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Fire regimes and forest changes in mid and upper montane forests of the southern Cascades, Lassen Volcanic National Park, California, U.S.A.

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Abstract

Aim Spatial and temporal variation in fire regime parameters and forest structure were assessed.

Location A 2630-ha area of mid- and upper montane forest in Lassen Volcanic National Park (LVNP).

Methods Two hypotheses were tested concerned with fire-vegetation relationships in southern Cascades forests: (1) fire regime parameters (return interval, season of burn, fire size, rotation period) vary by forest dominant, elevation and slope aspect; and (2) fire exclusion since 1905 has caused forest structural and compositional changes in both mid- and upper montane forests. The implications of the study for national park management are also discussed.

Results Fire regime parameters varied by forest compositional group and elevation in LVNP. Median composite and point fire return intervals were shorter in low elevation Jeffrey pine (*Pinus jeffreyi*) (JP) (4–6 years, 16 years) and Jeffrey pine–white fir (*Abies concolor*) (JP-WF) (5–10 years, 22 years) and longer in high elevation red fir (*Abies magnifica*)—western white pine (*Pinus monticola*) (RF-WWP) forests (9–27 years, 70 years). Median fire return intervals were also shorter on east-facing (6–9 years, 16.3 years) and longer on south- (11 years, 32.5 years) and west-facing slopes (22–28 years, 54-years) in all forests and in each forest composition group. Spatial patterns in fire rotation length were the same as those for fire return intervals. More growing season fires also occurred in JP (33.1%) and JP-WF (17.5%) than in RF-WWP (1.1%) forests. A dramatic decline in fire frequency occurred in all forests after 1905.

Conclusions Changes in forest structure and composition occurred in both mid- and upper montane forests due to twentieth-century fire exclusion. Forest density increased in JP and JP-WF forests and white fir increased in JP-WF forests and is now replacing Jeffrey pine. Forest density only increased in some RF-WWP stands, but not others. Resource managers restoring fire to these now denser forests need to burn larger areas if fire is going to play its pre-settlement role in montane forest dynamics.

Keywords
Fire regimes, forest change, California, dendroecology, disturbance, montane forests.

INTRODUCTION

The role of natural disturbances such as fire, insect attacks and windstorms in maintaining or changing species distribution and abundance patterns in forested landscapes is widely recognized (e.g. White, 1979; Sprugel, 1991). In the Pacific North-west, fire has affected most areas with the greatest frequency and patterns of succession, community structure and composition and diversity have all been linked to recurring fire (Franklin & Dyrness, 1973; Agee, 1981, 1993; Stewart, 1989; Morrison & Swanson, 1990; Halpern & Spies, 1995; Taylor & Skinner, 1998). The role of fire in ecosytem dynamics has changed since the turn of the century. A United States Federal policy of suppressing fires on public land has been in place since 1905 (Pyne, 1982). Removal of fire for nearly a century has caused dramatic changes in the structure and composition of forests, at least in the most fire-prone ecosytems (Franklin & Dyrness, 1973; Agee, 1981, 1993, 1995). Stands are now more dense because seedlings and saplings are not thinned by periodic low-intensity surface fires and there has also been a compositional shift from fire-tolerant to fire-intolerant species (e.g. McNeil & Zobel, 1980; Weatherspoon *et al*., 1992; Agee, 1993; Chang, 1996; Skinner & Chang, 1996). The impact of fire suppression on forest conditions in less fire-prone higher elevation forests is more uncertain (e.g. Pitcher 1987; Taylor & Halpern, 1991; Agee, 1993; Chappell & Agee, 1996). Moreover, restoring fire to changed forests is a top priority for National Park resource managers who are mandated to perpetuate pre-settlement ecosystem structures and processes on park lands (e.g. Bonnicksen & Stone, 1982; Parsons *et al*., 1986; Kilgore & Nichols 1995).

Despite the recognition that fire is a key disturbance process in Pacific North-western montane forests little is known about fire regimes in the pre-settlement period. Identifying the characteristics (e.g. seasonal timing, frequency, return interval, severity and extent of fire) of pre-settlement fire regimes, how they vary spatially and temporally, and how fire regimes influence forest structure and composition is essential for understanding fires role in long-term montane forest dynamics. Furthermore, data on pre-settlement fire regimes and forest conditions can serve as an ecological reference to evaluate how federal fire polices have affected montane forest ecosystems.

Trees in the mid- and upper montane zone in the southern Cascades are segregated primarily by elevation and secondarily by topographic position (e.g. Franklin & Dyrness, 1973; Rundel *et al*., 1977; Barbour, 1988; Parker, 1991). Low elevation (< 1700 m) xeric uplands are dominated by either Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) and/or ponderosa pine (*Pinus ponderosa* Dougl.). White fir (*Abies concolor* Gord & Glend.) may be locally abundant on more mesic upland sites at low elevation but it increases in abundance with elevation and forms mixed stands with ponderosa and Jeffrey pine, incense cedar (*Calocedrus decurrens* Torrey Florin) and sugar pine (*Pinus* lambertiana Dougl.) between 1700 and 2000 m. Above 2000 m, white fir is replaced by red fir (*Abies magnifica* A. Murr.) and western white pine (*Pinus monticola* Dougl.) which are upper montane zonal dominants. Topographic lowlands that are mesic, receive cold air drainage, have poor soils or have experienced high severity fire are usually dominated by lodgepole pine (*Pinus contorta* Dougl.) (Franklin & Dyrness, 1973; Ziegler, 1978; Parker, 1993).

Pre-settlement fire regimes in mid and upper montane forests may vary with forest dominant, elevation and slope aspect. Limited evidence from fire-scarred trees suggests that median fire return intervals are shorter (12–14 years) in low elevation Jeffrey pine and ponderosa pine forests and longer (17–29 years) in mixed pine and white fir, red fir (20–47 years) and lodgepole pine forests (39–60 years) (McNeil & Zobel, 1980; Taylor, 1993; Solem, 1995; Bekker, 1996; Chappell & Agee, 1996). Moreover, in mixed pine–white fir forests fire return intervals seem to be shorter on drier south-facing slopes than on other aspects (Bekker, 1996). Variation in other fire regime parameters and the magnitude of twentieth-century forest changes due to fire exclusion have not been quantified in the southern Cascades.

In this study, dendroecological and photographic evidence are used to test two hypotheses concerned with fire–vegetation relationships in southern Cascade montane forests. First, fire-scar records are used to test the hypothesis that a suite of pre-settlement fire regime parameters (i.e. return interval, seasonal timing, extent, rotation period) varies both between (dominant species, elevation) and within (slope aspect) mid- and upper montane forests. Secondly, tree age and size structure data and repeat photography are used to test the hypothesis that federal fire exclusion policy has caused twentieth-century forest changes (density, composition) in both mid- and upper montane forests. The implications of these data for national park resource mangers, who are charged with restoring fire to altered montane forest ecosystems in the southern Cascades, are then discussed.

STUDY AREA

Montane forests were studied in a 2630-ha area on Prospect Peak in Lassen Volcanic National Park (LVNP) at the southern tip of the Cascades in northern California (Fig. 1). LVNP's climate is characterized by cold wet winters and warm dry summers. At Manzanita Lake (1750 m), 20 km west of Prospect Peak, most (84%) of the mean annual precipitation (104.9 cm) falls between November and May as snow. Depth of April snowpack commonly exceeds 5 m in the upper montane (> 2400 m) zone (Taylor, 1990a, 1995). Mean monthly temperatures at Manzanita Lake are lowest in January (–1.1 °C) and highest in July (16.9 °C).

Prospect Peak (2420 m) is a gently sloping (≈ 10°) basaltic shield volcano (Williams, 1932; Kane, 1984) covered with shallow well-drained soils. There are no stream courses on the peak. Below 2100 m, on the southern and eastern flanks of the peak, soils are buried beneath a layer (0.3–1.5 m) of ash deposited by the most recent (mid-1600s) eruption of Cinder Cone (Michael Clynne, pers. comm.). There is no forest cover between Cinder Cone and the southern base of Prospect Peak. Lava and scoria from the Cinder Cone eruption buried and killed the earlier forest and these young surfaces are still bare (Diller, 1891). Nonforested lava outcrops also occur on the south and west sides of Prospect Peak, especially above 2100 m (Fig. 1).

