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Fire Regimes of Mixed Conifer Forests in the North-Central Sierra Nevada at Multiple Spatial Scales

Abstract

Dendrochronology was used to quantify past fire regimes in mixed conifer forests in the north-central Sierra Nevada. Historic management activities, particularly railroad logging, severely limited the number of fire scar samples available. Fires were recorded between 1649 and 1921 and median point fire intervals, composite fire intervals at the 3-5 ha spatial scale, and composite fire intervals at the 9-15 ha spatial scale were 9-15, 6-14, and 5-10 yr. The seasonality of past fires in the north-central Sierra Nevada differs from that reported elsewhere, with the majority of fires occurring in latewood. There is a general trend of increasing latewood and growing season fires from the southern Cascades south to the southern Sierra Nevada. Superposed epoch analysis determined that widespread fires were significantly correlated to droughts the year of the fire, and in some cases, to a significantly wet year before the fire year. Fire return intervals are similar to those found in mixed conifer forests in the southern Cascades and southern Sierra Nevada but difference in the size of sampled areas complicates fire interval comparisons. In this study, we present fire statistics at several spatial scales and encourage others to do so. If all fire history research reported fire statistics at similar spatial scales it would allow for robust comparisons between diverse locations.

Introduction

Fire was the central theme of United States forest management during the 20th century (Agee 1998) and this has continued into the new millennium. Early United States wildland fire policies focused on fire suppression and control, which coincided with the creation of the United States Forest Service in 1905 (Pyne 1982).

Fire was and continues to be a major ecosystem process in the forests of the Sierra Nevada, California (Skinner and Chang 1996, Husari and McKelvey 1996). Ignitions from both lightning and Native Americans were common on the west-slope of the Sierra Nevada before Euro-American settlement (Anderson and Moratto 1996, Husari and McKelvey 1996).

The Nisenan Native American community once inhabited the forests in the north-central Sierra Nevada (Kroeber 1925, 1929; Matson 1972) and they have lived in this area for at least 2000 yr (Cook 1976). Fire was commonly used by this culture to improve hunting efficiency and to produce cordage materials of high quality (Wilson and Towne 1978).

A malaria epidemic was introduced in northwest California in 1833 and it devastated the Nisenan population (Cook 1955). The discovery of gold in California in 1849 further affected the Nisenan. The actual discovery location was on the American River in their territory, and by 1851, most of their territory was completely overrun by gold miners (Wilson and Towne 1978). Widespread killing, destruction of villages, and the persecution of the Nisenan destroyed them as a viable culture by 1851 (Wilson and Towne 1978). Other land uses that have impacted Sierra Nevada fire regimes include livestock grazing, mining, and logging.

After some debate, the policy of fire suppression was accepted early in the 20th century in the western United States (Clar 1959, Pyne 1982). This policy eventually produced undesirable ecosystem effects including higher tree densities (Biswell 1959), higher fuel loads (Dodge 1972), and changes in wildlife habitats (Leopold et al. 1963), primarily in forests that once experienced frequent, low-moderate intensity fire regimes. Presently > 30 million ha of federal forests in the western United States are at moderate to high risk of severe wildfire (National Wildfire Coordinating Group 2001) and many of these areas need restoration.

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Uncertainty in desired conditions has complicated forest restoration in the western United States. Many federal agencies have defined pre-historical ecosystem structures as their primary restoration objective (Manley et al. 1995). A debate continues about how, where, and to what extent natural variations or reference conditions derived from historical ecology should be applied to land management (Millar and Wolfebden 1999). Still, there is a building consensus that, at a minimum, it is useful to know and understand the past to manage ecosystems properly for the future (Swetnam et al. 1999).

No crossdated (Stokes and Smiley 1977, Swetnam et al. 1985) fire history information exists from the coniferous forests of the north-central Sierra Nevada (Skinner and Chang 1996), an area of > 2 million ha. Past fire occurrence in portions of the Sierra Nevada have been estimated from imprecise ring counts from an early forest pathology study (Boyce 1921).

This early work used field-based ring counts and included one plot in northern Sierra Nevada in the Plumas National Forest (Boyce 1921). Show and Kotok (1924) summarize the work done by Boyce (1921) but years reported as producing large fires are not in total agreement. A more comprehensive analysis of the data collected by Boyce (1921) included estimates of average fire intervals from each of the six sampled sites (Wagener 1961).

In 1915 Boyce collected samples from 510 stumps in the northern plot, of which 354 had fire scars, over an area of 82 ha (Wagener 1961). The fire record began in 1640 and 38 different fires were reported for an average interval of 7 yr. Difficulties with field-based ring counts were reported and this reduced the accuracy of the fire interval estimates (Burcham 1959, Wagener 1961).

The nearest published fire history information to the north-central Sierra Nevada is from mixed conifer forests from the southern Cascade mountains (Taylor 2000, Beaty and Taylor 2001) and southern Sierra Nevada (Kilgore and Taylor 1979, Caprio and Swetnam 1995). In the southern Cascades, analysis of 56 fire scarred samples yielded a median fire interval of ~7 yr (Beaty and Taylor 2001). Ponderosa pine-mixed conifer forests in the southern Sierra Nevada had median fire return intervals of 5-11 yr (Caprio and Swetnam 1995).

The objective of this study was to reconstruct fire regimes in mixed conifer forests in the north-central Sierra Nevada using dendrochronology. Estimates of past fire frequency, seasonality, extent, and possible relationships with climate were examined. The land-use history of the study area was also examined to aide in explaining past fire occurrence.

