Introduction

Fire has played a vital role in shaping the composition and structure of conifer forests in California (Kilgore 1973) and the Pacific Northwest (Franklin and Dymess 1973; Franklin and Hemstrom 1981; Morrison and Swanson 1990; Agee 1990). Fire severity varies by forest cover type from infrequent high-severity fires (e.g., western hemlock (Tsuga heterophyla (Raf.) Sarg.) — Douglas-fir Pseudotsuga menziessii (Mirb.) Franco); Pacific silver fir (Abies amabilis (Dougl.) Forbes) (Franklin and Hemstrom 1981) that regenerate new stands to frequent low-severity fires that kill seedlings and saplings, maintaining open understories (e.g., mixed conifer; ponderosa pine (Pinus ponderosa Dougl. ex P. Laws & C. Laws)) (Weaver 1967; Kilgore and Taylor 1979; McNeil and Zobel 1980). Forests that experience moderate-severity fires (i.e., red fir (Abies magnifica A. Mur.) (Pitcher 1987; Taylor 1990; Taylor and Halpern 1991). There are few data that describe the fire regime (i.e., frequency, severity, size) or fire effects on stand structure in red fir forests of California or the Pacific Northwest (e.g., Pitcher 1981, 1987; Taylor and Halpern 1991).

Red fir forests cover >800 000 ha of the montane zone in the southern Cascade and Sierra Nevada ranges of California and southern Oregon (Franklin and Dymess 1973; Barbour and Woodward 1985; Barbour 1988). Severe fires in red fir stands initiate patches of tree regeneration (Pitcher 1987; Taylor and Halpern 1991), while low-severity fires thin seedlings and saplings (Kilgore 1971) and produce a mineral seedbed favorable for red fir establishment (Gordon 1970). Small (0.25—1.0 ha) red fir stands (n = 5) in the Sierra Nevada and on Swan Mountain had fire-free intervals ranging from 5 to 126 years. But few fire-starred trees were examined by Pitcher (1987) and Taylor and Halpern (1991), and samples were from a small area.

The objectives of this study were to (i) describe the fire regime (i.e., frequencies, sizes, severities of fire) of a red fir dominated forest over a large study area (400 ha) and (ii) determine whether the size, age, and horizontal pattern of older age-classes were related to fire generated disturbances. The forest structure data were collected from two old-growth stands (3.0 ha each) within the larger study area.

Study area

This study was conducted in the Swan Mountain Experimental Forest in northeastern California (40°26'N, 121°7'W). Swan Mountain is a volcanic cone with deep (1.0—2.5 m), well-drained soils derived from vesicular andesite. Slopes are gentle, undulating, and there are few topographic irregularities (e.g., rock outcrops, stream valleys, etc.) that would act as fuel breaks to inhibit spread of fire. Annual precipitation is about 1100 mm, with 80% falling as snow between October and May. Maximum snow depth averages 2.5 m (Gordon 1979).
Table 1. Site and stand characteristics for plots 1 and 2, Swain Mountain Experimental Forest, California

<table>
<thead>
<tr>
<th></th>
<th>Plot 1</th>
<th>Plot 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation (m)</td>
<td>1963</td>
<td>1954</td>
</tr>
<tr>
<td>Slope (degrees)</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Aspect (degrees)</td>
<td>266</td>
<td>65</td>
</tr>
<tr>
<td>Plot dimensions (m)</td>
<td>100 × 300</td>
<td>100 × 300</td>
</tr>
</tbody>
</table>

(B) Stand and tree characteristics

<table>
<thead>
<tr>
<th></th>
<th>Plot 1</th>
<th>Plot 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red fir</td>
<td></td>
<td></td>
</tr>
<tr>
<td>White fir</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basal area (m²·ha⁻¹)</td>
<td>64.4</td>
<td>44.9</td>
</tr>
<tr>
<td>Density (ha⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live trees</td>
<td>14.3</td>
<td>7</td>
</tr>
<tr>
<td>Dead standing</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Stumps</td>
<td>99.6</td>
<td>80.6</td>
</tr>
<tr>
<td>Height (m)</td>
<td>49.8±3.5</td>
<td>45.2±2.0</td>
</tr>
</tbody>
</table>

*Values represent the mean ± SD.

