International *Journal* of Wildland Fire

Scientific Journal of IAWF

Volume 10, 2001

Address manuscripts and editorial enquiries to:
International Journal of Wildland Fire
Editor in Chief
Dr Gwynfor Richards
Department of Mathematics and Computer Science
Brandon University
Brandon, Manitoba, Canada R7A 6A9
Telephone: +1 204 727 7362
Fax: +1 204 728 7346
Email: richards@brandonu.ca

International Association of Wildland Fire

Address subscription enquiries to:
CSIRO PUBLISHING
PO Box 1139 (150 Oxford St)
Collingwood, Vic. 3066
Australia
Telephone: +61 3 9662 7644
Fax: +61 3 9662 7611
Email: ijwf@publish.csiro.au

CSIRO PUBLISHING

Published by CSIRO Publishing
for the International Association of Wildland Fire

www.publish.csiro.au/journals/ijwf

International Journal of Wildland Fire, 2001, **10**, 161–167

Fire history differences in adjacent Jeffrey pine and upper montane forests in the eastern Sierra Nevada

Scott L. Stephens

Natural Resources Management Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA; present address: Division of Forest Science, Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720-3114, USA. Telephone: +1 510 642 7304; fax: +1 510 643 5438; email: stephens@nature.berkeley.edu

Abstract. Fire history and forest structural characteristics of adjacent Jeffrey pine (*Pinus jeffreyi*) and upper montane forests was investigated in the eastern Sierra Nevada at the University of California Valentine Natural Reserve. Jeffrey pine forests had lower canopy cover, higher amounts of fine fuels, and higher shrub cover when compared to upper montane forest that were dominated by red fir (*Abies magnifica*). Fire dates were determined using standard dendrochronolgy techniques from fire-scarred Jeffrey pine, lodgepole pine (*Pinus contorta* var. *murrayana*), red fir, and western white pine (*Pinus monticola*) trees, snags, stumps, and downed logs. Fires were recorded from 1745 to 1889 and mean fire return intervals were 9 and 24.7 years for the Jeffrey pine and upper montane forest types, respectively. The median fire return interval was 9.0 years for Jeffrey pine and 24.0 years for upper montane forests. Significant differences were found in mean fire intervals and fire history distributions between the two similarly sized fire history plots even though they were only separated by approximately 100 m. This study suggests that fire regimes can vary over very fine spatial scales. Differences in fire regimes are likely due to differences in fuel beds and fire behavior.

Additional keywords: fuel load, spatial fire history, tree canopy cover, flammability, California red fir, lodgepole pine.

Introduction

Fire has been an important ecological process in the forested ecosystems of the Sierra Nevada for thousands of years. The frequent, low- to moderate-severity fires that characterized pre-historical (the period before the influence of European settlement) disturbance regimes in many of these forests affected not only overall forest structure, composition, and fuel loads, but also a wide range of other ecosystem components and processes (Kilgore 1973; Weatherspoon *et al.* 1992; Agee 1993; Skinner and Chang 1996).

Fire frequency was reduced in the Sierra Nevada late in the 19th century due to the introduction of livestock grazing, elimination of Native American ignitions, and fire suppression policies (Vankat 1977; Kilgore and Taylor 1979). The reduction in fire frequency has resulted in forests that are more susceptible to large, high-severity wildfires (McKelvey and Busse 1996). In response, fuels and silvicultural treatments (van Wagtendonk 1996; Stephens 1998) have been proposed at broad spatial scales to reduce fire hazard and increase ecosystem sustainability (USDA 1995).

Past fire frequency may have been affected by fuel and vegetation characteristics but no studies have documented this because of the difficulty in determining if changes in fire regimes were due to differences in the environment (i.e. temperature, relative humidity, precipitation, windspeed) or due to differences in fuel and vegetation characteristics (i.e. fuel load, fuel bulk density, tree canopy cover).

Fire scars can be assigned to a calendar year when cross-dating techniques are used (Dieterich 1980; Swetnam *et al.* 1985). With this technique, a composite fire history can be produced and differences in mean fire return intervals (MFI) (Stokes 1980) over the sampling period can be examined. Statistical analysis can also be conducted spatially to determine whether fire regimes are significantly different between two or more locations (Grissino-Mayer 1995).

Many Native American cultures on the west-side of the Sierra Nevada used fire to achieve specific land management objectives such as food and basket material production (Anderson 1993). However, the Owens Valley and Mono Lake Paiutes that inhabited the eastern Sierra Nevada did not use fire as an important land management tool (Fowler and

10.1071/WF01008 1049-8001/01/020161

Walter 1985; Weaver and Basgall 1986; Blake and Wagner 1987). Lightning and volcanic activity would be other plausible ignition sources in the eastern Sierra Nevada.