Methods

Study Area Description

Our study was undertaken in mixed conifer forests at the University of California Blodgett Forest Research Station, located ~ 20 km east of Georgetown, California (Figure 1). Blodgett Forest is located at the latitude 38° 54' 45" N, longitude 120° 39' 27" W, between 1100 and 1410 m above sea level, and encompasses 1780 ha. Tree species in this area include sugar pine (*Pinus lambertiana*), ponderosa pine (*Pinus ponderosa*), white fir (*Abies concolor*), incense-cedar (*Calocedrus decurrens*), Douglas-fir (*Pseudotsuga menziesii*), California black oak (*Quercus kelloggii*), and tanoak (*Lithocarpus densiflorus*).

Soils at Blodgett are well-developed, well-drained Haploxeralfs (Alfisols), derived from either andesitic mudflow or granitic/granodiorite parent materials (Hart et al. 1992). Cohasset, Bighill, Holland, and Musick are common soil series. Soils are deep, weathered, sandy-loams overlain by an organic forest floor horizon. Common soil depths range from 85-115 cm.

Climate at Blodgett is Mediterranean with a summer drought period that extends into the fall. Winter and spring receive the majority of precipitation that averages 160 cm (Blodgett Forest Research Station weather records from 1960-2000). Average temperatures in January range between a low of 0°C and high of 8°C. Summer months are mild with average August temperatures between 10°C and 29°C and some light summer precipitation from thunderstorms (averaging 4 cm over the summer months, Blodgett Forest Research Station weather records from 1960-2000).

Seasonal livestock grazing began at Blodgett in the early 1800s. During the early 1800s some large pine trees were harvested for local construction, and after gold was discovered in 1849, a large number of miners arrived. Oxen logging began in the 1890s but tree harvesting was relatively minor because of limited technology and poor access.

From 1900-1913 extensive railroad logging occurred over the majority of Blodgett Forest and almost all commercial trees (dbh > 30 cm) were harvested. Economically desirable species included ponderosa pine, Douglas-fir, and sugar pine because of their high value, but all species with good form (few lower limbs, no externally visible defects) were harvested. The first Blodgett Forest inventory in 1935 reported an average of only 15 trees/ha >60 cm dbh, half of which were incense-cedar. The removal of the majority of the trees by railroad logging prevented us from collecting tree demography data to complement our fire history information. Analysis of demography data could have determined if tree regeneration was continuous or episodic in these forests.

Forest Structure

To characterize existing forest structure, information was collected from 0.04 ha systematic forest inventory plots placed in each management unit that was sampled for fire scars. The circular inventory plots are separated by ~120 m and the management units vary in size from 10-25 ha. Height and dbh of all trees >30 cm dbh were measured. Average basal area per hectare, average number of trees per hectare, average percent basal area by species, and average quadratic mean diameter were calculated.

Current forest structure data were compared to similar data (all trees inventoried >30 cm dbh) collected in Sierra Nevada mixed conifer forests in 1899 (Stephens 2000). The 1899 data represent the best plot-level forest structure information from Sierra Nevada mixed conifer forests that had not been influenced by fire suppression or harvesting.

Master Tree Ring Chronology

The only mixed conifer master tree ring chronologies available near Blodgett Forest are from ponderosa and Jeffrey pines (*Pinus jeffreyi*) (Grissino-Mayer and Fritts 1998). Samples of remnant, fire scarred incense-cedar would not crossdate (Stokes and Smiley 1977, Swetnam et al. 1985) with the adjacent pine chronologies. As a result, a master tree ring chronology using incense-cedar was created since no chronologies exist for this species in the Sierra Nevada.

Increment cores for the master tree ring chronology were collected from trees in xeric sites at Blodgett. Two cores, opposite each other and parallel to the contour, were extracted from each of 24 live incense-cedar trees that survived the historical logging. Cores were mounted with the tracheids up and sanded with a belt sander using belts up to 400 grit.

Ring widths were measured to the nearest 0.01 mm for all cores using a ring reader and a digital sliding stage. Measurements of all cores were compiled and analyzed using COFECHA to check for crossdating errors (Holmes 1983). Only measurements, or series, identified as having proper dating and significant correlation at $P < 0.001$ were used to create the master tree ring chronology. Of the 48 series, 39 met these criteria, and were analyzed using ARSTAN to develop the master chronology indices (Holmes 1983).

Fire History

Our sampling strategy maximized the completeness of an inventory of fire dates within Blodgett Forest over as a long time period as possible, while also collecting samples that were spatially dispersed throughout the forest (Swetnam and Baisan 2002). The entire Blodgett Forest was reconnoitered to determine where clusters with fire-scarred materials were located. Each cluster that contained a minimum of seven fire scarred samples over an area ≤ 15 ha was selected for sampling.

Partial cross sections were cut with a chainsaw from all fire-scarred stumps, snags, downed logs, and live trees, that met the cluster definition described above. In most cases, several partial sections were needed to obtain a sample with a maximum number of fire scars and a minimum of rotted wood. Live trees were not sampled more than twice and they were sampled conservatively (by minimizing the size of removed section) to reduce the probability of mechanical failure (Heyerdahl and McKay 2001, Stephens 2001). Each fire scarred sample was sanded with a belt sander using a series of belts up to 400 grit.