Native Americans and early European settlers may have influenced fire regimes on Prospect Peak but there is no evidence that they did so. There are native American occupation sites nearby and tribes in the Lassen area are known to have used fire to drive game and manage plant populations for food and fibre, but there are no sites in the study area (Schulz, 1954; Ann K. Smith, pers. comm.). Europeans first traversed the study area in large numbers in 1850 with the opening of Noble's trail, which runs along the east and south flanks of Prospect Peak (Strong, 1973). Parts of LVNP were heavily grazed by sheep and cattle between 1870 and 1905 (Strong, 1973; Taylor, 1990b) but the impact of stockmen and grazing on fire regimes is unknown. Forests on Prospect Peak became part of the Lassen National Forest Reserve in 1905, part of the Lassen

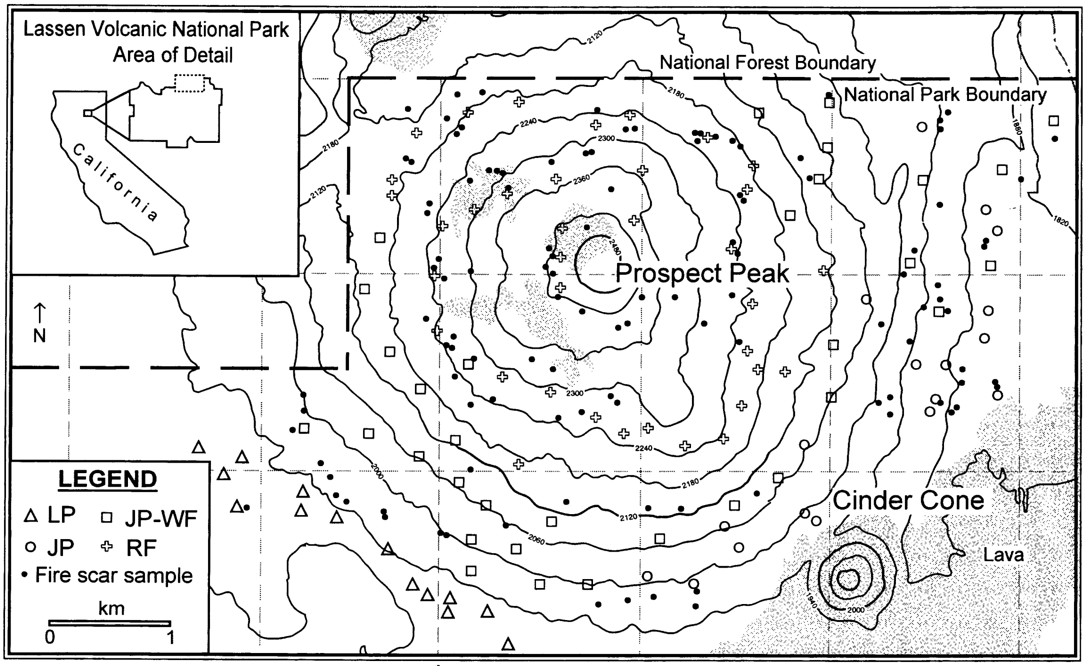

Figure 1 Location of study area, forest sample plots and fire-scar samples on Prospect Peak, Lassen Volcanic National Park, California. The different symbols represent Jeffrey pine (JP), Jeffrey pine–white fir (JP-WF), red fir–western white pine (RF-WWP) and lodgepole pine forests (LP) (see Table 1). Shaded areas are lava or scoria and have no forest cover.

National Forest in 1907 and part of LVNP in 1916. A policy of suppressing fire was implemented in 1905 with the establishment of the national forest reserve system (Strong, 1973).

METHODS

Forest structure and composition

Sites for forest sampling were selected by stratifying the study area by slope aspect and forest cover type using a topographic and forest cover type map and distributing samples ($n = 100$) among strata along an elevational gradient. Sites were not sampled on the north slope below 2250 m because they were outside LVNP and had been logged. Stands with homogeneous structure, composition and environment were chosen subjectively and sampled using 400-m^2 plots, but plot sizes were occasionally larger (1000 m^2) or smaller (200 m^2), depending on stand density. All live trees ≥ 4.0 cm at breast height (d.b.h.) were measured and saplings (> 1.4 m tall < 4.0 cm d.b.h.) and seedlings (0.5 m–1.4 m tall) were counted in each plot. Data on the age structure of tree populations in each plot were also collected. An average of twenty trees (range 9–33) that spanned the range of tree diameters in each plot were cored 30 cm above the ground. Tree ages were then determined by counting annual growth rings beneath a binocular microscope. The location (GPS), elevation, slope aspect and steepness, slope position and slope configuration of each plot was also recorded and the last four topographic variables were used to generate a relative moisture index value (TRMI) (Parker, 1982). Plot locations were also placed on the topographic–forest cover type map.

Forest types were identified on Prospect Peak using the following procedure. First, importance values (IV) were calculated for each species in each plot as the sum of relative density and relative basal area (maximum 200). Secondly, Ward's method was used to cluster species' IV in all plots. Ward's method minimizes the within-cluster sum of squares with respect to between-cluster variance (Everitt, 1974).

Twentieth-century forest changes were identified from recent patterns of tree regeneration. If twentieth-century fire suppression caused forest changes, then a pattern of increased tree establishment and survival beginning about 100 years ago should be evident in the age structure of tree populations. The following method was used to identify temporal patterns of regeneration in each forest type. First, plots with similar size–class distributions were grouped using Ward's method of cluster analysis (Everitt, 1974). The variables clustered were the density (ha^{-1}) of seedlings, saplings and trees of each species in 10-cm d.b.h. classes from 4 cm to 144 cm d.b.h. Secondly, tree age-structures for each size-structural group were developed by combining all stem ages from plots in a group into 20-year age-classes.

Twentieth-century forest changes were also documented using repeat photography. Four stands, first photographed on Prospect Peak in 1925 (Weislander, 1935), were relocated and rephotographed in 1993.

Fire regimes

Fire regimes (i.e. return interval, extent, season, fire rotation) were reconstructed using two types of data: (1) fire scars in partial wood cross-sections removed from fire-scarred trees; and (2) radial growth changes in tree cores (e.g. Arno & Sneck, 1977; Barrett & Arno, 1988). A total of 126 partial cross-sections were collected from dead and live trees from all strata (forest cover type, aspect, elevation) on Prospect Peak. All sample locations were determined with a GPS and they were placed on the topographic–forest cover type map.

Fire dates in cross-sections were identified by first sanding each specimen to a high polish and then cross-dating the sample's tree ring series (e.g. Stokes & Smiley, 1968) with a nearby tree ring chronology (e.g. Holmes *et al*., 1986). The calendar year of the tree ring in which each fire scar occurred was then recorded.

The season each fire burned was interpreted from the position of each fire scar within an annual growth ring (cf. Baisan & Swetnam, 1990). Scar positions were: early (first 1/3 of earlywood); middle (second 1/3 of earlywood); late (last 1/3 of earlywood); latewood (in latewood); dormant (at ring boundary). In this area, dormant season fires are interpreted to be fires that burned in late summer or autumn after radial growth ceased for the year (e.g. Caprio & Swetnam, 1995).

Fire dates in cores from plots were identified by dating the onset of sudden radial growth declines (200% decline in radial growth for 5 years compared to the previous 5 years) (e.g. Arno & Sneck, 1977; Barrett & Arno, 1988; Brown & Swetnam, 1995). All tree cores with growth declines were cross-dated and the first calendar year of a growth decline was deemed fire-related if an adjacent fire-scar sample recorded a fire in the same year.

Temporal variation in fire return intervals were identified by comparing fire occurrence in the pre-settlement (before 1850), settlement (1850–1904) and fire exclusion (post-1905) periods. These periods were chosen for comparison because they correspond to changes in land use in LVNP that could affect fire occurrence. A composite record of fire dates was used for temporal comparisons because they are more sensitive to changes in ignition frequency or burning patterns that may be related to land-use changes than samples from a restricted area (Dieterich, 1980).

Spatial variation in fire return intervals was identified by comparing median fire return intervals for both composite and point samples in each forest type/slope aspect group using a distribution-free Kruskal–Wallis *H*-test (Sokal & Rohlf, 1981). Two composite fire chronologies were calculated for each forest type/slope aspect group: one for all recorded fires and the second for more widespread fires that scarred > 10% of samples. Point fire intervals or the record of successive fires in single samples were also calculated. A point interval reflects the time dependence of fire occurrence related to fuel accumulation at a single point and they give a conservative estimate of fire occurrence. Composite fire intervals, in contrast, tend to decrease as samples are combined because nonoverlapping fires from a larger study area are combined into a single fire chronology (Kilgore & Taylor, 1979; Arno & Petersen, 1983).

Fire extent was estimated from fire area maps. Fire maps were drawn by placing the date of each fire on mapped sample points and then drawing a fire boundary around each group of points that recorded a fire that year. Only fires recorded at three or more points were mapped. Most fires burned areas outside the study area boundary but these areas were not measured as part of a fire. Two assumptions were made when drawing fire boundaries: (1) that the boundary occurred equidistant between points with and without evidence of fire; and (2) that fires burned uphill until they reached a barrier to fire-spread, such as lava flows or a change in fuel bed (i.e. long-needle vs. compact short-needle surface fuels) (e.g. Agee *et al*., 1990; Agee, 1993). Fire boundary locations between points could therefore be modified if barriers were present. Aerial photographs and the forest cover type map were used to identify barriers. Finally, the area of each mapped fire was estimated using a planimeter.

Fire rotation, or the number of years needed to burn an area the size of a study area (Heinselman, 1973), was estimated for each forest cover type and slope aspect group using the mapped fire areas. Forest cover/aspect areas were estimated from the forest cover type/topographic map. The time period used to estimate fire rotation varied among forest cover/aspect units because fire record lengths were different in each unit. For example, no fires were mapped before 1751 in red fir–western white pine forests but seventeenth- and eighteenth-century fires were common in Jeffrey pine forests.