Fire records for the period 1917–1989 reported 40 lightning fires on Swain Mountain, and these fires were all suppressed. Ninety-five percent of these fires burned <0.5 ha; others burned >1.0 ha. Fire-free intervals in two small plots on Swain Mountain averaged 41 years, with more severe fires initiating patches of red and white fir regeneration (Taylor and Halpern 1991).

The study area encompassed a 400-ha tract that was shelterwood harvested in 1984–1985. A sparse canopy of dominant red fir (and white fir (Abies concolor (Gord. & Glend.) Lindl.)) was left to act as a seed source to regenerate new even-aged stands. Small stems (<30 cm DBH) were removed after logging, and the tract was then burned to create a mineral seedbed for tree establishment. There was little ground cover in the study area when it was sampled in 1990.

Old and white fir seedlings were present, and were seedlings of several shrubs: Ceanothus velutinus Douglas., Ceanothus cordulatus Kel., Arctostaphylos patula Greene, and Ribes spp.

Old-growth (>200 years) stands on Swain Mountain vary in structure. Forest structure was studied by subjectively locating two 30-ha (100 × 300 m) stands that were typical of old growth in the 400-ha study area. The following criteria were used to select the stands: (i) homogeneity of site (slope, aspect, slope pitch); (ii) presence of large-diameter (>1.0 m) stumps; and (iii) dominance by red fir.

Methods

Size and age structure

A 5 × 5 m grid was established within each plot, and the position and diameter of each stump and live or dead standing tree was mapped. Diameter was measured at 0.5 m for standing trees and at stump height (DSH) (range 10–140 cm) for stumps.

Stand age structure was determined from ring counts of 1281 mapped stumps. Stumps were aged using the following technique. First, a clear cross section of the stump was exposed by cutting a 4 mm wide strip of wood from the outside of the pit using a wood-cutting tool. Second, the annual rings were counted in the cut strip using a 10×–20× hand lens. The pattern of early radial growth (i.e., first 20 years) of each stump was also classified as fast (≤5 rings/cm), intermediate (5–15 rings/cm), or slow (>15 rings/cm).

Ages of hollow or rotten-centered stumps (9.2% of stumps) were estimated using the following procedure. First, the length of the missing portion of the radius was estimated (cm). Second, the number of growth rings in the missing part of the radius was estimated and added to the ring count of the intact portion of the stump. The number of rings per centimetre to add to intact portions of the radius was derived from measurements of the first 25 cm of radial growth (mean 3.9 ± 2.7 rings/cm) on 11 complete stump sections.

Ages of 152 live trees were estimated from age on DSH regressions for each species in each plot (P < 0.001). Coefficients of determination (r²) were 0.41 and 0.32 for red fir and 0.31 and 0.31 for white fir in plots 1 and 2, respectively.

Spatial pattern

Three features of the horizontal distribution of tree populations were examined: type, intensity, and scale. The type and scale of pattern were identified using Morisita’s (1959) index:

\[
I_0 = q \sum_{i=1}^{q} \frac{n_i(n_i - 1)}{N(N - 1)}
\]

where q is the number of quadrats, n_i is the number of individuals in the ith quadrat, and N is the total number of individuals in all quadrats. If individuals are clumped, I_0 > 1.0; if regularly distributed, I_0 < 1.0; and if I_0 = 1.0, the population is randomly distributed. Each I_0 value was tested with an F-statistic to determine whether it varied significantly (P < 0.01) from the value for a random distribution (Morisita 1959). Scale of pattern (m²) was determined by computing I_0 values for quadrats of different sizes (e.g., Williamson 1975). Morisita’s index values were computed for square quadrats of successively larger size, when possible, to avoid fluctuations in I_0 due to block shape (Pielou 1977). Morisita’s index values were computed only for populations with >20 individuals because the index value varies erratically when populations are small. The intensity of clustering was interpreted from the I_0 value. The higher the I_0 value, the greater the intensity of clustering.

Fire history

Eighty-three stump cross sections, or partial cross sections, with fire scars were removed from each plot and the surrounding 400-ha study area to reconstruct fire history. Fire scars in red and white fir often heal completely, leaving buried scars. Samples were prepared for examination by sanding each cross section with successively finer grades of sand paper. Annual growth rings in each sample were cross-dated using methods similar to those described by Stokes and Smiley (1968). Ring widths from fire-scar samples were compared with those from cores extracted from 25 main-canopy red fir trees near plot 1. Fifty-eight of the samples were successfully cross-dated, and only fire dates from these samples are reported. Criteria outlined by Morrison and Swanson (1990) and McBride (1983) were used to identify fire scars.