Fire scars were identified by the characteristic disruption and healing patterns of radial tree ring growth (McBride 1983). Calendar years were assigned to each fire scar using crossdating

(Dieterich 1980, Swetnam et al. 1985). To assist in the comparison of fire statistics from this and other research, we present data using a range of spatial scales. First, mean and median point fire return intervals (PFI) were developed for each tree as a point in the landscape. PFI are likely to be constrained by the time required for sufficient fuel to accumulate to permit consecutive fires at a single point, and are generally a conservative estimate of fire occurrence (Kitzberger and Veblen 1997).

Composite fire intervals (CFI) refer to fires affecting a group of trees or occurring within a specified area and they provide a more comprehensive record of past fires (Dieterich 1980, Agee 1993). CFI were computed at two spatial scales 1) C10: fires that scarred at least 2 trees and 10% of the recording trees (RT) in each cluster (spatial scale 9-15 ha), and 2) SC10: fires that scarred at least 2 trees and 10% of the RT in each sub-cluster (spatial scale 3-5 ha). Each fire scar cluster was separated into two or three independent sub-clusters based on the proximity of the samples to one another. We used a filter with a minimum of 2 trees scarred per fire and at least 10% of the RT to remove the impacts of small spot fires (Swetnam and Baisan 2002).

The position within the ring in which a scar occurred was noted as EE (early earlywood), ME (middle earlywood), LE (late earlywood), LW (latewood), D (dormant), or U (undetermined) to serve as an estimate of the season of fire occurrence (Ahlstrand 1980, Dieterich and Swetnam 1984).

We used a non-parametric Kruskal Wallis test to determine if significant differences ($P < 0.05$) existed in mean fire return intervals at the point (PFI) and composite (C10) spatial scales (Zar 1999). If a significant difference was detected then a non-parametric Tukey multiple comparison test (Nemenyi test) was done to determine if significant differences existed between samples (Zar 1999).

The FHX2 software package was used to perform temporal and superposed epoch analyses (Grissino-Mayer 2001). Temporal analysis determined if significant differences ($P < 0.05$) in mean fire return intervals existed for a given cluster (spatial scale 8-15 ha, C10 spatial scale) between two distinct time periods (prehistorical period, 1750-1850: historical period, 1850-1900). A Student's t-test was used to determine if significant differences existed in fire return intervals (Grissino-Mayer 2001).

Superposed epoch analysis (Baisan and Swetnam 1995, Swetnam and Betancourt 1998) was used to determine if significant ($P<0.05$ or $P<0.01$) correlations existed between the composite fire history and a seasonal moisture availability. The Palmer Drought Severity Index (PDSI) was used to capture seasonal moisture availability. PDSI is a measure of prolonged moisture availability that takes into account precipitation, evapotranspiration, and soil moisture (Palmer 1965).

Cook et al. (1999) reconstructed summer PDSI for points on a grid across the continental United States using a network of annual tree ring chronologies. Two different grid points of reconstructed summer PDSI were used based on proximity to Blodgett Forest. One was located on the east side of Lake Tahoe, Nevada (PDSI 13), 80 km east of the study area, and the second from the east side of Clear Lake, CA (PDSI 6), 160 km west of the study area. All fires since 1669 (the first year of the PDSI record) that met or exceeded a minimum of 25% RT and two trees scarred per fire were used for this analysis. The 25% of RT was selected to include only fires that were relatively widespread.

Results

Mean tree density, basal area, and dbh at Blodgett main and Pilot Creek (trees above 30 cm dbh) is ~ 200 trees/ha, 46 m^2/ha, and 46 cm (Table 1). Pilot Creek is dominated by incense-cedar and Douglas-fir. The forests of Blodgett main are composed of mixed species with white fir dominating the majority of the plots (Table 1).

Six fire scar clusters were located at Blodgett Forest, four on the main property (210, 292, 390, 450) and two in the Pilot Creek area (LP, UP, ~ 4 km north of Blodgett main) that is separated from the main property by a perennial stream (Figure 1). We sampled 73 fire scarred stumps, snags, and trees, 23 from Pilot Creek, and 50 from Blodgett main. Eight-four percent of the trees were crossdated (15 Pilot Creek, 46 Blodgett main). The remaining trees were not usable because of excessive decomposition. Incense-cedar accounted for the majority of the samples (72%), the remaining samples were ponderosa pine. Fire scar samples from live trees were rare (9% of collection).

TABLE 1. Stand characteristics for each fire history cluster and surrounding management unit at Blodgett Forest Research Station, Georgetown, California.

Cluster	Elevation (m)	Trees/ha (>30 cm dbh)	Mean basal area (m^2/ha)	Percentage of basal area by species (%)	All trees average quadratic mean diameter (cm)
UP	1220	168	28.4	33 incense-cedar 28 California black oak 24 Douglas-fir	48.6
LP	1130	216	35.4	53 Douglas-fir 29 California black oak 16 incense-cedar	50.0
210	1300	258	58.5	32 white fir 25 California black oak 17 Douglas-fir	45.0
292	1310	211	55.0	32 white fir 21 Douglas-fir 17 incense-cedar	44.6
390	1410	229	58.8	38 white fir 21 Douglas-fir 14 incense-cedar	47.8
450	1330	142	38.0	58 ponderosa pine 16 sugar pine 12 incense-cedar	36.9

There were few recording trees before 1750 and after 1910 in the majority of the study sites (Figure 2). PFI varied significantly with Lower Pilot Creek (LP) recording shorter intervals than clusters 450 and 210 (Table 2). CFI at the C10 spatial scale varied significantly with LP, UP, 292, and 390 having shorter CFI than clusters 450 and 210 (Table 3). CFI at the SC10 spatial scale were intermediate in comparison to the PFI and C10 spatial scales (Table 4). Years when both Blodgett main and Pilot Creek burned included 1750, 1768, 1812, 1829, 1865, and 1870. Fire scars occurred most frequently in latewood of the annual growth rings with fewer scars at the ring boundary associated with dormant season fires (Table 3).