RESULTS

Forest composition

Four forest types were identified from the cluster analysis of species importance values and the forest types were segregated by elevation and relative soil moisture ($P < 0.001$, ANOVA) (Table 1). Lodgepole pine forests (LP) ($n = 14$) occur on mesic flats at the base of the peak between 1840 m and 1960 m and they are strongly dominated by lodgepole pine. Jeffrey pine forests (JP) ($n = 18$) occur on the lower flanks of the peak between 1855 m and 2100 m; ponderosa pine is codominant in some stands and white fir is a common associate. Jeffrey pine–white fir forests (JP-WF) ($n = 33$) occupy mid-elevations between 1840 m and 2220 m. Stands are mixed but white fir is always the dominant and red fir is a common associate above 2100 m. Red fir–western white pine forests (RF-WWP) ($n = 35$) occupy the highest elevation sites (2083–2420 m) on Prospect Peak and stands are strongly dominated by red fir. Western white pine is a characteristic associate, except at lower altitudes where white fir is more abundant.

Fire regimes

Fire record

Eighty-six cross-dated fire dates were identified from 666 fire scars in the 126 fire-scar samples on Prospect Peak. Fires were recorded between 1507 and 1937 but the length of the fire record varied by forest type. Nineteen fires scarred samples ($n = 68$) between 1685 and 1937 in RF-WWP forests, forty-five fires scarred samples ($n = 22$) between 1546 and 1903 in JP-WF forests, and sixty-four fires scarred samples

Table 1 Mean importance value (maximum 200), basal area (m^2 ha^{-1}) and density (ha^{-1}) of trees (> 4.0 cm d.b.h.) in forest types identified by cluster analysis of species importance values on Prospect Peak. Forest types are Jeffrey pine (JP), Jeffrey pine–white fir (JP-WF), red fir–western white pine (RF-WWP) and lodgepole pine (LP).

	Forest type											
	LP n = 14			JP n = 18			JP-WF n = 33			RF-WWP n = 35		
Species	IV	BA	Density	IV	BA	Density	IV	BA	Density	IV	BA	Density
White fir	10.7	0.3	37.5	36	17.8	168	141	50.7	973	11.9	5.4	54.9
Red fir	4.2	0.4	55.4	0.2	0.02	2.8	15.5	4.5	99	153	64	736
Lodgepole pine	183	54.3	1143	0	0	0	0	0	0	0.1	0.01	0.8
Jeffrey pine	2.6	0.3	10.7	145	54.8	580	38.9	20.3	115	7	1.5	17.9
Sugar pine	0	0	0	0	0	0	1.1	0.7	0.3	0	0	0
Western white pine	0	0	0	0	0	0	2.4	2.6	6	28.3	9.9	113
Ponderosa pine	0	0	0	18.6	8.4	36.7	0	1.4	2.3	0	0	0
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Elevation (m)	1928	1880	1960	1945	1855	2100	2044	1840	2220	2232	2083	2420
TRMI	47	40	58	36	26	56	32	21	51	33	21	46

n = number of samples in each forest type. Elevation and relative soil moisture (TRMI) varied among forest groups ($P < 0.001$, ANOVA). TRMI varies between 0(xeric) and 60(mesic).

(n = 36) in JP forests between 1507 and 1932. Scars in samples (n = 12) from lodgepole pine trees could not be reliably attributed to fire (i.e. no charcoal present), therefore dates of scars for LP forests are not reported.

Composite fire intervals were calculated for different periods for each forest type. The earliest fire date in a forest type must have been recorded by at least two samples. The period was 1656–1994 for JP and JP-WF forests, and 1751–1994 for RF-WWP forests. Point interval estimates were calculated for all recorded fires in multiple-scarred samples (n = 99). Consequently, the length of the fire record varied with each sample.

Season of fires

The position of fire scars in annual growth rings varied ($P < 0.05$, Kolmorgorov–Smirnoff two-sample test) by forest type on Prospect Peak (Table 2). More fires in low-elevation JP forests (33.1%) occurred during the growing season (early to latewood) than in JP-WF (17.5%) or RF-WWP (1.1%) forests.

Table 2 Position of fire scars within annual growth rings from fire-scar samples in different forest types (see Table 1) on Prospect Peak.

	Forest type					
Season of fire	n	JP	n	JP-WF	n	RF-WWP
Dormant	184	66.90%	104	82.50%	92	98.90%
Latewood	9	3.30%	1	0.80%	0	0
Late	43	15.60%	9	7.10%	1	1.10%
Middle	29	10.50%	12	9.50%	0	0
Early	10	3.60%	0	0	0	0
Unknown	86	23.80%	65	34%	21	18.40%

n = the number of fire scars. Seasonal categories are: early, first 30% of earlywood; middle, second 30% of earlywood; late, last 30% of earlywood; latewood, in latewood; dormant, at ring boundary. Nondormant season fires were more frequent in Jeffrey pine forests than in the other forest types ($P < 0.05$, Kolmorgorov–Smirnoff two-sample test).

Fire return intervals

Temporal patterns

There was no difference ($P > 0.05$, t-test) in the composite mean fire return interval for the pre-settlement (before 1850) and settlement (1850–1904) period for any forest type on Prospect Peak. However, the composite mean fire return interval for the fire suppression period was longer ($P < 0.001$, t-test) than for the other periods and fire occurrence dropped abruptly after 1905 (Table 3; Fig. 2).

Table 3 Mean composite fire return interval (years) for the pre-settlement (before 1850), settlement (1850–1904) and fire suppression (1905–94) periods in each forest type (see Table 1) on Prospect Peak. There was no difference in the mean fire return interval between the pre-settlement and settlement period but it was longer ($P < 0.05$, t-test) during the fire suppression period.

Forest type	Time period	mean	n	Time period	mean	n	Time period	mean	n
JP	1656–1849	4.9	39	1850–1904	5.2	10	1905–94	89	1
JP-WF	1656–1849	7.5	51	1850–1904	4.9	10	1905–94	—	0
RF-WWP	1751–1849	15.3	6	1850–1904	5.9	7	1905–94	44	2

n = the number of fire return intervals.