No published information exists concerning fire history on the east side of the Sierra Nevada (Skinner and Chang 1996). One unpublished fire history study has been conducted in the eastern Sierra Nevada by the US Forest Service Inyo National Forest (B. Hawkins, personal communication, 1996). In that study, fire scarred trees were sampled with a chain saw and the number of rings counted between fire scars. These data were then compiled to produce a chronology of fire events and the average composite MFI was 15 years in Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.)–red fir (*Abies magnifica* Murr.) forests and 27 years in red fir forests. Individual fire intervals varied from 7 to 31 years, and 9 to 91 years for the Jeffrey pine–red fir and red fir forests, respectively. All ring counts were conducted in the field in this study and the area sampled was estimated to be roughly 10 ha for each forest type.

Two fire history studies have been conducted in upper montane forests of the Cascades Mountains of northern California (Taylor and Halpern 1991; Taylor 1993). Forests dominated by red fir with an understory of small to intermediate (15–30 cm d.b.h.) sized red and white fir [*Abies concolor* (Gord. & Glend.) Lindl.] had an average fire-free interval of 42 years (range 5–65 years, fire history plot size 0.48 ha) (Taylor and Halpern 1991). Using two larger fire history plots (3 ha) in the same region and forest type resulted in mean fire-free intervals of 18.6 and 15.7 years from 1740 to 1945 (Taylor 1993). Prehistoric information on the structure of upper montane forests in the Sierra Nevada is also limited (Stephens 2000).

Differences in tree characteristics such as bark thickness and decay resistance may complicate the reconstruction of accurate fire histories in some forest types. True fir (*Abies* spp.) trees can heal fire-scarred lesions quickly which can make it difficult to accurately sample them without access to complete stump cross-sections (Taylor 1993). In contrast, Jeffrey pine is an excellent fire scar sampling species because once fire injured the tree rescars easily, scars are externally visible, and the injured wood decomposes at a very low rate.

The objective of this study was to develop fire histories and forest structural characteristics for adjacent Jeffrey pine and upper montane forests of the eastern Sierra Nevada. The hypothesis tested was that the fire histories of adjacent Jeffrey pine and upper montane forests were not significantly different.

Methods

Study area

Fire history was investigated in Jeffrey pine and upper montane forests at the University of California Valentine Camp Natural Reserve, approximately 1 km west of the town of Mammoth Lakes, California. The fire history plots are located in T4S R27E E 1/2 of section 4, latitude 37° 37′ 30″ N, longitude 118° 59′ 30″ W, between 2530 and 2600 m above sea level.

Valentine Camp lies in the transition zone between the sagebrush desert of the Great Basin and the coniferous forests of the eastern Sierra Nevada. Valentine Camp's climate is typical of the Sierra Nevada's eastern slopes, except that the reserve receives more precipitation due to its proximity to Mammoth Pass and Minaret Summit gap. Average precipitation is 51–64 cm and winter snow comprises approximately 85% of the total; sporadic summer thunderstorms contribute the rest (Howald and Orr 1981). In January, average temperatures range from a low of –10°C to a high of 4°C. Summers are generally moderate and dry, with an average August daily temperature of 25°C and low of 6°C.

The soils of the reserve are young and undeveloped, consisting of pumice ash, glacial till, and lava, with only small amounts of organic material (Shepard *et al.* 1978). Major soil types found on the reserve include loamy skeletal soil, coarse loamy soil, and sandy skeletal soil. Thixotropic soils also occur on the reserve in small pockets where thick layers of volcanic ash have accumulated.

Forest structure and fuel loads

Ten 0.1 ha circular plots were randomly placed within the Jeffrey pine (five plots) and upper montane (five plots) fire history plots (Fig. 1) to determine forest composition. Diameter at breast height (d.b.h.) was measured on all trees greater than 2.5 cm d.b.h. The following characteristics were calculated for each forest type: average basal area, average density, average quadratic mean diameter by species, percentage basal area by species, and percentage tree density by species.

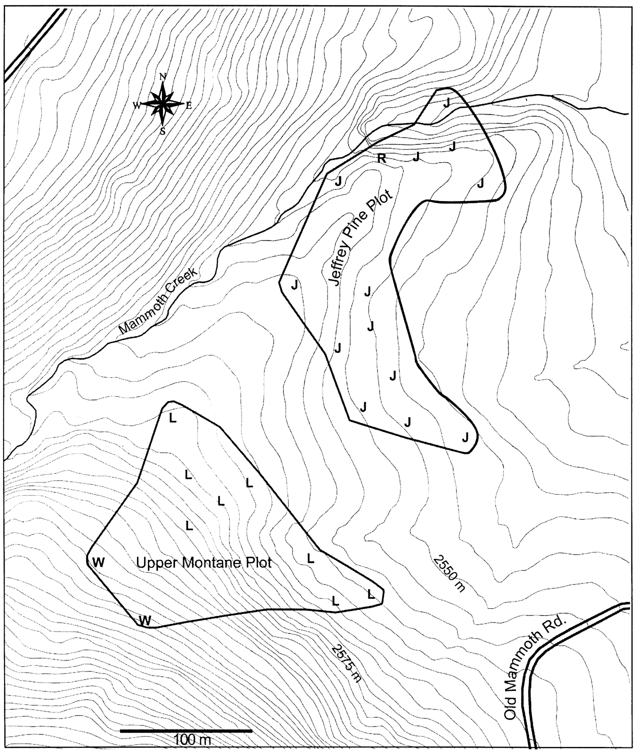

Fig. 1. Fire history plots and locations of sampled trees at the University of California Valentine Camp Reserve, California.The following symbols depict tree species: J, Jeffrey pine; R, red fir; L, lodgepole pine; W, western white pine. Area surrounded by the Jeffrey pine fire history plot was not included in this plot because it is a mountain alder (*Alnus incana* ssp. *tenuifolia* Nutt.) thicket.