Temporal analyses determined that in two of three clusters (C10 spatial scale) in Blodgett main with sufficient sample depth, CFI from 1750-1849 were significantly shorter than the CFI from 1850-1900 (Table 5). No significant differences were detected in the Pilot Creek plots. After 1900, fires were rare but the number of recording trees decreased after 1910 (Figure 2).

Superposed epoch analysis revealed a significant correlation between the PDSI 6 (Clear Lake) and 25% scar class fires, for a wet year preceding the fire event, and a drought year the year of the fire event (Figure 3). PDSI 13 (east Lake Tahoe) was also significantly correlated with the 25% scar class fires, but only for a drought year the year of the fire event (Figure 3).

Discussion

The results from this work indicate that fire was a common ecosystem process in the mixed conifer forests of the north-central Sierra Nevada. The seasonality of past fires in the north-central Sierra Nevada differs from that reported elsewhere with the majority of Blodgett fires recorded in the latewood of the annual growth rings (Table 3).

The local incense-cedar master tree-ring chronology facilitated crossdating. This is the first fire history study to use primarily incense-cedar in North America. A related species in the Cupressaceae, Chilean cedar (*Austrocedrus chilensis)*, has been used to analyze fire, climate, and land use interactions in forests of Argentina (Kitzberger and Veblen 1997).

Past railroad harvesting severely limited the number of fire scar samples available from this area of the north-central Sierra Nevada. Live trees

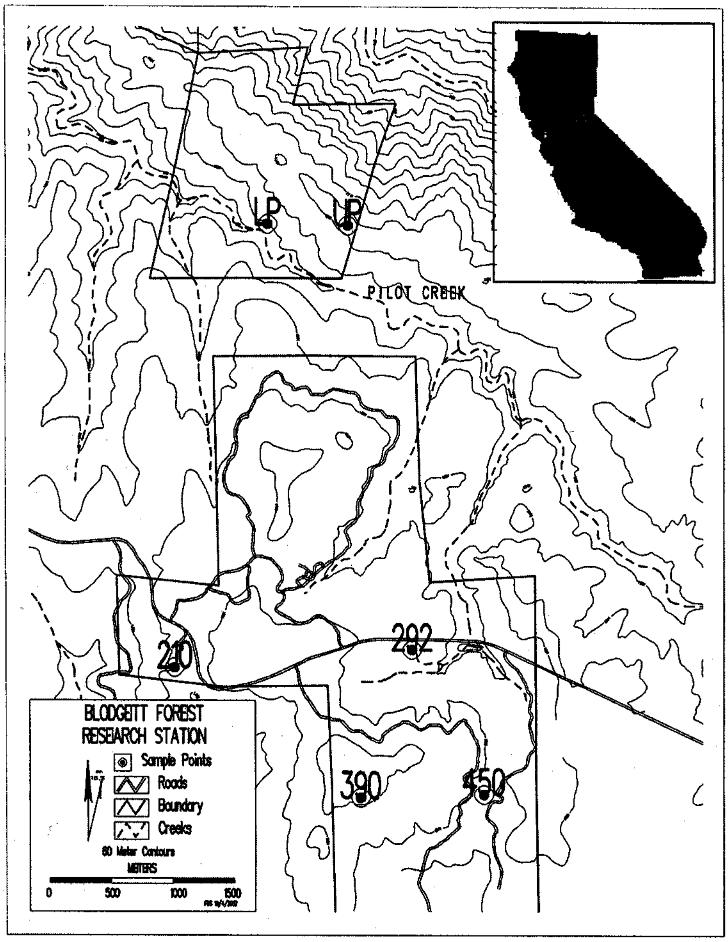

Figure 1. Fire scar sample locations from Blodgett Forest Research Station, Georgetown, California. Location of Blodgett Forest Research Station is given in the upper corner of the figure.

TABLE 2. Point fire return intervals from Blodgett Forest Research Station, Georgetown, California. Mean values in a column followed by the same letter are not significantly different ($P<0.05$).

Cluster	Mean fire interval (yr)	Median fire interval (yr)	Minimum-maximum fire interval (yr)	Number of fire intervals	All trees average coefficient of variation
UP	12.0^{ab}	10.0	3-33	40	0.68
LP	9.6^{a}	8.0	3-35	65	0.62
210	17.3^{b}	13.5	6-40	46	0.54
292	14.9^{ab}	12	3-53	113	0.68
390	13.3^{ab}	9	2-82	79	0.91
450	20.2^{b}	15	3-91	37	0.96

with fire scars were rare, a testimony to the efficiency of the past railroad harvesting. Incense-cedar dominated the 1935 Blodgett inventory and this is consistent with early logging operations in the north-central Sierra Nevada that commonly focused on the high-valued ponderosa pine, sugar pine, and Douglas-fir (Stephens 2000).

Railroad harvesting of similar intensity and duration was common in the northern and central Sierra Nevada (Laudenslayer and Darr 1990). Rarity of live fire scarred trees and heavily decomposed remnant materials have probably contributed to the lack of published fire history information from the north-central Sierra Nevada. The majority of fire history information in this study came from trees harvested ~100 yr ago

TABLE 3. Composite cluster fire history statistics from Blodgett Forest Research Station, Georgetown, California (filter of 10% of samples scarred and a minimum scar class of 2). Mean values in a column followed by the same letter are not significantly different ($P < 0.05$).