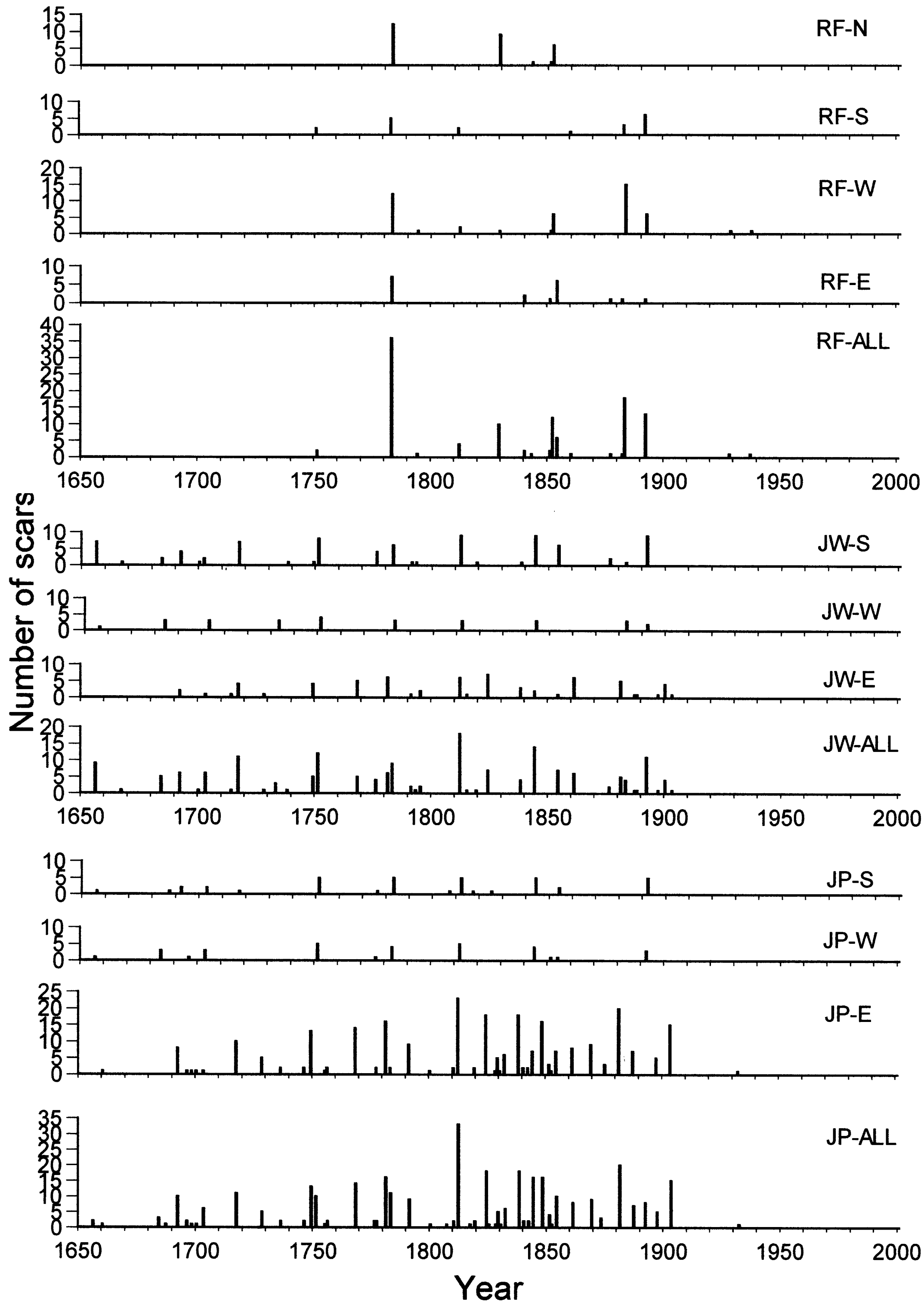

Figure 2 *caption on following page*

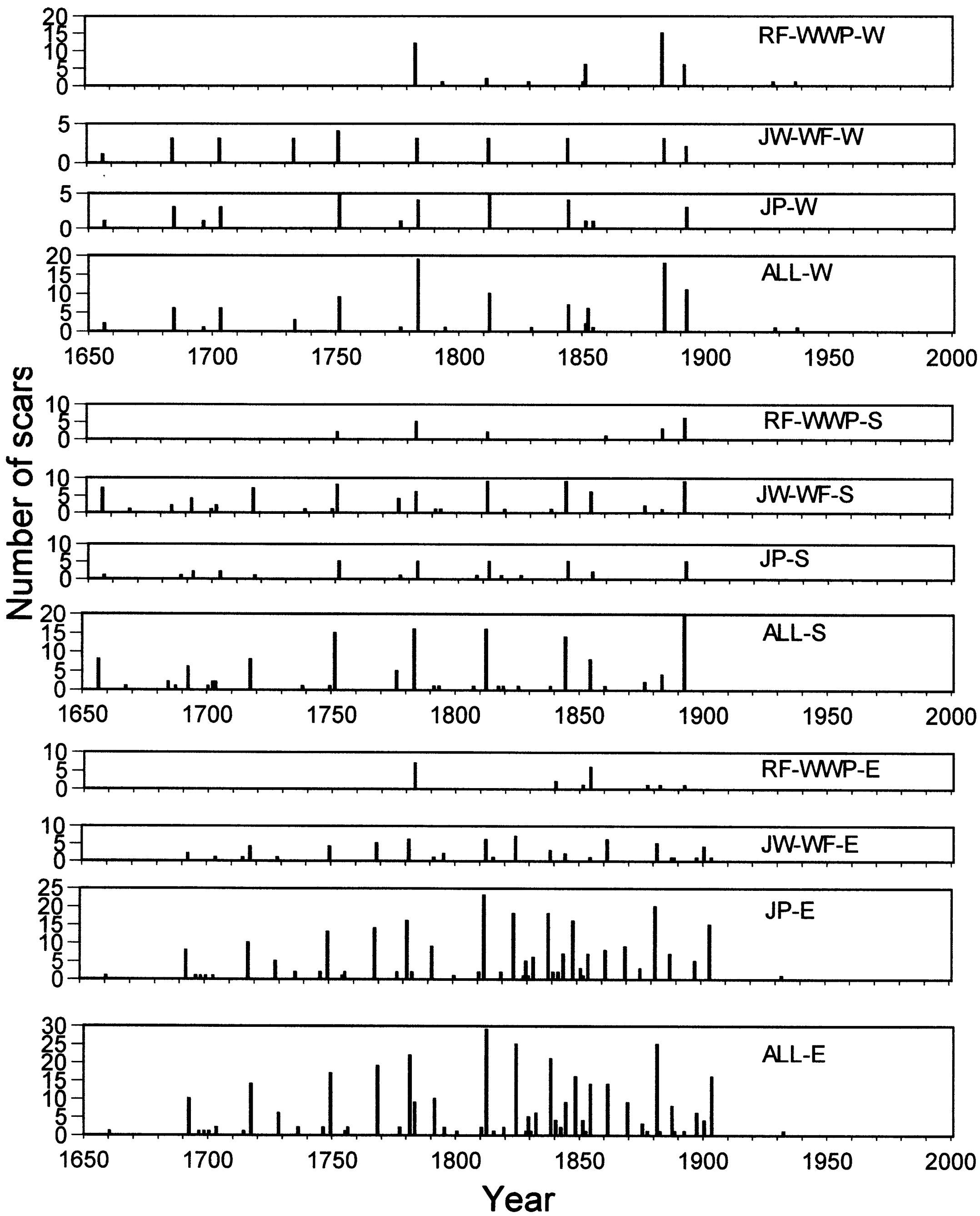

Figure 2 Composite fire chronology for Jeffrey pine (JP), Jeffrey pine–white fir (JP-WF) and red fir (RF-WWP) forests on Prospect Peak arranged by slope aspect. For JP and JP-WF forests the fire record is for the period 1656–1994 and for RF-WWP forests it is 1751–1994.

Spatial patterns

There was spatial variation in fire return intervals between and within forest types on Prospect Peak. Median fire return intervals for the composite record of all fires were shortest for JP (4 years) and JP-WF (5 years) and longer for RF-WWP (9 years) forests ($P < 0.05$) (Table 4). The fire return interval pattern for the composite record of larger fires (> 10% scarred) was the same and median values were shorter for JP (6 years) and JP-WF (10 years) and longer for RF-WWP (27 years) ($P < 0.05$) (Table 4).

Fire return intervals also varied by slope aspect. Median fire return interval values for the composite record of all fires were shorter on east- (6 years) and south- (11 years) and longer on west-facing (22 years) slopes ($P < 0.05$) (Table 4; Fig. 2). The pattern was the same for more widespread fires (> 10% scarred). Median fire return interval values were

Table 4 Composite fire interval (years) statistics for years with one recorded fire and years when fires scarred > 10% of trees by forest type (see Table 1) and slope aspect group on Prospect Peak. Median values in a row with a number and median values in a column with a letter were different (*P* < 0.05, Kruskal–Wallis *H*-test).

	Aspect														
	East			South			West			North			All		
Forest type	Median	Range	*n*	Median	Range	*n*	Median	Range	*n*	Median	Range	*n*	Median	Range	*n*
All scarred															
JP	5.5[1,a]	1–32	42	12.5[1,a]	5–38	14	25[1]	3–48	11				4[a]	1–29	51
JP-WF	9.5[1,a]	1–21	22	9[1,a]	2–25	20	29[1]	9–39	9				5[a]	1–17	36
RF-WWP	10.5[a]	3–57	6	29[a]	9–48	6	17	1–36	9	11	1–46	4	9[a]	1–36	16
All	6[1]	1–57	70	11[1]	2–48	40	22[1]	1–48	29				3	1–25	70
> 10% scarred															
JP	6.5[1]	3–25	22	12.5[1,a]	5–38	14	25[1]	3–48	11				6[a]	2–21	25
JP-WF	9.5[1]	1–21	22	19.5[1,a]	7–34	12	29[1]	9–39	9				10[a]	2–29	21
RF-WWP	35.5	14–57	2	30.5[a]	9–71	4	31	9–69	3	46	23–67	3	27[a]	9–46	4
All	9[1]	1–25	49	11[1]	2–71	39	28[1]	3–69	23				9	2–32	23

n = the number of intervals.

Table 5 Point fire interval (years) statistics by forest type (see Table 1) and slope aspect group on Prospect Peak. Median values in a row with a number and median values in a column with a letter were different (*P* < 0.05, Kruskal–Wallis *H*-test).

	Aspect														
	East			South			West			North			All		
Forest type	Median	Range	*n*	Median	Range	*n*	Median	Range	*n*	Median	Range	*n*	Median	Range	*n*
JP	13.2[1,a]	9.5–32	26	32[1,a]	4.5–32	5	30.5[1,a]	21.5–32	5				16[a]	9.5–32	36
JP-WF	19.5[1,a]	15.5–34	8	32[1,a]	19–48	10	31.5[1,a]	29–48	4				29.8[a]	15.5–38	22
RF-WWP	57[1,a]	26–86	8	109[1,a]	71–109	7	77[1,a]	45–109	15	60[1,a]	46–69	11	70[a]	26–109	41
All	16.3[1]	9.5–85	40	32.5[1]	14.5–109	22	54[1]	21.5–109	24				31.75	9.5–109	86

n = the number of samples. The fire record includes all fire intervals on multiple-scarred samples beginning in 1507.

shorter on east- (9 years) and south- (11 years) and longer on west-facing slopes (27 years) (*P* < 0.05) (Table 4; Fig. 2).

There was also variation in fire return intervals by slope aspect within a forest type. Median fire return intervals for both composite chronologies were shorter in JP and JP-WF forests on east- and south-facing slopes and longer on west-facing slopes (*P* < 0.05) (Table 4). However, composite median fire return intervals were similar on all slope aspects in RF-WWP forests (*P* > 0.05) (Table 4).