Canopy cover is the summation of crown areas as seen from above the canopy, and field methods used to measure it include crown line intercept transects, visual estimation, 'moosehorns' (a hand-held device to measure overstory cover), and densiometers (Gill *et al.* 2000). Densiometers are relatively simple to use but commonly over-estimate cover (Cook *et al.* 1995). Crown line intercept transects are unbiased and record the amount of tree crown that intersects a linear surface transect (Gill *et al.* 2000).

In this study, canopy cover was measured using two methods, crown line intercepts and spherical densiometers. Three 10 m crown line intercept transects with random azimuths were placed, beginning at each inventory plot center, and a clinometer was used to determine when the transect entered or exited tree crowns with a spatial resolution of 0.1 m. In addition, a concave spherical densiometer was placed directly over the plot center in the four cardinal directions (north, west, south, east) and the numbers of equi-spaced dots within the grid that did not intersect tree crowns were counted. The number of dots was then multiplied by 1.04 and subtracted from 100 to estimate canopy cover. An average of the four canopy cover measurements was then calculated to estimate canopy cover for each of the 10 plots.

Surface and ground fuels were also sampled at each plot using the line intercept method (Brown 1974). The same transects used to estimate canopy cover were used to inventory surface and ground fuels. One and 10-hour fuels were sampled from 0 to 2 m, 100-hour fuels from 0 to 3 m, and 1000-hour and larger fuels from 0 to 10 m on each transect. Duff and litter depth were measured at 2 and 3 m and fuel height at 5 and 10 m along each transect. Shrub percentage cover was measured continuously using the line intercept method on each of the 10-m fuel transects.

Surface and ground fuel loads were calculated by using appropriate equations developed for Sierra Nevada forests (van Wagtendonk *et al.* 1996, 1998). Coefficients required to calculate all surface and ground fuel loads were arithmetically weighted by the basal area fraction (percentage of total basal area by species) to produce accurate estimates of fuel loads (Jan van Wagtendonk, personal communication, 1999).

Fire history

Cross sections of fire-scarred trees, stumps, and down logs were obtained in 1995 from the two adjacent fire history plots (Fig. 1). Fire-scar samples were taken from all live trees, snags, stumps, and down logs exhibiting fire history evidence within the two fire history plots. Fire scarred trees were sectioned with a chainsaw in order to locate the best series of fire scars, and up to three wedges or cross-sections were removed from each down log or stump and taken to the laboratory for analysis. Live trees were sampled more conservatively, with only a small amount of living tissue removed from each scarred area.

Valentine Camp has experienced only light forest harvesting from early settlers and 19th century miners and, therefore, very few stumps were available for sampling. Live trees with fire scars were much more common and they contributed 79% of the fire history data.

Structural weakening of the stem as a result from fire-scar sampling can increase mortality from wind-throw (Agee 1993) but is minimized in pine species if less than 20% of the live cross-section is sampled (Steve Arno, personal communication, 1994). As of 1999, no trees sampled in this study have failed due to wind-throw. All fire scar samples were taken to the laboratory and sanded with belt sanders using 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 cross-dating (Dieterich 1980). Composite fire histories were produced for the Jeffrey pine and upper montane fire history plots. Composites of multiple trees will usually provide a more comprehensive record of past fires for the site in question (Dieterich 1980; Agee 1993).

The MFIs given in this study are for the period of record. The period of record is defined as the period beginning with the earliest scar recorded in the plot and ending with the last scar recorded in the plot (Skinner and Chang 1996). Long periods of fire exclusion (late 1800s to present) will not be used in the calculation of MFI since they would bias MFI to longer intervals.

The FHX2 software package was used to analyse all fire history information (Grissino-Mayer 1995, software available on world wide web). An *F*-test was first performed to determine if significant differences existed in the sample variances between the two fire history plots. Student's *t*-test was then used to determine if significant differences ($P < 0.05$) existed in MFI and the Kolmogorov-Smirnov test was used to determine if significant differences ($P < 0.05$) occurred in the fire history distributions between the two fire history plots (Barber 1988; Grissino-Mayer 1995).