Results and discussion

Stand characteristics

The proportions of red fir and white fir differed between plots. Red and white fir were codominant in plot 1, with similar basal area and stem density (Table 1). In plot 2, red fir was dominant, with 20-fold greater basal area and 10-fold greater stem density than white fir. Combined basal area for both firs were near the upper limits reported for old-growth red fir and mixed red fir—white fir forests in California (Vankat and Major 1978; Parker 1984; Barbou and Woodward 1985). The average height of dominant live red fir trees in the two plots was 49.5 m (n = 44) and for white fir, 45.2 m (n = 6) (Table 1).

Size structure

Red and white fir occurred in a wide range of diameter classes (Figs. 1a, 1b). In plot 1, diameter-class distributions differed (P < 0.001, Kolmogorov–Smirnoff two-sample test) with white fir concentrated in smaller (<75 cm) size classes.
In contrast, diameter-class distributions for red and white fir in plot 2 were not different ($P > 0.01$). The diameter-class distributions of red fir differed between plots ($P < 0.001$), with individuals <85 and >165 cm more common in plot 2 than in plot 1. White fir diameter-class distributions were not significantly different ($P > 0.01$) between plots, but white fir had a greater density (3-fold) in plot 1 than in plot 2.

The diameter-class distributions in plot 1 were bimodal, with modal classes differing between species (Figs. 1a, 1b). The modal class for red fir was 105–114 cm, while that for white fir was 45–54 cm. In contrast, red fir in plot 2 had a monotonically decreasing diameter-class distribution. White fir in plot 2 were sparsely distributed over a wide range of size classes.

**Age structure**

Tree age-class distributions in each plot were different (Figs. 2a, 2b). Red fir in plot 1 were concentrated in the 145 to 194-year age-classes and in plot 2, in the 135- to 184-year age-classes. White fir was concentrated in younger age-classes than red fir in plot 1, with most stems in the 115- to 154-year age-classes. A few white fir were present in most age-classes <194 years in plot 2. Individuals >195 years were uncommon in plot 1, with the oldest being 232 years. In con-
| Quadrat size (m²) | Size class (DSH) ≤75 ≤75 >75 >55 >55 White | Age-class (years) ≤138 ≤138 >138 Red White Red White Red White |
|------------------|--------------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 25               | 2.007**                              | 1.860**              | 3.294**              | 1.862**              | 3.191**              | 2.119**              | 2.801                | 1.508**              | 2.146**              |
| 100              | 1.720                               | 1.447               | 2.334**              | 1.690**              | 2.660               | 0.000                | 1.401**              | 1.422**              |
| 225              | 1.416                               | 1.373               | 1.684**              | 1.323**              | 2.308**             | 1.104                | 1.306**              | 1.052**              |
| 400              | 1.541**                             | 1.302**             | 1.647**              | 1.347**              | 2.460**             | 2.143                | 1.289**              | 1.245**              |
| 625              | 1.261                               | 1.284               | 1.384**              | 1.239**              | 2.340**             | 2.514**              | 1.070**              | 1.207**              |
| 900              | 1.049                               | 1.157               | 1.378**              | 1.222**              | 1.554**             | 2.327**              | 1.575**              | 1.147**              |
| 1225             | 1.289                               | 1.121**             | 1.158               | 1.135**              | 1.487**             | 1.982                | 1.498**              | 1.145**              |
| 1600             | 1.140                               | 1.142               | 1.182               | 1.170**              | 1.476**             | 2.121**              | 1.495**              | 1.181**              |
| 2625             | 1.026                               | 1.123               | 1.322**              | 1.184**              | 1.628**             | 2.343**              | 1.141**              | 1.161**              |
| 2500             | 1.066                               | 1.126               | 1.252               | 1.143**              | 1.382               | 1.835                | 1.087**              | 1.100**              |
| 3025             | 1.037                               | 1.064               | 1.008               | 1.154**              | 1.124               | 2.145**              | 1.022                | 1.048                |
| 3600             | 0.999                               | 1.008               | 1.048               | 1.079**              | 1.254               | 1.687                | 1.056                | 1.076**              |
| 4225             | 1.065                               | 1.036               | 1.022               | 1.142**              | 1.249               | 1.964**              | 1.004                | 1.057**              |
| 4900             | 0.999                               | 1.028               | 1.033               | 1.115**              | 1.415**             | 2.471**              | 1.025                | 1.072**              |
| 5625             | 0.980                               | 1.006               | 1.083               | 1.113**              | 1.249               | 1.740**              | 1.022                | 1.068**              |
| 6400             | 0.990                               | 1.013               | 1.085               | 1.102**              | 1.112               | 1.395                | 1.060**              | 1.090**              |
| 7225             | 1.009                               | 1.034               | 1.090               | 1.132**              | 1.141**             | 1.531**              | 1.049**              | 1.088**              |
| 8100             | 0.987                               | 1.047               | 1.095**             | 1.114**              | 1.122               | 1.395                | 1.060**              | 1.102**              |
| 9025             | 0.990                               | 1.095               | 1.083               | 1.174**              | 1.081               | 1.269                | 1.102**              | 1.125**              |
| 10000            | 0.988                               | 1.103               | 1.111**             | 1.181**              | 1.109               | 1.200                | 1.107**              | 1.125**              |