Point fire return intervals were longer than composite intervals and they also varied by forest type and slope aspect. Median point fire return intervals were shorter for JP (16 years) and JP-WF (29.8 years) and longer for RF-WWP (70 years) forests (*P* < 0.05) (Table 5). Point fire return intervals were also shorter on east facing slopes and longer on other aspects across all forests and in each forest type (*P* < 0.05) (Table 5).

There was also a strong correlation between mean point fire return interval and elevation. The Pearson product–moment correlation between mean point fire return intervals and elevation was $r = 0.83$ ($P < 0.01$) on Prospect Peak (Fig. 3).

Fire areas

Fire areas varied by year and by forest type on Prospect Peak. The mean and median fire area for the period 1627–1904 was 457 ha and 366 ha (range, 39–1537 ha), respectively (Fig. 4). Eight fires > 800 ha burned on Prospect Peak and they occurred in 1692, 1717, 1751, 1783, 1812, 1844, 1854 and 1892. Mean and median fire areas were largest for JP (mean = 241 ha, median = 200 ha, range 39–742 ha) which cover 742 ha, and JP-WF forests (mean = 195 ha, median = 167 ha, range = 6–666 ha) which cover 753 ha and smallest for RF-WWP forests (mean = 176 ha, median = 129 ha, range = 11–733 ha) which cover 1135 ha on Prospect Peak (Fig. 4).

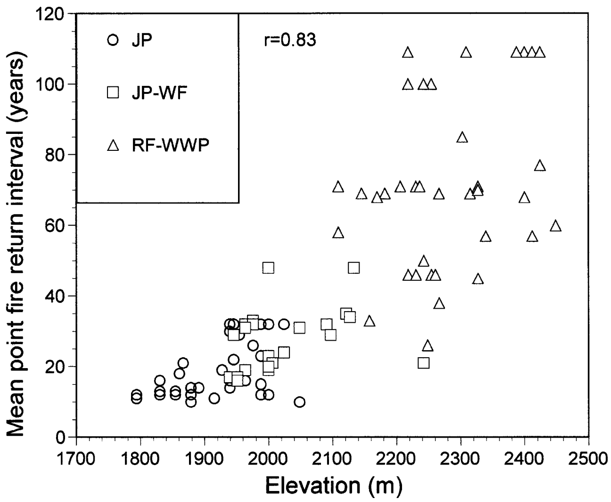

Figure 3 Plot of mean point fire return interval and elevation on Prospect Peak. r = Pearson product–moment correlation coefficient.

Table 6 Pre-settlement fire rotations (years) by forest type (see Table 1) on Prospect Peak.

Forest type	Slope aspect				
	All	East	South	West	North
JP	24.5	17.1	28	25.1	
JP-WF	31.3	17.7	30.5	42.9	
RF-WWP	75.9	72.2	73.8	62.3	64

Fire rotation

Fire rotations varied by forest type and slope aspect on Prospect Peak (Table 6). Fire rotations were shortest for JP (24.5 years) and JP-WF (31.3 years) and longer for RF-WWP (75.9 years) forests (Table 6). There was also spatial variation in fire rotations within a forest type. Fire rotations for JP, and JP-WF forests were shorter on east-facing slopes than on south- and west-facing ones. Fire rotations were similar on all slope aspects in the RF-WWP zone (Table 6).

Forest size and age-structure

Ten forest structural groups were identified on Prospect Peak by the cluster analysis. Two groups were identified in lodgepole pine forests and two characteristics distinguish the groups. LP-1 stands are much denser and white fir and Jeffrey pine < 24 cm d.b.h. are more abundant in LP-2. Trees in both groups are mostly 60–120-year-old lodgepole pine but stems > 180 years old are present in both groups (Fig. 5).

Two Jeffrey pine groups were identified and Jeffrey pine is the most abundant species in both of them. JP-1 stands have dense (1768 stems ha^{-1}) mixed populations of understorey (stems < 34 cm d.b.h.) Jeffrey pine and white fir and a sparse (thirty-nine stems ha^{-1}) overstorey (stems > 54 cm d.b.h.) of mainly Jeffrey pine. JP-2 stands have more ponderosa pine, fewer (494 stems ha^{-1}) understorey (stems < 34 cm d.b.h.) Jeffrey pine and white fir, and more (seventy-three stems ha^{-1}) overstorey (stems > 54 cm d.b.h.) Jeffrey pine and ponderosa pine than JP-1 stands. In both groups, overstorey pines range in age from 120 to 300 + years and most understorey stems began to establish about 100 years ago (Fig. 5).

Three JP-WF groups were identified on Prospect Peak and they are distinguished by both stand density and composition. JP-WF-1 stands have the densest (2318 stems ha^{-1}) understoreys (stems < 34 cm d.b.h.) and white fir stems in the understorey are more abundant (fifteen-fold) than those of Jeffrey pine. The overstorey (stems > 54 cm d.b.h.) is relatively dense (seventy-two stems ha^{-1}) and contains more Jeffrey pine (three-fold) than white fir stems. In JP-WF-2 stands, the understorey (stems < 34 cm d.b.h.) is also dense (1722 stems ha^{-1}), and contains seventeen-fold more white fir than Jeffrey pine stems. The overstorey (> 54 cm d.b.h.) is sparse (fifty-six stems $ha^{-1)}$) and is about half Jeffrey pine and

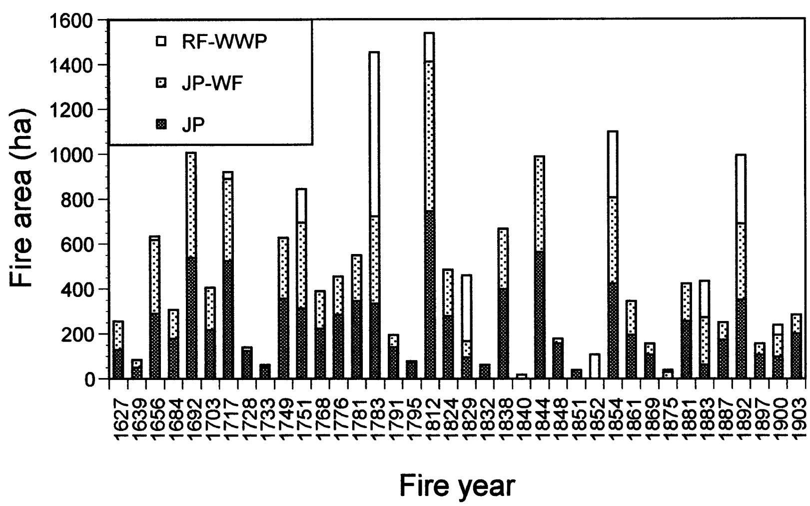

Figure 4 Areas burned by individual fires by forest type (see Table 1) on Prospect Peak. Fire areas were estimated only for fires that scarred or injured three or more trees. Fire areas were calculated in red fir–western white pine forests for the period 1751–1903 and the period for other forests was 1627–1903.