Results

The Jeffrey pine fire history plot is dominated by Jeffrey pine and red fir (Table 2). Jeffrey pine accounted for 56% of plot basal area and this species had the largest average d.b.h. (53 cm). Red fir was the most common tree in the Jeffrey pine fire history plot (53% of plot stocking) but contributed only 31% of plot basal area because of their smaller size. White fir and lodgepole pine (*Pinus contorta* var. *murrayana* (Grev. & Balf.) Critchf.) were also found in the Jeffrey pine fire history plot but at much lower densities. Forest overstory cover estimated using crown line intercepts and spherical densiometers was 27.8 and 44.4%, respectively (Table 4). Average basal area of the five inventory plots was 61.7 m^2/ha.

Understory plants include many shade intolerant plants such as greenleaf manzanita (*Arctostaphylos patula* E. Greene), buckbrush (*Ceanothus cordulatus* Kellogg), big sagebrush (*Artemisia tridentata* Nutt.), antelope bitterbrush (*Purshia tridentata* Pursh), snowberry (*Symphoricarpos rotundifolius* A. Gray), and Anderson's Lupine (*Lupinus andersonii* S. Watson) (Howald and Orr 1981).

Table 1. Summary of fire history information from Valentine Camp, California

Forest type	Jeffrey pine	Upper montane
Mean composite fire interval (years)	9.0	24.8
Median fire return interval (years)	8.0	24.0
Fire interval range (years)	4–17	13–38
Average plot elevation (m)	2550	2575
Range in plot elevation (m)	2530–2565	2555–2600
Aspect	South-east	East
Slope (%)	0–10	10–30
Plot area (ha)	2.1	2

Table 2. Jeffrey pine fire history plot characteristics
Standard error is given in parentheses

Species	Average d.b.h. (cm)	Percentage basal area	Percentage trees/ha
Pinus jeffreyi	52.2 (12.24)	55.9	32.3
Abies magnifica	32.0 (5.44)	31.1	53.3
Abies concolor	44.6 (6.62)	12.1	10.8
Pinus contorta	21.2 (4.85)	0.9	3.6

Table 3. Upper montane fire history plot characteristics
Standard error is given in parentheses

Species	Average d.b.h. (cm)	Percentage basal area	Percentage trees/ha
Abies magnifica	31.4 (2.78)	72.0	72.8
Pinus contorta	33.2 (3.18)	24.9	22.3
Abies concolor	20.3 (3.55)	0.5	1.2
Pinus monticola	26.6 (3.93)	2.3	3.3
Pinus jeffreyi	35.5 (0)	0.29	0.2
Tsuga mertensiana	5.0 (0)	0.01	0.2

Table 4. Measurement of forest canopy cover within the fire history plots
Standard error is given in parentheses

Forest type	Percentage cover	
	Transect	Spherical densiometer
Jeffrey pine	27.8 (9.81)	44.4 (6.52)
Upper montane	63.7 (2.81)	83.2 (4.77)

The upper montane fire history plot is dominated by red fir and lodgepole pine (Table 3). Red fir was the most common species and contributed to 72% of plot basal area and 73% of plot stocking. Lodgepole pine was the next most common species contributing 25% of plot basal area and 22% of plot stocking. Western white pine (*Pinus monticola* Dougl.), mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.), white fir, and Jeffrey pine were also found in this area but they were relatively rare. Forest overstory cover estimated using crown line intercepts and spherical densiometers was 63.7 and 83.2%, respectively (Table 4). Average basal area of the five inventory plots was 66.7 m^2/ha.

Common understory species in the upper montane fire history plot include shade tolerant waterleaf phacelia (*Phacelia hydrophylloides* A. Gray) and spotted coralroot (*Corallorhiza maculata* Raf.) (Howald and Orr 1981). Upper montane forests are widely distributed and they can be found on both the western and eastern sides of the Sierra Nevada (Rundel *et al*. 1977).

Shrub percentage cover in the Jeffrey pine and upper montane fire history plots was 31 and 2%, respectively (Table 5). Average fuel height in the Jeffrey pine and upper montane fire history plots was 27.7 and 4.4 cm, respectively (Table 5). Fine fuel load (dead and down fuels with diameters less than 7.62 cm) was larger in the Jeffrey pine fire history plot but 1000-hour (fuel with diameters greater than 7.62 cm) fuel loads were over six times greater in the upper montane fire history plot (Table 5).

Sixteen fire-scarred trees, snags, and stumps were sampled in the Jeffrey pine (14 had usable information) and 11 in the upper montane (10 had usable information) fire history plots (Fig. 1). Three fire-scar samples could not be used because of excessive rotten wood. Fires were recorded from 1745 to 1889 and mean fire return intervals were 9.0 and 24.7 years for the Jeffrey pine and upper montane forest types, respectively (Table 1). Intervals between fires recorded by individual trees varied from 4 to 17 years and 13 to 38 years for Jeffrey pine and upper montane forest types, respectively. The median fire return interval was 9.0 years for Jeffrey pine and 24.0 years for the upper montane forests.

The two fire history plots have similar areas (2.1 ha Jeffrey pine fire history plot, 2.0 ha upper montane fire history plot) and were separated by approximately 100 m (Fig. 1). Sample variances between the two fire history plots were not significantly different (P = 0.274) and therefore, Student's t-test with equal variance was used to determine if MFI was significantly different. Significant differences in MFI (P = 0.0003) and fire history distributions (P = 0.0293) were detected between the Jeffrey pine and upper montane fire history plots. Composite fire histories were produced for Jeffrey pine and upper montane forests (Figs 2 and 3).