Cluster	Mean fire interval (yr)	Median fire interval (yr)	Fire interval range (yr)	Area sampled (ha)	Number of fire scarred samples collected	Number of fire scars in each cluster	Scars with season identified fires (%)	Latewood fires (%)	Dormant fires (%)	Aspect
UP	8.8^a	6.0	3-22	15	7	47	26	70	30	SW
LP	7.3^a	5.0	3-20	9	8	73	60	84	16	SW
210	10.5^b	10.0	2-17	11	12	59	46	70	30	NE
292	6.8^a	5.0	2-29	15	13	126	44	79	21	E, NE
390	6.5^a	6.0	2-13	15	14	93	55	84	16	SW
450	9.4^b	7.0	3-22	14	7	44	41	67	33	NE
Pilot Creek composite	5.7	4.5	3-18	-	15	120	47	79	21	-
Blodgett main composite	4.7	4	4-28	-	46	443	46	79	21	-

TABLE 4. Composite sub-cluster fire history statistics from Blodgett Forest Research Station, Georgetown, California (filter of 10% of samples scarred and a minimum scar class of 2). There were insufficient fire intervals, at a filter of 10% of samples scarred and a minimum scar class of 2, to create sub-clusters in UP and 450.

Cluster	Sub-cluster	Mean fire interval (yr)	Median fire interval (yr)	Fire interval range (yr)	Area (ha)	Number of fire intervals	Coefficient of variation	Year of last fire
LP	North	11.7	11	6-21	5	9	0.43	1921
	South	7.9	8	4-12	3	8	0.33	1882
210	North	13.6	14	2-21	3	10	0.41	1898
	South	13.9	13	10-22	3	7	0.32	1865
292	East	12.8	13	9-19	5	8	0.25	1852
	Central	11.7	10	4-25	5	9	0.55	1838
	West	14.8	12	5-29	4	12	0.63	1899
390	East	10.4	6	4-21	4	5	0.73	1852
	Central	10.5	9	3-20	5	11	0.56	1865
	West	11.3	11	5-17	5	7	0.39	1900

TABLE 5. Temporal analysis of mean composite fire intervals from Blodgett Forest Research Station, Georgetown, California. Plot spatial scale 8-15 ha. Mean values in a column followed by the same letter and not significantly different ($P < 0.05$). There were insufficient fire intervals, at a filter of 10% of samples scarred and a minimum scar class of 2, to perform analysis in cluster 450. CFI: composite fire interval.

Plot	210	292	390	UP	LP
CFI 1750-1849	9.0^a	5.1^a	6.1^a	7.9^a	6.4^a
CFI 1850-1900	15.3^b	23.5^b	8.0^a	8.3^a	9.2^a

(Figure 2) and many stumps had no structurally sound wood available for sampling. High annual precipitation has contributed to rotten remnant materials and incense-cedar was the most persistent species in this environment.

While the exact plot locations of an 1899 mixed conifer inventory are not precisely known (Stephens 2000), one occurred inside the boundaries of Blodgett Forest (Bob Heald, University of California Center for Forestry, personal communication). The 1899 forest structure data were collected before the influences of logging and fire

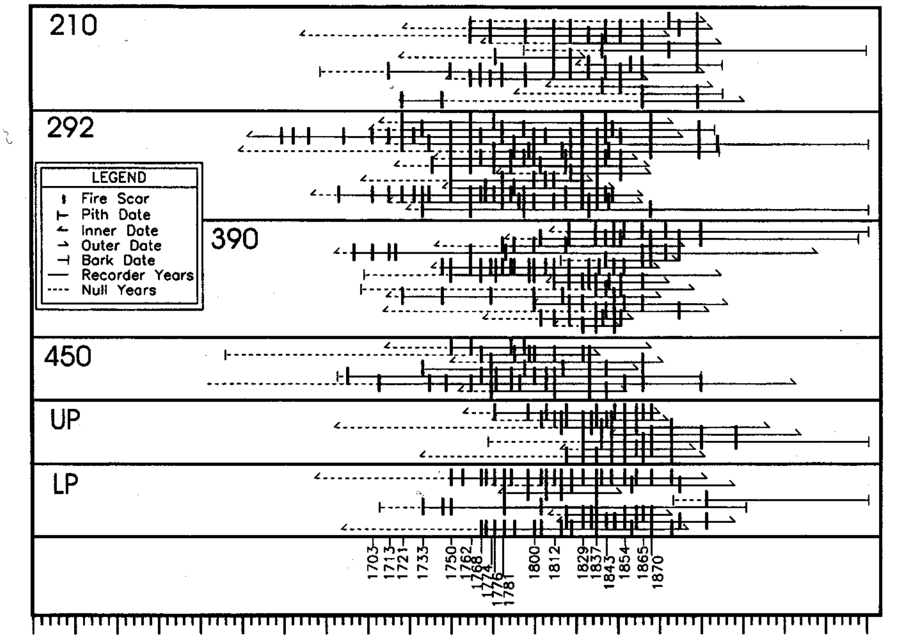

Figure 2. Fire history from Blodgett Forest Research Station, Georgetown, California. Each horizontal line is a fire record from a single tree. Horizontal dashed and solid lines indicate null and recorder years, respectively. Null years are not included in fire interval statistics. The vertical lines indicate a fire scar from a single tree. The composite identifies years when fires scarred ≥2 trees and ≥25% of recording trees.

suppression but are biased to areas that contained only large trees. Some areas of mixed conifer forests in the north-central Sierra Nevada had average tree density, basal area, and dbh of 225 trees/ha, 140 m^2/ha, and 90 cm (Stephens 2000). Current forest density is similar to that recorded in the 1899 inventory but mean dbh is ~50% lower. Since the 1899 data were biased to include only areas with large trees, we cannot fully compare them to contemporary data that include information from all areas of the forest.