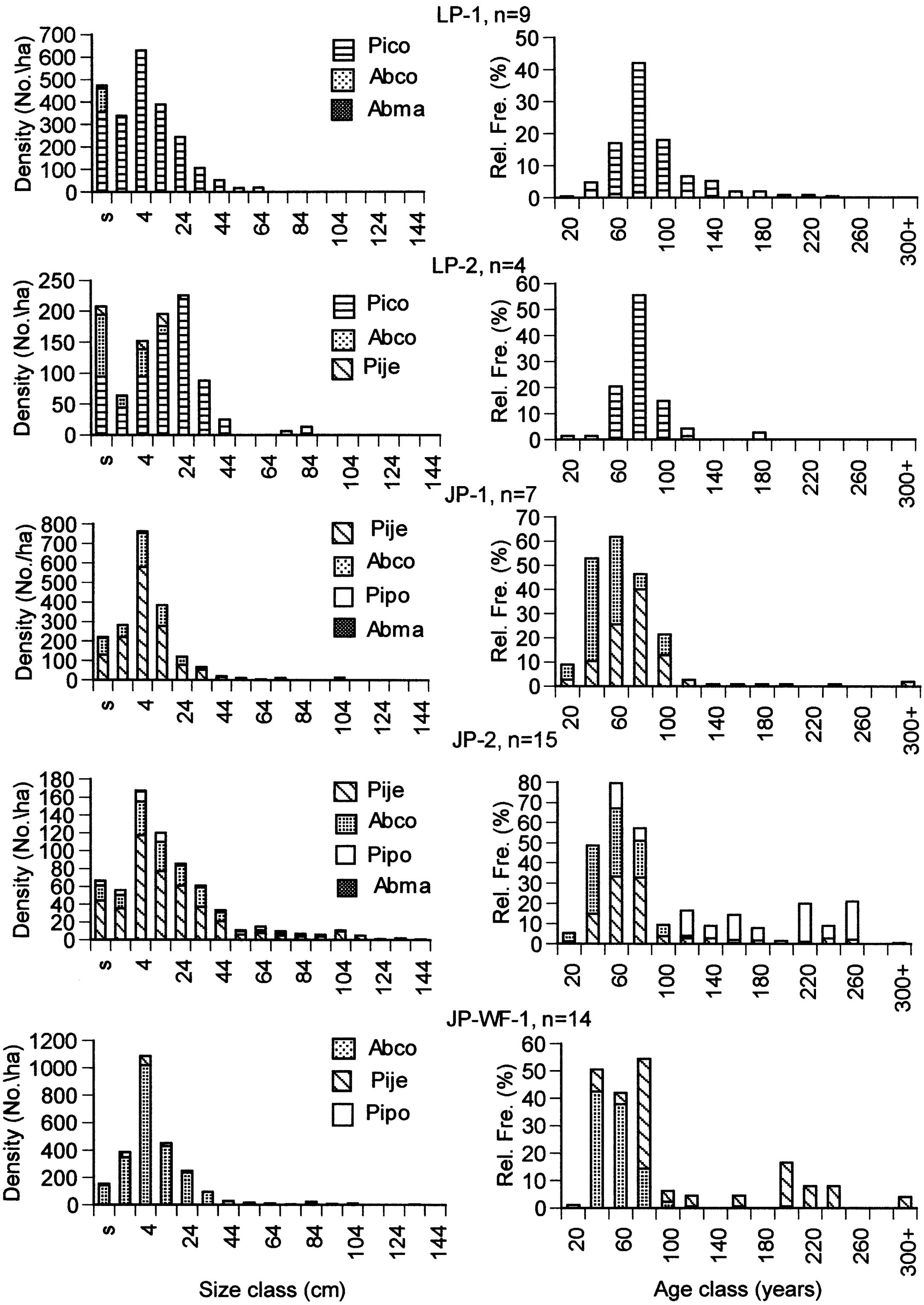

Figure 5 *caption on following page*

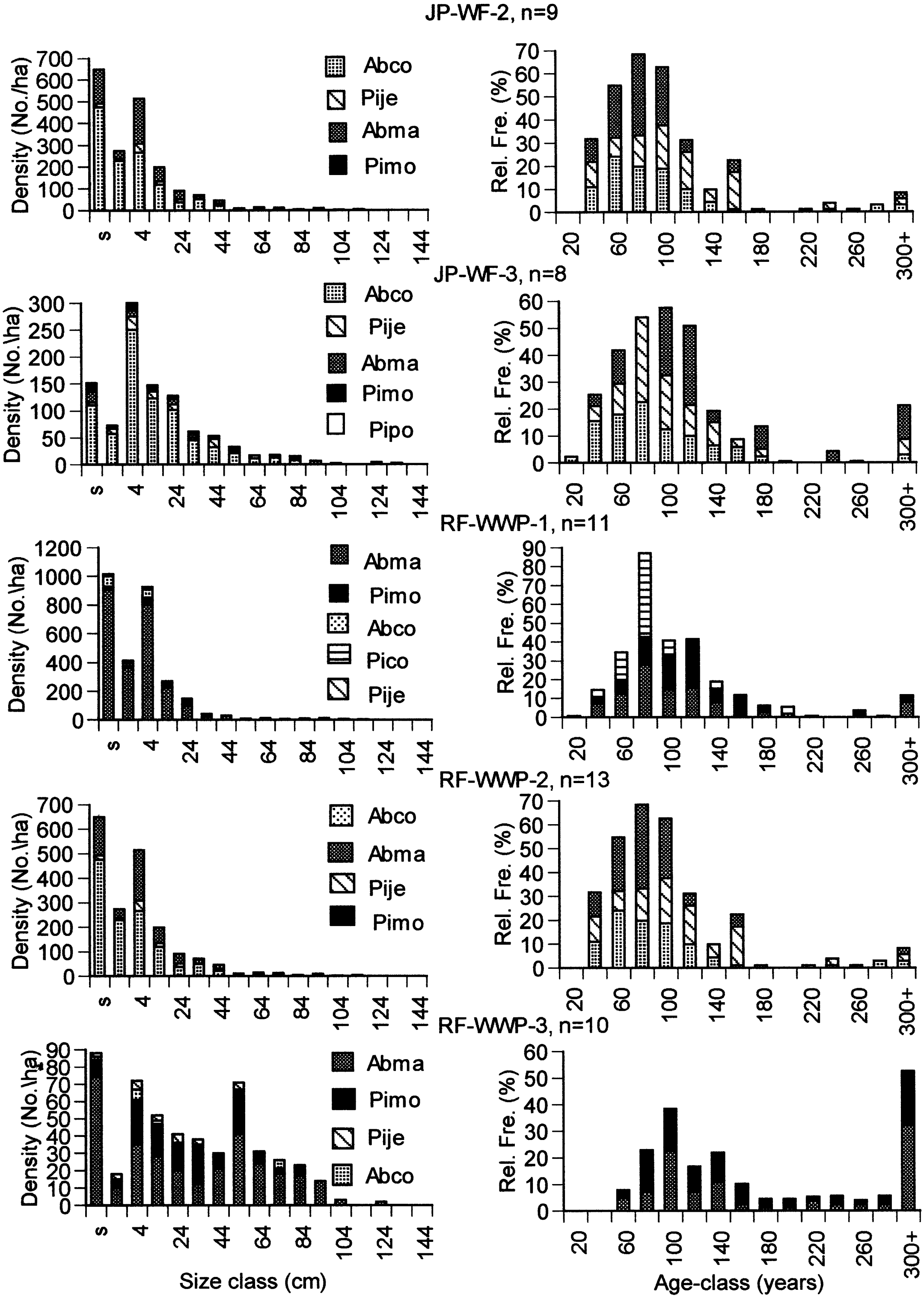

Figure 5 Size and age–structure of tree populations in size structural groups identified by cluster analysis of seedlings, saplings, trees in 10 cm d.b.h. classes (ha^{-1}) in 100 plots on Prospect Peak. Only a subsample of trees were aged in each plot and the *y*-axis is the relative frequency of all aged stems in a 20-year age-class. Forest types are given in Table 1 and species are white fir (Abco), red fir (Abma), lodgepole pine (Pico), Jeffrey pine (Pije), western white pine (Pimo) and ponderosa pine (Pipo). Note that only every other size and age–class is labelled and that the vertical scale is not the same on each graph.

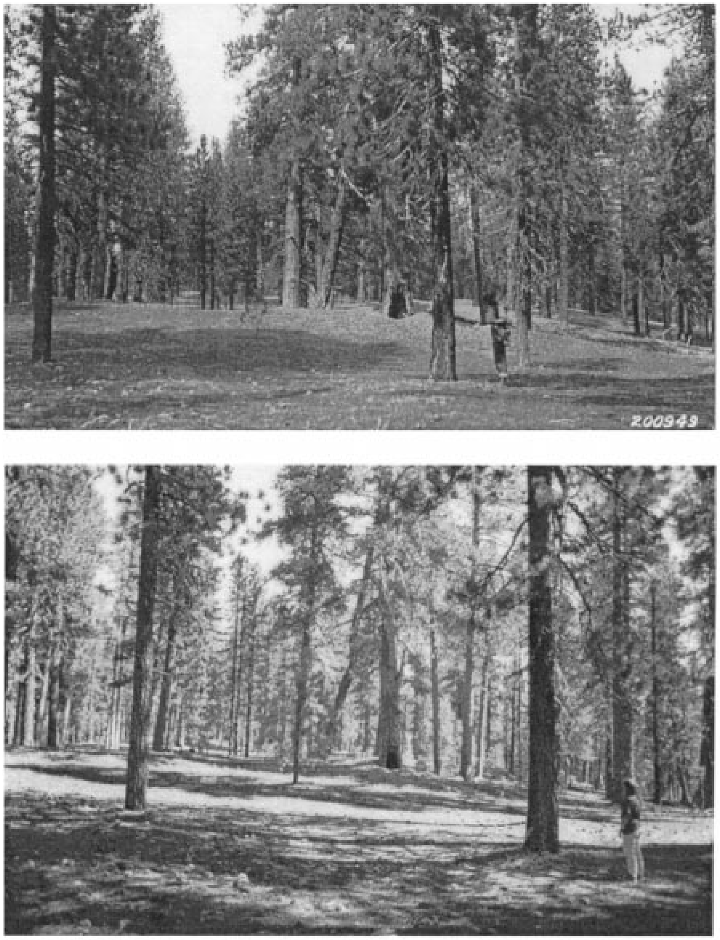

Figure 6 Top, September 1925: this scene shows an old-growth Jeffrey pine stand on the east side of Prospect Peak. The stand is composed of even-sized groups of trees and there is little herbaceous cover. Bottom, July 1993: trees in the scene have increased in height and diameter and fine fuels (cones, needles) have increased on the forest floor. New saplings have also established in the background and the forest is more dense than it was in 1925.

half white and red fir. In JP-WF-3 stands, understorey (stems < 34 cm d.b.h.) stem density is lower (798 stems ha^{-1}) and still mainly white fir, but Jeffrey pine and western white pine are present (Fig. 4). The overstorey (stems > 54 cm d.b.h.; ninety-six stems ha^{-1}) is a mixture of Jeffrey pine and white and red fir; firs are four-fold more abundant than Jeffrey pine. All groups have overstorey stems that range in age from 140 to 300 + years. The dense understorey populations began to establish 80–100 years ago in JP-WF-1 stands, 100–120 years ago in JP-WF-2 and 120–140 years ago in JP-WF-3 (Fig. 5).