Of the fires recorded in the upper montane fire history plot, 86% were also recorded in the adjacent Jeffrey pine fire history plot. Only one fire was recorded uniquely in the upper montane plot (1758) whereas 20 different fires were recorded in the Jeffrey pine fire history plot but not recorded in the adjacent upper montane fire history plot.

Discussion

The last fire that burned through the fire history plots occurred over 100 years ago. Fire was relatively common before this period and the lack of fire has probably affected current forest composition and structure. Even with this long fire-free period, the Jeffrey pine fire history plot is still dominated by large Jeffrey pines and the upper montane fire history plot by red fir. Canopy cover would change at a slower rate when compared to tree density because of the long periods needed for trees to mature and contribute to the overstory. Even with the long fire-free interval, canopy cover is only slightly higher than that recorded in the Jeffrey pine forests of the Sierra San Pedro Martir Mountains of northern Baja California, Mexico, which have never been harvested or experienced a policy of fire suppression (S. Stephens, unpublished data, 1999).

Table 5. Average fuel load and shrub cover within the fire history plots
Standard error is given in parentheses

Forest type	1, 10, 100 hour fuel load (t/ha)	1000 hour fuel load (t/ha)	Litter and duff load (t/ha)	Shrub cover (%)	Fuel height (cm)
Jeffrey pine	3.13 (1.05)	1.78 (1.22)	28.38 (7.48)	31.0 (8.31)	27.67 (6.63)
Upper montane	2.44 (0.62)	11.88 (5.54)	33.19 (9.71)	2.07 (1.29)	4.4 (0.32)

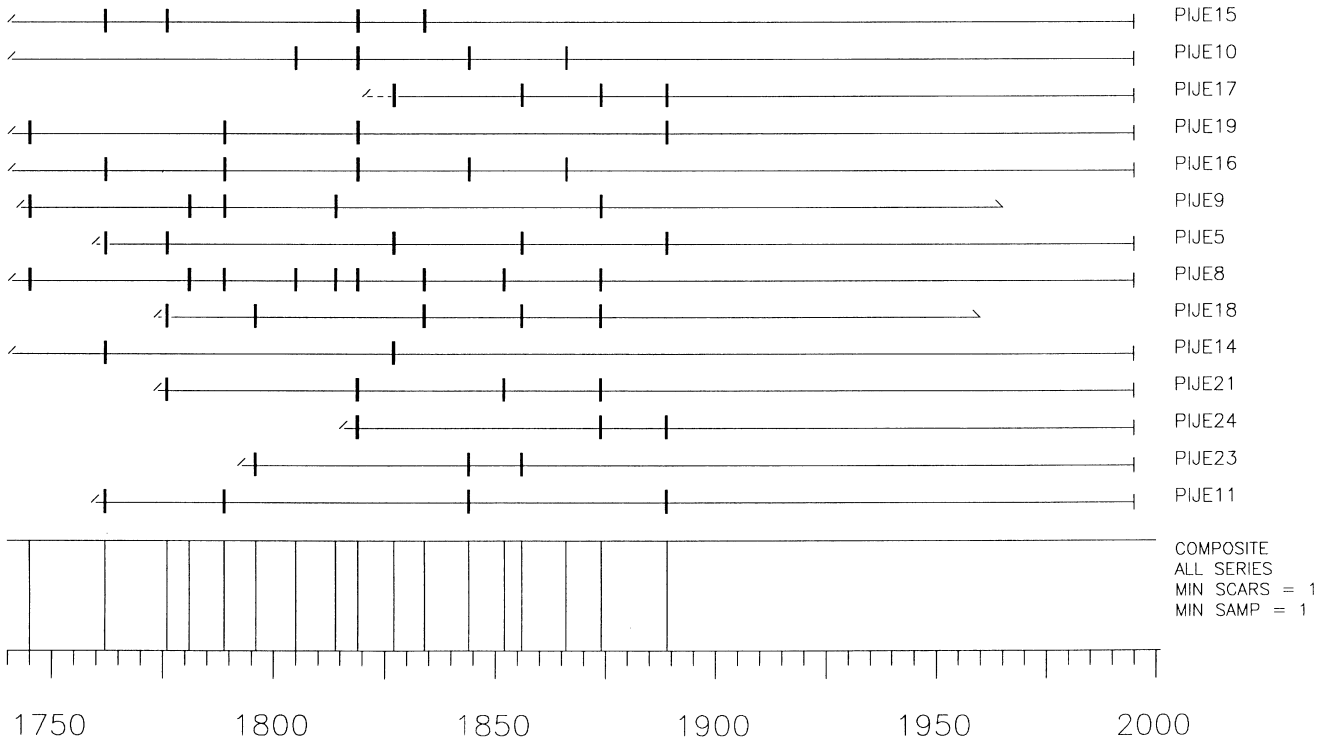

Fig. 2. Composite fire history of Jeffrey pine fire history plot at the University of California Valentine Camp Reserve, California. Each horizontal line represent one fire scarred tree, stump, or downed log. Each vertical tick mark represents an individual fire scar.