Difference in sampling methods and the size of sampled areas complicates CFI comparisons between fire history studies. As sampling areas

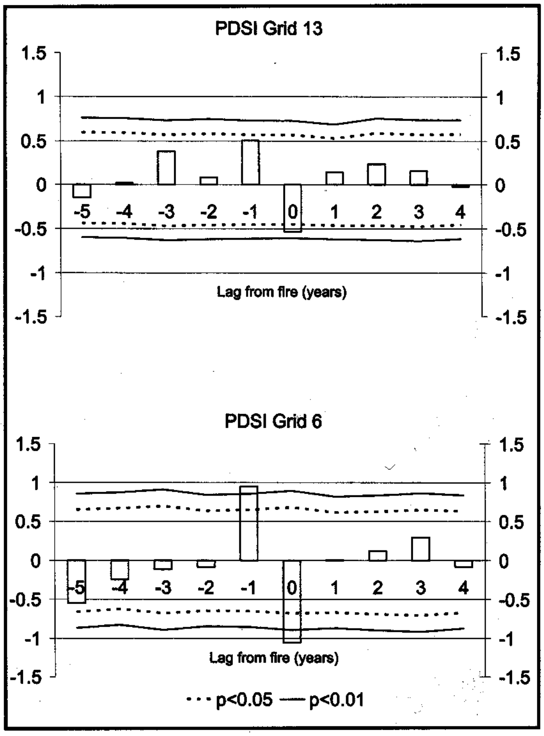

Figure 3. Superposed epoch analysis of fires scarring more than 25% of trees and a minimum of two trees scarred per fire compared to reconstructed summer Palmer Drought Severity Indexes for eastern Lake Tahoe, Nevada (Grid Point 13), and Clear Lake, California (Grid Point 6). Horizontal solid lines and dashed lines indicate 99% and 95% percent confidence intervals, based on Monte Carlo simulations (Swetnam and Betancourt 1998).

increase the resulting mean fire intervals will decrease because more fire events will be included in the summary fire statistics (Tables 2, 3, and 4) (Baker and Ehle 2001). In this study, we present fire statistics at several spatial scales and encourage others to do so. If all fire history research from low severity regimes reported fire statistics at the PFI and SC10 spatial scales, it would allow for robust comparisons between diverse locations. We agree with Baker and Ehle (2001) that it is appropriate to present fire regime statistics at several spatial scales to provide evidence of variability in burn patterns.

There is a general trend of increasing latewood and growing season fires southward from the southern Cascades to the southern Sierra Nevada (Table 6). Dormant season fires dominate in the northern latitudes, late season in the north-central Sierra Nevada, and late season and growing season fires in the southern Sierra Nevada. Seasonal interpretation of scar position requires cambia phenology studies to characterize tree-ring growth within a year at different locations and elevations (Caprio and Swetnam 1995). Seasonality of past fires in the Rocky and Blue Mountains also follows a latitudinal gradient with predominantly early season fires in the south and late season fires in the north (Brown and Shepperd 2001, Heyerdahl et al. 2001).

Temporal analysis determined that two of three fire scar clusters in Blodgett main had significantly shorter CFI from 1750-1850 (pre-historical period) when compared to 1850-1900 (historical period) (Table 5). The Pilot Creek clusters were not significantly different. Native American ignitions were probably eliminated in the 1840s and 1850s because of the demise of the Nisenan culture. The decrease in Blodgett main CFI around 1850 is possibly explained because of its easier access, gentler topography, and impacts of livestock grazing that could have reduced herbaceous fuels. Pilot Creek was accessed at a later time by

TABLE 6. Fire history information from the southern Cascades and Sierra Nevada before the impact of Euro-American settlement.

Area and vegetation	Median FRI (yr)	FRI range (yr)	Area sampled (ha)	Fire season[1]	Type	Source
Southern Cascades, Jeffrey pine-white fir	7.5	2-29	n.a.	82% D, 1% L, 10% ME, 7% LE	composite	Taylor 2000
Southern Cascades, mixed conifer	7	1-21	n.a.	90% D, 5% L, 5% ME	composite	Beaty and Taylor 2001
North-central Sierra Nevada, mixed conifer	8-15	3-91		21% D, 79% L	point	this work
North-central Sierra Nevada, mixed conifer	6-14 4-5	2-29 2-22	3-5 8-15	21% D, 79% L	composite	this work
Southern-central Sierra Nevada mixed conifer, Yosemite NP	2-3	1-25	20-50	23% D, 54% L, 18% LE, 4% ME, 1% EE	composite	Swetnam et al. 1998
Southern Sierra Nevada, giant sequoia-mixed conifer, Sequoia NP	5-9	3-14	3-16	n.a.	composite	Kilgore and Taylor 1979
Southern Sierra Nevada, mixed conifer, Mountain Home State Forest	3-5	1-12	20-50	20% D, 61% L, 16% LE, 1% ME	composite	Swetnam et al. 1998

[1] D-dormant, L-latewood, LE-late earlywood, ME-middle earlywood, EE-early earlywood. n.a.-not available. FRI-fire return interval. NP-National Park.