Three RF-WWP groups were identified by the cluster analysis. RF-WWP-1 stands have a dense (2775 stems ha^{-1}) understorey (stems < 34 cm d.b.h.) of mainly (85%) red fir mixed with western white pine, Jeffrey pine, white fir and lodgepole pine. Overstorey (> 54 cm d.b.h.) stems are sparse (65 ha^{-1}) and also mainly red fir (83%) (Fig. 5). RF-WWP-2 stands have a moderate density (831 stems ha^{-1}) understorey (stems < 34 cm d.b.h.) of mainly white fir and red fir but western white pine and Jeffrey pine are present. The overstorey (stems > 54 cm d.b.h.) is moderately dense (ninety-two stems ha^{-1}) and mainly (79%) red fir with some white fir and western white pine. In RF-WWP-3 stands, understorey (stems < 34 cm d.b.h.) stems are sparse (271 ha^{-1}) and overstorey (stems > 54 cm d.b.h.) stems are abundant (170 stems ha^{-1}); stands are codominated by red fir and western white pine. In all groups, overstorey stems 140–300 + years old are abundant and understorey populations in each group began to establish 120–140 years ago (Fig. 5).

The repeat photograph pairs show that forests have changed on Prospect Peak over the last 70 years (Figs 6, 7, 8, 9). Forests in three scenes have increased in density, in some cases dramatically (e.g. Figs 7, 8), and in all scenes stems have increased in size and diameter; fuels (e.g. needles, branches, boles) have increased on the forest floor. Compositional changes have also occurred. Shrubs have disappeared from some forests (e.g. Figs 7, 8) and white fir has invaded the understorey of forests with mainly Jeffrey pine in the overstorey (Fig. 7).

DISCUSSION

Patterns of species abundance varied across the mid- and upper montane zone on Prospect Peak. Tree species were segregated mainly by elevation and secondarily by topographically controlled patterns of soil moisture. The species abundance patterns found on Prospect Peak are the same as those reported for other parts of LVNP (e.g. Taylor, 1990a; Parker, 1991, 1995), other parts of the southern Cascades

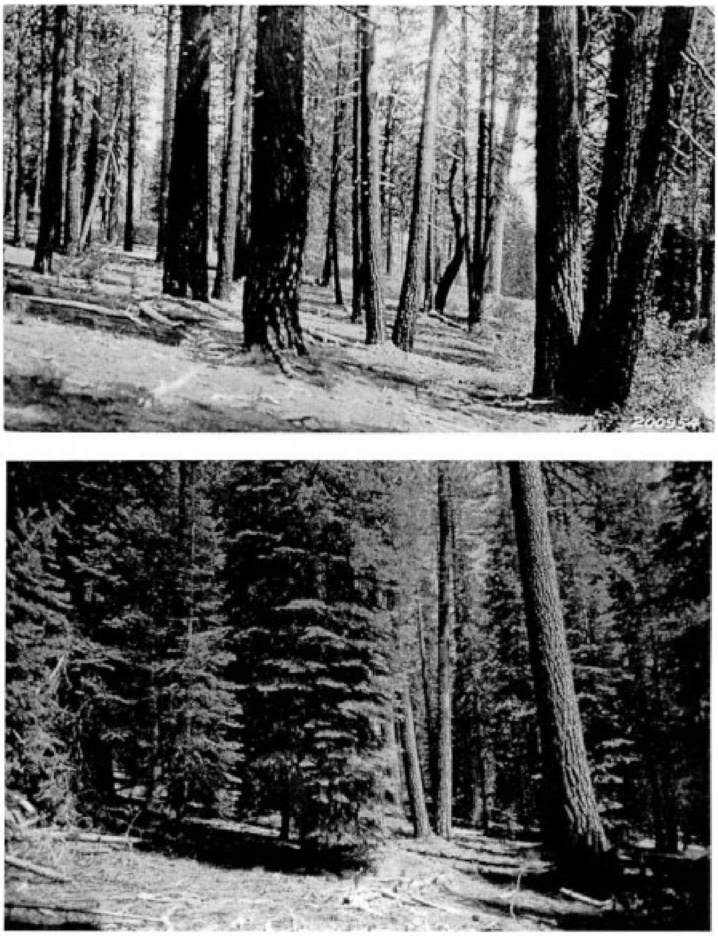

Figure 7 Top, October 1925, on the south side of Prospect Peak. The scene shows a mixed Jeffrey pine–white fir stand with few seedlings, saplings or small diameter stems in the forest understorey. A small patch of brush (*Ceanothus velutinus* Hook.) is present in the foreground (right) but there is little herbaceous cover. Note the charred bark on the large diameter stems. Fire scars on a nearby sample tree indicate the stand last burned in 1892. Bottom, June 1993: white fir now occurs in the forest understorey and ground fuels (needles, twigs, branches) have accumulated on the forest floor. This site was revisited in 1994 and all large-diameter Jeffrey pines in the scene were dead due to a bark beetle attack.

(e.g. Franklin & Dyrness, 1973; Rundel *et al*., 1977; Solem, 1995; Bekker, 1996) and they are regionally typical.

Fire regime characteristics varied with forest dominant and elevation on Prospect Peak. Both point and composite fire return intervals were shortest in low-elevation JP forests, longest in high elevation RF-WWP forests, and intermediate in mid-elevation mixed JP-WF forests. Moreover, there was a strong correlation between mean point fire return interval and elevation. The correlation of fire return interval length with elevation and forest dominant is probably due to several factors that influence flammability. First, rates of fine fuel production are higher in warmer low-elevation pine forests so fuel recovery after a fire is faster: sites can burn again sooner (Agee *et al*., 1978; Stohlgren, 1988; van Wagtendonk, pers. comm.). Secondly, fuels at low elevation are dry enough to burn for a longer period each summer than they are at high elevation (Rothermel, 1983). Thirdly, surface fire intensity is higher in low-density fuel beds (i.e. Jeffrey pine) than in higher-density ones (i.e. red fir) (e.g. Albini, 1976; Rothermel, 1983) so there is a higher probability that fires will scar trees in JP than in RF-WWP forests.

Fire rotation lengths on Prospect Peak also varied with forest dominant and elevation. The rotation period was longest in upper montane RF-WWP (75.9 years) shorter in mid-montane JP-WF (34.3 years) and JP (24.5 years). Fire rotation length in a forest type in each case is close to mean point fire return interval: RF-WWP (75 years), JP-WF (28 years), JP (19 years). Fire frequency models of boreal forest where fires are large and stand replacing estimate fire return intervals and the fire cycle (time needed to burn an area equal to the whole forest) from stand age distributions (cf. Van Wagner, 1978). The similarity of fire rotation length and the mean point fire return interval suggests that point fire return interval data may be used to estimate the fire cycle in forests with more frequent less severe surface fires.

The time at which fires burn during the year has a strong effect on vegetation response to fire (e.g. Kauffman, 1990; Agee, 1993) and the position of scars within a tree ring, or season of burn, varied between mid- and upper montane forests. Growing season fires (early, middle, late, latewood) are more frequent in lower elevation JP and JP-WF than in upper montane RF-WWP forests. Biweekly radial growth data for Jeffrey pine for a site north-east of Prospect Peak suggest that growing season fires in JP and JP-WF occur between mid-May and late August and dormant ones occur after that. Trees began growth by mid-May and ended by late August (Pacific South-west Research Station, unpublished