Fire history studies utilizing cross-dating techniques can provide accurate and precise information of the temporal and spatial distribution of the past fires, but the MFI calculated from such studies will be conservative. This occurs because not all fires scar each tree and scars may be destroyed by later fires, rot, and insects. Fires recorded in this study were probably ignited by lightning since ethnographic evidence suggest that Native Americans did not use fire frequently in this area (Fowler and Walter 1985; Weaver and Basgall 1986; Blake and Wagner 1987).

The spatial arrangement and types of fuels have a strong influence on fire spread, especially when burning conditions are not extreme (Turner and Romme 1994). In some cases, species composition and fuel characteristics may not foster the spread of a fire once ignited (Despain 1985; Knight 1987) and this was observed in this study because of the differences in the number of fires recorded in the two adjacent fire history plots. Differing abilities of species to record past fires may complicate this interpretation.

Several fire histories have detected differences in MFI along elevational transects (Romme and Knight 1981; Veblen *et al.* 1994; Turner and Romme 1994; Caprio and Swetnam 1995) but it not possible to determine if the changes detected are produced from differences in climate or indirectly through vegetation and fuels. In this study, the climate experienced by the two adjacent fire history plots was probably similar. With similar climates, differences in fuels (load, bulk density) and vegetation (tree canopy cover) could have influenced their respective fire histories.

Surface and ground fuel characteristics in the two forest types could influence their respective fire frequencies or the ability of the fires to be recorded. Bulk densities of litter and duff ground fuels are approximately twice as large in white and red fir stands than in Jeffrey pine stands (van Wagtendonk *et al.* 1998). Denser forest floor fuel profiles will dry at slower rates and, therefore, will require a longer drying period before combustion is possible. Cycles of flammability depend on the species composition of the live biomass, drying conditions, wind, and the characteristics of the dead fuel (Knight 1987).

The upper montane forest has high canopy cover which reduces light penetration, windspeed, and subsequent drying of surface and ground fuels; fuels in the Jeffrey pine forest would dry faster because of lower canopy cover. The microclimates in these two forests are different and this could also influence ignition frequencies and subsequent fire behavior. Species composition in the two fire history plots could also be affected by microclimate differences.

A fire ignited in the Jeffrey pine forest would probably burn at higher intensity than in an upper montane forest because of differences in surface fuels (Jeffrey pine has higher fine fuel load, needle-drape over higher shrub cover would produce higher fireline intensity). This could also allow the Jeffrey pine trees to record past fires more

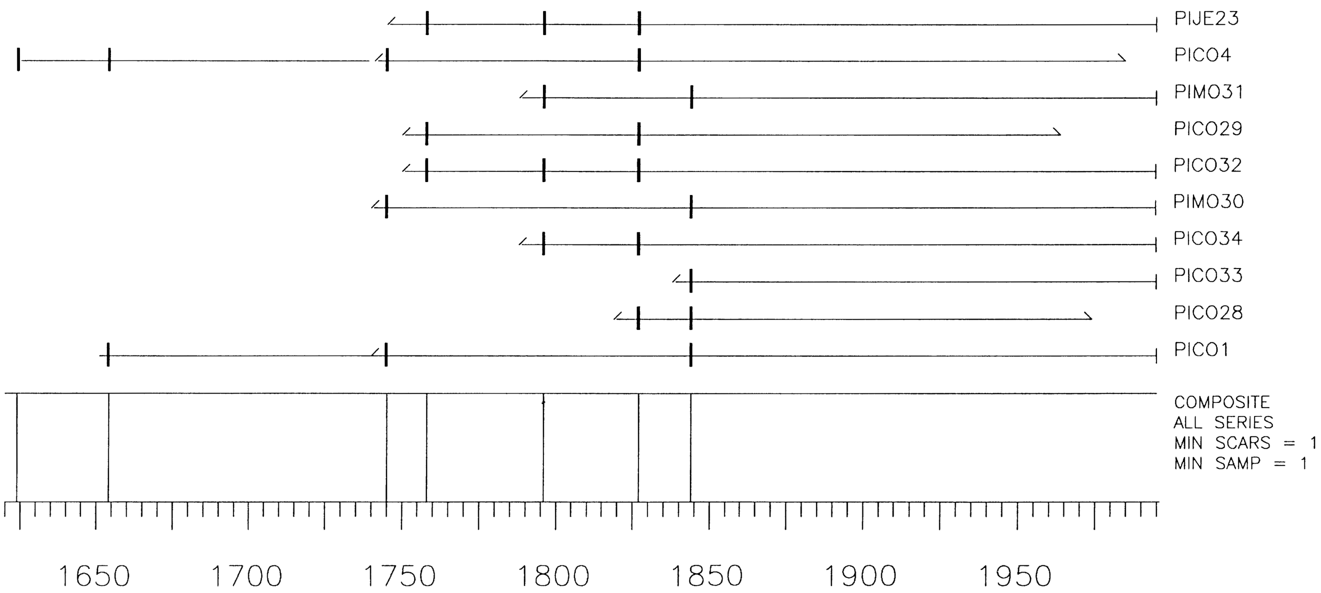

Fig. 3. Composite fire history of upper montane fire history plot at the University of California Valentine Camp Reserve, California. Each horizontal line represent one fire scarred tree, stump, or downed log. Each vertical tick mark represents an individual fire scar.