Euro-Americans because it is more remote, it has much steeper topography, and a perennial stream had to be crossed for easy access. After 1900, fires were rare, which agrees with other research in the Sierra Nevada (Husari and McKelvey 1996). Livestock grazing and changing climates may have influenced this fire regime in the 20th century (Millar and Wolfebden 1999, Stephens et al. 2003).

Clusters 210 and 450 recorded the longest CFI at the C10 spatial scale (Table 3). PFI reflect a similar trend but are ~ 5-6 yr longer (Table 2). Clusters 210 and 450 are located on north and northeastern aspects, whereas the majority of the other plots are on drier southwest aspect (Table 3). Differences in aspect and local fuel characteristics probably contributed to the differing mean fire return intervals (MFI). A possible confounding factor is sample composition of clusters 210 and 450 that were 100% incense-cedar in contrast to the other plots that contained some ponderosa pine samples. Differing abilities of species to record and preserve the fire record is another possible explanation of why the MFI were significantly different (Stephens 2001).

Large fire years were correlated to drought years and, when the Clear Lake PDSI was used, to a significantly wet year before the fire year (Figure 3). Significant drought years have been correlated to large-scale fires in the southern Sierra Nevada (Swetnam et al. 1998), but this has not been reported in the southern Cascades (Taylor 2000, Beaty and Taylor 2001). The north-central Sierra Nevada may be more similar to the southern Sierra Nevada in the influences of climate and past fires.

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Literature Cited

Agee, J. K. 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, D.C.

Agee, J. K. 1998. The landscape ecology of western forest fire regimes. Northwest Science 72:24-34.

Ahlstrand, G. M. 1980. Fire history of a mixed conifer forest in Guadalupe Mountains National Park. Pages 4-7 *In* M.A. Stokes and J.H. Dieterich (technical coordinators), Proceedings of the Fire History Workshop. USDA Forest Service General Technical Report RM-81. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Anderson, M. K., and M. J. Moratto. 1996. Native American land-use practices and ecological impacts. Pages 187-206 *In* Sierra Nevada Ecosystem Project: Final report to Congress. Vol. II Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37, Centers for Water and Wildland Resources, University of California, Davis.

Baisan, C. H., and T. W. Swetnam. 1995. Historical fire occurrence in remote mountains of southwestern New Mexico and northern Mexico. Pages 153-156 *In* J. K. Brown, R. W. Mutch, C. W. Spoon, and R. H. Wakimoto (technical coordinators), Proceedings of the Symposium on Fire in Wilderness and Park Management. USDA Forest Service General Technical Report INT-320. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Baker, W. L., and D. Ehle. 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 31:1205-1226

Beaty, R. M., and A. H. Taylor. 2001. Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, southern Cascades, California, USA. Journal of Biogeography 28:955-966.

Biswell, H. H. 1959. Man and fire in ponderosa pine in the Sierra Nevada of California. Sierra Club Bulletin 44:44-53.

Boyce, J. S. 1921. Firescars and decay. The Timberman 22:37.

Brown, P. M., and W. D. Shepperd. 2001. Fire history and fire climatology along a 5 degree gradient in latitude in Colorado and Wyoming, USA. Palaeobotanist 50:133-140.

Burcham, L. T. 1959. Planned burning as a management practice for California wild lands. California Department of Natural Resources, Division of Forestry. Sacramento, California.

Caprio, A. C., and T. W. Swetnam. 1995. Historic fir regimes along an elevational gradient on the west slope of the Sierra Nevada. Pages 173-179 *In* J. K. Brown, R. W. Mutch, C. W. Spoon, and R. H. Wakimoto (technical coordinators), Proceedings of the Symposium on Fire in Wilderness and Park Management. USDA Forest Service General Technical Report INT-320. Inter Mountain Forest and Range Experiment Station, Ogden, Utah.

Clar, C. R. 1959. California government and forestry. Division of Forestry, State of California. Sacramento, California.

Cook, S. F. 1955. The epidemic of 1830-1833 in California and Oregon. University of California Publications in American Archaeology and Ethnology 43:303-326.

Cook, S. F. 1976. The population of the California Indians, 1769-1970. University of California Press, Berkeley, California.

Cook, E. R., D. M. Meko, D. W. Stahle, and M. K. Cleaveland. 1999. Drought reconstructions for the continental United States. Journal of Climate 12:1145-1162.

Dieterich J. H. 1980. The composite fire interval – a tool for more accurate interpretation of fire history. Pages 8-14 *In* M. A. Stokes and J. H. Dieterich (technical coordinators), Proceedings of the Fire History Workshop. USDA Forest Service General Technical Report RM-81. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

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

Dodge, M. 1972. Forest fuel accumulation – a growing problem. Science 177:139-142.

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

Grissino-Mayer, H. D., and H. Fritts. 1998. International Tree-Ring Data Bank. IGBP PAGES/World Data Center-A for Paleoclimatology. NOAA/NGDC Paleoclimatology Program, Boulder CO, USA. Available online at http://www.ngdc.noaa.gov/paleo/treering.html

Hart, S. C., M. K. Firestone, and E. A. Paul. 1992. Decomposition and nutrient dynamics of ponderosa pine needles in a Mediterranean-type climate. Canadian Journal of Forest Research 22:306-314.

