of herds of grazing animals in the valley. Additionally, these changes were also contrary to what would be expected due to variation in precipitation and temperature patterns. Both the DRY and MESIC plots ceased to have frequent fires in the twentieth century following the introduction of fire exclusion as a management goal. Fires were only occasionally found to have been synchronous in both the DRY and MESIC plots in the same year. However, fire activity found in both DRY and MESIC plots was found to be associated with dry years (PDSI), and the dryer years with fires appear to have been related to variation in the PNA but not directly to ENSO or PDO.

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