efficiently than the upper montane forest. The low number of stumps in the upper montane forest could have biased the results because some scars may have been healed over and not externally visible.

One fire occurred in 1758 in the upper montane forest type that was not recorded in the Jeffrey pine forest. This one event could have been ignited by lightning but probably burned a very small area. Fuel moisture and weather conditions probably prevented fire spread into adjacent Jeffrey pine forests for this particular ignition. In contrast, 20 different fires were recorded in the Jeffrey pine fire history plot that were not recorded in the adjacent upper montane fire history plot, which suggests that the Jeffrey pine forest may be more flammable (Mutch 1970), may record fire more readily, or a combination of both.

This study suggests that significant differences in fire frequency may occur over very fine spatial scales. The Jeffrey pine forest in this study burned much more frequently than the adjacent montane forest even though no physical barriers such as rock outcrops or streams separated the fire history plots.

Conclusion

Average MFI in the Jeffrey pine and upper montane forest types was 9 and 24.7 years, respectively. Significant differences ($P < 0.05$) were found in the mean fire intervals and fire history distributions between the two forest types that were separated by only 100 m. Although the sources of these fires are uncertain, lightning is the most plausible explanation given the past land uses of this area.

This study suggests that fire regimes can vary over very fine spatial scales. The Jeffrey pine forest site appears to have burned more frequently than the adjacent upper montane forest site even though no physical barriers between the units were present. The differences in fire regimes are likely due to differences in fuel beds and fire behavior.

Acknowledgements

I thank Scott Christenson and Lewis Stephens for their assistance in the collection of field data. I thank Peter Brown, Rowan Rowntree, Robert Martin and two anonymous reviewers for their comments on this manuscript. I also thank Nancy Peterson Walter for providing me with information on Native American cultures of the eastern Sierra Nevada. Daniel Dawson, Robert Jellison, Eric Reinboldt and Matt Novak assisted in figure production. I especially thank Daniel Dawson of the University of California Natural Reserve System for supporting this work.

References

Agee JK (1993) 'Fire ecology of Pacific Northwest forests.' (Island Press: Washington D.C.) 493 pp.

Anderson MK (1993) Experimental approach to assessment of the potential ecological effects of horticultural practices by indigenous people on California Wildlands. Ph.D. dissertation, University of California, Berkeley.

Barber GM (1988) 'Elementary statistics for geographers.' (The Guilford Press: New York) 513 pp.

Blake EA, Wagner MR (1987) Collection and consumption of Pandora moth (*Coloradia naddora lindseyi*) larvae by Owens Valley and Mono Lake Paiutes. *Bulletin of the Entomological Society of America* **33**, 22–27.

Brown JK (1974) Handbook for inventorying downed wood material. USDA Forest Service General Technical Report INT-16.

Caprio AC, Swetnam TW (1995) Historic fire regimes along an elevational gradient on the west slope of the Sierra Nevada. USDA Forest Service General Technical Report INT-320.

Cook JG, Stutzman TW, Bowers CW, Brenner KA, Irwin LL (1995) Spherical densiometers produce biased estimates of forest canopy cover. *Wildlife Society Bulletin* **23**(4), 711–717.

Despain DG (1985) Ecological implications of ignition sources in park and wilderness fire management programs. In 'Proceedings, symposium and workshop on wilderness fire'. (Tech Coords JE Lotan, BM Kilgore, WC Fischer and RW Mutch.) USDA Forest Service, General Technical Report INT-182. pp. 93–97.

Dieterich JH (1980) The composite fire interval—a tool for more accurate interpretation of fire history. Proceedings of the fire history workshop, USDA Forest Service General Technical Report RM-81. pp. 8–14.

Fowler CS, Walter NP (1985) Harvesting Pandora moth larvae with the Owens Valley Paiute. *Journal of California and Great Basin Anthropology* **7**, 155–165.

Gill SJ, Biging GS, Murphy E (2000) Modeling conifer tree crown radius and estimating canopy cover. *Forest Ecology and Management* **126**, 405–416.

Grissino-Mayer HD (1995) FHX2: Software for the analysis of fire history from tree rings. (Laboratory of Tree-Ring Research, The University of Arizona: Tucson) 111 pp.

Howald AM, Orr BK (1981) 'A flora of Valentine Eastern Reserve.' (The Herbarium: Department of Biological Sciences, University of California, Santa Barbara) 97 pp.