Heyerdahl, E. K., and S. J. McKay. 2001. Condition of live fire-scarred ponderosa pine trees six years after removing partial cross sections. Tree-Ring Research 57:131-139.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2001. Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. Ecology 82:660-678.

Holmes, R. L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin 43:69-78.

Husari, S. J., and K. S. McKelvey. 1996. Fire management policies and programs. Pages 1101-1118 *In* Sierra Nevada Ecosystem Project: Final report to Congress. Vol. II Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37, Centers for Water and Wildland Resources, University of California, Davis, California.

Kilgore, B. M., and D. Taylor. 1979. Fire history of a sequoia-mixed conifer forest. Ecology 60:129-142.

Kitzberger, T., and T. T. Veblen. 1997. Influences of humans and ENSO on fire history of *Austrocedrus chilensis* woodlands in northern Patagonia, Argentina. Ecoscience 4:508-520.

Kroeber, A. L. 1925. Handbook of the Indians of California. Bureau of American Ethnology, Bulletin 78. Washington D.C.

Kroeber, A. L. 1929. The valley Nisenan. University of California Publications in American Archaeology and Ethnology 24:253-290.

Laudenslayer, W. F., and H. H. Darr. 1990. Historical effects of logging on forests of the Cascade and Sierra Nevada Ranges of California. Transactions of The Western Section of the Wildlife Society 26:12-23.

Leopold, S. A., S. A. Cain, C. A. Cottam, I. N. Gabrielson, and T. L. Kimball. 1963. Wildlife management in the national parks. American Forestry 69:32-35, 61-63.

Manley, P. N, G. E. Brogan, C. Cook, M. E. Flores, D. G. Fullmer, S. Husari, T. M. Jimerson, L. M. Lux, M. E. McCain, J. A. Rose, G. Schmitt, J. C. Schuyler, and M. J. Skinner. 1995. Sustaining ecosystems: a conceptual framework. USDA Forest Service Report R5-EM-TP-001. Pacific Southwest Region, San Francisco, California.

Matson, R. G. 1972. Aspects of Nisenan ecology. Pages 39-44 *In* Papers on Nisenan environment and subsistence. Center for Archaeological Research Publication 3. University of California, Davis, California.

McBride, J. R. 1983. Analysis of tree rings and fire scars to establish fire history. Tree-Ring Bulletin 43:51-67.

Millar, C. I., and W. Wolfebden. 1999. The role of climate change in interpreting historic variability. Ecological Applications 9:1207-1216.

National Wildfire Coordinating Group. 2001. Review and update of the 1995 federal wildland fire management policy. Interagency Fire Center, Boise, Idaho.

Palmer, W. C. 1965. Meteorological drought. Weather Bureau Research paper No.45. US Department of Commerce, Washington, D.C.

Pyne, S. J. 1982. Fire in America: A Cultural History of Wildland and Rural Fire. Princeton University Press, Princeton, New Jersey.

Show, S. B., and E. I. Kotok. 1924. The role of fire in the California pine forests. USDA Bulletin 1294. Washington D.C.

Skinner, C. N., and C. Chang. 1996. Fire regimes, past and present. Pages 1041-1069 *In* Sierra Nevada Ecosystem Project: Final report to Congress. Vol. II Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37. Centers for Water and Wildland Resources, University of California, Davis, California.

Stephens, S. L. 2000. Mixed conifer and upper montane forest structure and uses in 1899 from the central and northern Sierra Nevada, California. Madrono 47:43-52.

Stephens, S. L. 2001. Fire history of adjacent Jeffrey pine and upper montane forests in the Eastern Sierra Nevada. International Journal of Wildland Fire 10:161-167.

Stephens, S. L., C. N. Skinner, and S. J. Gill. 2003. Dendrochronology-based fire history of Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico. Canadian Journal of Forest Research 33:1090-1101.

Stokes, M. A., and T. L. Smiley. 1977. An Introduction to Tree-Ring Dating. University of Chicago Press. Chicago, Illinois.

Swetnam, T. W., and C. H. Baisan. 2002. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and Southwestern United States. *In* T. T. Veblen , W. Baker, G. Montenegro, and T. W. Swetnam (editors), Fire and Climatic Change in the Americas. Springer-Verlag, New York.

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

Swetnam, T. M., C. D. Allen, and J. L. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications 9:1189-1206.

Swetnam, T. W., M. A. Thompson, and E. K. Sutherland. 1985. Spruce budworm handbook, using dendrochronology to measure radial growth of defoliated trees. USDA Forest Service Agriculture Handbook 639.

Swetnam, T. W., C. H. Basin, K. Morino, and A. C. Caprio. 1998. Fire history along elevational transects in the Sierra Nevada, California. Unpublished final report to Sierra Nevada Global Change Program. Sequoia, Kings Canyon, and Yosemite National Parks. Laboratory of Tree Ring Research, University of Arizona. Tucson, Arizona.

Taylor, A. H. 2000. Fire regimes and forest changes along a montane forest gradient, Lassen Volcanic National Park, southern Cascade Mountains, USA. Journal of Biogeography 27:87-104.

Wagener, W. W. 1961. Past fire incidence in Sierra Nevada forests. Journal of Forestry 59:739-748.

Wilson, N. L. and A. R. Towne. 1978. Nisenan. Pages 387-397 *In* R. F. Heizer (editor), Handbook of North American Indians, vol. 8. Smithsonian Institution Press, Washington D.C.

Zar, J. H. 1999. Biostatistical Analysis, 4th edition. Prentice Hall. Upper Saddle River, New Jersey.

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