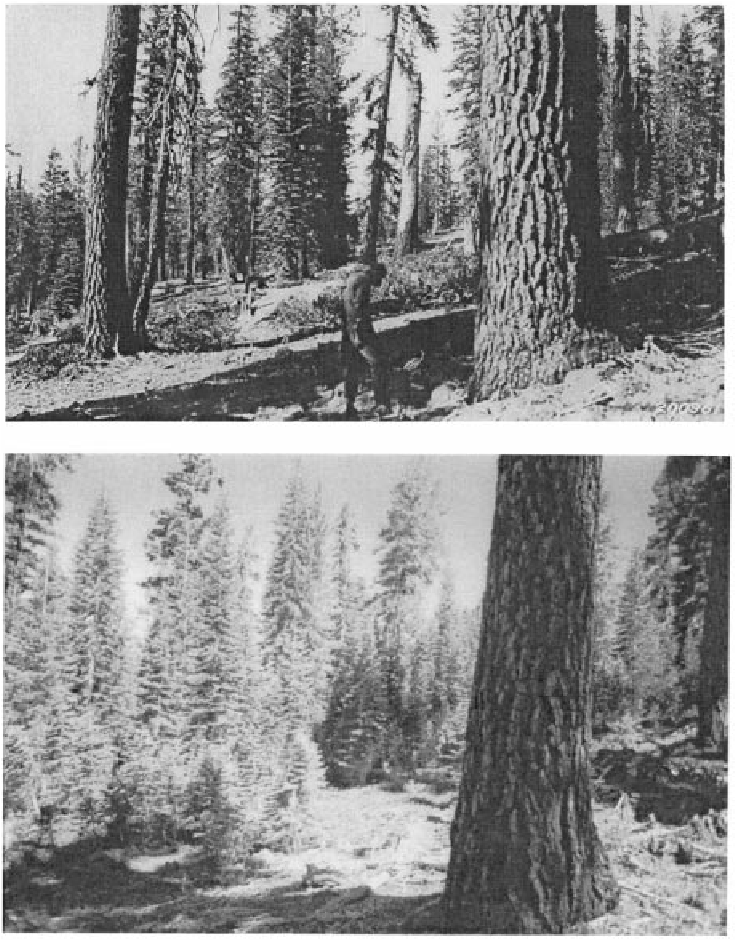

Figure 8 Top, October 1925, on the west side of Prospect Peak. The scene shows a red fir–western white pine stand with few seedlings and saplings on the forest floor. There are patches of brush (*Ceanothus velutinus*, *Castonopsis sempervirens* (Kellogg) Hjelmq.) in the understorey but little herbaceous cover. Fire scars on a nearby sample tree indicate the stand last burned in 1883. Bottom, July 1993: trees in the stand have increased in height and diameter and new seedlings and saplings have established in the understorey since 1925. The tree in the foreground (left) of the 1925 scene died and fell and seedlings and saplings have established in this opening. Ground fuels (needles, twigs, branches, boles) have also increased on the forest floor.

data). There are no nearby phenology data for red fir or western white pine but fires in these forests were mainly dormant and they probably burned late in the summer and autumn. Lightning ignitions are most frequent in the surrounding area in July and August (Hood, 1995) and fuels are drier in lower elevation forests at this time so they could carry fires earlier in the summer. Fires burning in lower montane forests may not spread readily into the upper montane zone until August or September, when fuels become drier.

Fire return intervals on Prospect Peak varied by slope aspect and they were shortest on the east-facing slope and longer on the south- and west-facing slopes. This pattern is due probably to variability in landscape structure that affects fuel bed continuity and the rate of fire import to Prospect Peak from adjacent areas. First, large lava outcrops punctuate the south- and west-facing slopes so fuels are discontinuous and this reduces the probability of fire spread from an ignition point. Secondly, there is no fuel below the JP zone on the south side of the peak. Lava and scoria deposited by the eruption of Cinder Cone in the mid-seventeenth century has not yet been colonized by plants. This bare area acts as a barrier to fire spread so fires burning south of the barrier would rarely spread onto the south slope of the peak. Thirdly, less flammable (high density fuel beds) LP forests occur below the JP zone on the south-west and west side of the peak. This forest belt probably reduced fire spread from JP forests west and south of the LP belt. JP forests on the east side of Prospect Peak, in contrast, are connected to an extensive JP forest which extends east and north of the study area. Fires ignited in this extensive forest could spread more easily onto the east side of the peak. Moreover, there are few lava outcrops on the eastern slope that would inhibit fire spread. This fire return interval–aspect pattern underscores the important contribution of topography and landscape structure (e.g. Baker, 1989; Hunter, 1993; van Wagtendonk 1995; Larsen, 1997; Taylor & Skinner, 1998), or place, in influencing fire regime variability and it suggests that fire regime data should be extrapolated cautiously to other locations.

Fire occurrence declined dramatically on Prospect Peak after 1905 due to Federal land management policy and similar late nineteenth- and early twentieth-century fire declines occurred elsewhere in the Cascade Range and in the Sierra Nevada (Vankat, 1977; Vankat & Major, 1978; Kilgore & Taylor, 1979; McNeil & Zobel, 1980; Caprio & Swetnam, 1995; Solem, 1995; Bekker, 1996). An earlier, settlement period (1850–1904) change in fire frequency did not occur

Figure 9 Top, August 1925, on the east side of Prospect Peak. The scene shows a red fir–western white pine stand with few seedlings, saplings or small trees in the understorey and little herbaceous cover. Logs in various stages of decay are present on the forest floor. Bottom, July 1993: few structural changes have occurred since 1925 but ground fuels (boles) have increased on the forest floor.

on Prospect Peak as it seems to have in some California montane forests (e.g. Caprio & Swetnam, 1995), so a pre-settlement fire regime was present on Prospect Peak until 1905.

Forest changes caused by twentieth-century fire exclusion are well documented in lower montane forests of the Sierra Nevada, southern Cascade and San Bernadino Mountains (Vankat & Major, 1978; Parsons & DeBenedetti, 1979; Savage, 1994, 1997; Minnich *et al*., 1995; Solem, 1995; Bekker, 1996; Kilgore & Taylor, 1979; McNeil & Zobel, 1980). Elimination of frequent surface fire has caused a forest density increase and a forest compositional shift from fire-resistant pines to fire-intolerant white fir and incense cedar. In each case, the onset of forest changes coincides with the date of fire suppression. This forest change pattern was clearly evident in the stand structural data and in the repeat photographs for mid-montane JP and JP-WF forests. JP and JP-WF forests are now more dense; the density increase began after fire was eliminated in about 1905, and shade-tolerant fire-intolerant white fir has increased relative to Jeffrey pine. Both the fire occurrence and stand structure data implicate fire suppression as being the major cause of twentieth-century forest change in LVNP forests.

Forest density increases in upper montane red fir forests in some parts of the Sierra Nevada and Cascade mountains have also been attributed to the effects twentieth-century fire exclusion (e.g. Reynolds, 1959; Vankat & Major, 1978). However, these studies do not include data on pre-settlement fire regimes so it is uncertain if the cause of the forest density increase is fire suppression. Surface fires in red fir forests do kill stems in the forest understorey (e.g. Kilgore, 1971; Kilgore & Briggs, 1972; Chappel & Agee, 1996) and red fir is shade-tolerant and regenerates continuously (e.g. Gordon, 1970; Laacke, 1990) so an increase in the fire return interval could cause a forest density increase. Small (< 14 cm d.b.h.) stems < 140 years old are abundant in the understorey of RF-WWP forests and the last widespread (> 100 ha) fires occurred in RF-WWP forests in 1892 (south slope) 1883 (west slope) and 1854 (east slope). The longest interval between successive fires on any fire-scar sample was 109 years and the median interval was 70 years. From this it can be concluded that RF-WWP forests on Prospect Peak are probably now outside their historic range of variation with respect to fire return intervals. This suggests that twentieth-century fire suppression has caused RF-WWP forests to become more dense and structurally more homogeneous, at least at a landscape scale (e.g. Chappel & Agee, 1996). Structure in a particular stand, however, may not yet reflect the effects of fire suppression because the median point fire return interval is not much shorter than the fire suppression period.

MANAGEMENT CONSIDERATIONS

The National Park Service is mandated to maintain and restore forest conditions and processes to those present during the pre-settlement period (USDI, 1988). Since the mid-1980s, resource managers in LVNP have been using both prescribed fire and wildfire to restore fire effects to park ecosystems (NPS, 1984). Managers recognize that 90 years of fire suppression has caused forest changes but they do not know the extent or magnitude of change, nor what the characteristics of pre-settlement fire regimes were. Without specific data on pre-settlement forest structures and fire regimes appropriate target conditions cannot be identified for resource management plans. The characteristics and ecological effects of management burns may therefore be different to typical burns in the pre-settlement period. This point is illustrated by comparing pre-settlement fire regime data from Prospect Peak with data from the burning programme. Since 1984, management fires have burned about 2000 ha in LVNP and fires were small compared to pre-settlement fires. The largest management burn was a 810-ha prescribed wildfire and eight fires > 800 ha burned in the small Prospect Peak study area between 1627 and 1905. Management-ignited fires are smaller. The average ignited fire burned 41 ha and only 121 ha/year, on average, are burned using this method. The smallest fire identified on Prospect Peak since 1627 was 39 ha and the average burn area was 457 ha. These data indicate that the spatial scale of management fires is inappropriate. Management burns need to be larger to mimic fires that burned during the pre-settlement period.

Fire may also not be the most appropriate tool to manipulate forest structure in highly changed forests. Managers are now attempting to use small burns to reduce the high volumes of live fuel (understorey stems) and ground fuels that have accumulated due to fire suppression in JP and JP-WF forests. Repeated burns are needed to reduce stand density and ground fuels to historic levels (e.g. Agee, 1993). These low intensity burns, however, can kill large-diameter Jeffrey and ponderosa pines which are the structural legacy of the pre-settlement forest. Burns may kill fine roots, predisposing injured trees to bark beetle attack which may eventually kill them (e.g. Swezy & Agee, 1991). Bark beetles and fine-root mortality may be responsible for the high death rates of old large Jeffrey pine after prescribed fires in some burn areas in LVNP (pers. obs.). In such highly altered forests, managers should consider manipulating fuels physically before reintroducing fire (e.g. Agee, 1995; Parsons, 1995; Stephenson, 1996). This would lower fire intensity which may reduce the rate of large-tree mortality from management burns.

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