Kilgore BM (1973) The ecological role of fire in Sierran conifer forests: Its application to national park management. *Quaternary Research* **3**, 496–513.

Kilgore BM, Taylor D (1979) Fire history of a sequoia mixed conifer forest. *Ecology* **60**(1), 129–142.

Knight DH (1987) Parasites, lightning, and the vegetation mosaic in wilderness landscapes. In 'Landscape heterogeneity and disturbance'. (Ed. MG Turner) Chapter 4, pp. 59–83. (Springer-Verlag: New York)

McBride JR (1983) Analysis of tree rings and fire scars to establish fire history. *Tree-Ring Bulletin* **43**, 51–67.

McKelvey KS, Busse KK (1996) Twentieth century fire patterns on forest service lands. In 'Sierra Nevada Ecosystem Project, final report to congress. Assessments and Scientific Basis for Management Options'. Vol. II, pp. 1119–1138. University of California Davis, Centers for Water and Wildland Resources.

Mutch RW (1970) Wildland fires and ecosystems—a hypothesis. *Ecology* **51**, 1046–1051.

Romme WH, Knight DL (1981) Fire frequency and subalpine forest succession along a topographic gradient in Wyoming. *Ecology* **62**, 319–326.

Rundel PW, Parsons DJ, Gordon DT (1977) Montane and subalpine vegetation of the Sierra Nevada and Cascade Ranges. In 'Terrestrial vegetation of California'. (Eds MG Barbour and J Major) pp. 559–599. (John Wiley and Sons)

Shepard BJ, Wasserman M, Dodge B, Hoellwarth N (1978) Soil survey report: Valentine Eastern Sierra Reserve. (University of California Natural Reserve System: Santa Barbara, CA)

Skinner CN, Chang C (1996) Fire regimes, past and present. . In 'Sierra Nevada Ecosystem Project, final report to congress. Assessments and Scientific Basis for Management Options'. Vol. II, pp. 1041–1069. University of California Davis, Centers for Water and Wildland Resources.

Stephens SL (1998) Effects of fuels and silvicultural treatments on potential fire behavior in mixed conifer forests of the Sierra Nevada, CA. *Forest Ecology and Management* **105**, 21–34.

Stephens SL (2000) Mixed conifer and upper montane forest structure and uses in 1899 from the Central and Northern Sierra Nevada, CA. *Madrono* **47**(1), 43–52.

Stokes MA (1980) The dendrology of fire history. In 'Proceedings of a fire history workshop'. USDA Forest Service GTR RM-81. pp 1–3.

Swetnam TW, Thompson MA, Sutherland EK (1985) Spruce budworm handbook, using dendrochronology to measure radial growth of defoliated trees. Agriculture handbook No. 639. Cooperative State Research Service, Forest Service, U.S. Department of Agriculture.

Taylor AH (1993) Fire history and structure of red fir (*Abies magnifica*) forests, Swain Mountain Experimental Forest, Cascade Range, northeastern California. *Canadian Journal of Forest Research* **23**, 1672–1678.

Taylor AH, Halpern CB (1991) The structure and dynamics of *Abies magnifica* forests in the southern Cascade Range, USA. *Journal of Vegetation Science* **2**, 189–200.

Turner MG, Romme WH (1994) Landscape dynamics in crown fire ecosystems. *Landscape Ecology* **9**(1), 59–77.

United States Department of Agriculture Forest Service (1995) Course to the future: positioning fire and aviation management. U.S. Forest Service, Department of Fire and Aviation Management. Washington, D.C. 19 pp.

van Wagtendonk JW (1996) Use of a deterministic fire growth model to test fuel treatments. In 'Sierra Nevada Ecosystem Project, final report to congress. Assessments and Scientific Basis for Management Options'. Vol. II, pp. 1155–1166. University of California Davis, Centers for Water and Wildland Resources.

van Wagtendonk JW, Benedict JM, Sydoriak WM (1996) Physical properties of woody fuel particles of Sierra Nevada conifers. *International Journal of Wildland Fire* **6**(3), 117–123.

van Wagtendonk JW, Benedict JM, Sydoriak WM (1998) Fuel bed characteristics of Sierra Nevada conifers. *Western Journal of Applied Forestry* **13**(3), 73–84.

Vankat JL (1977) Fire and man in Sequoia National Park. *Annals of the Association of American Geographers* **67**,17–27.

Veblen TT, Hadley KS, Nell EM, Kitzberger T, Reid M, Villalba R (1994) Disturbance regime and disturbance interactions in a Rocky Mountain subalpine forest. *Journal of Ecology* **82**(1), 125–136.

Weatherspoon CP, Husari SJ, van Wagtendonk JW (1992) Fire and fuels management in relation to owl habitat in forests of the Sierra Nevada and Southern California. USDA Forest Service General Technical Report PSW-133. pp. 247–260.

Weaver RA, Basgall ME (1986) Aboriginal exploitation of Pandora moth larvae in east-central California. *Journal of California and Great Basin Anthropology* **8**, 161–179.