** Values are significantly >1.0 (F-test, P < 0.01) and represent clumped distributions.

Contrast, stems >195 years were common in plot 2, with a maximum tree age of 357 years.

Spatial patterns
Spatial patterns of size- and age-classes of red and white fir varied among and between plots (Table 2). Small (≤75 cm DSH) and large (>75 cm DSH) red fir in plot 1 were randomly distributed at nearly all spatial scales. In plot 2, small (≤65 cm DSH) red fir were weakly clumped from 25 to 1600 m², while larger (>65 cm DSH) stems were for the most part distributed randomly. Small white fir (≤55 cm DSH) in plot 1 were clumped largely at scales of 25–2500 m², while

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large (>55 cm DSH) stems were weakly clumped at all plot sizes (25–10 000 m²). Small (≤60 cm DSH) white fir in plot 2 had a spatial pattern similar to large white fir in plot 1: stems were clumped at most spatial scales.

Horizontal patterns of age-classes were different from those of size classes. In plot 1, young (≤138 years) red fir were clumped at scales of 25–2500 m² and older (>138 years) stems were clumped at most scales from 25 to 10 000 m². Younger (≤138 years) and intermediate-aged (138–241 years) red fir in plot 2 were clumped at most block sizes from 25 to 7225 m², while older stems were clumped or random at small to large scales. Young white fir (≤138 years) were clumped at intermediate and large scales but were randomly distributed at small and very large scales. Older (>138 years) white fir were clumped at nearly all scales.

**Fire history**

The fire record from fire-scared trees on Swain Mountain spans the period 1740–1985. No fires were recorded in stumps after 1945. Fires burned frequently between 1740 and 1945 in each plot and in the 400-ha study area (Table 3).

Fires occurred with similar frequency in the 3.0-ha plots. Fires were recorded in plot 1 in 1836, 1847, 1854, 1867, 1886, 1897, 1924, and 1938. These fires dates give an average fire-free interval of 18.6 years (range 7–47 years) (Table 3). In plot 2, fires occurred in 1828, 1854, 1886, 1897, 1911, 1924, 1930, 1933, 1938, and 1945, yielding a mean fire-free interval of 15.7 years (range 3–40 years).

Fires, of course, occurred more frequently in the expanded study area than in the plots (e.g., Arno and Petersen 1983). The average fire-free interval for the 400-ha study area was 12.9 years (range 1–57 years).

Fire size and severity may be roughly estimated from the fire chronology for the expanded study area. Fires that were recorded in both plots and adjacent areas occurred in 1854, 1886, 1897, 1924, and 1938 (Table 3). The mean fire-free interval for these larger fires was 26.2 years (range 11–47 years). The frequency of fire-scared trees in a given fire year probably also reflects fire severity, with larger, more severe fires scarring more trees than low-severity fires (Kilgore and Taylor 1979). Sixty-one percent of the dated fire scars were associated with the fire years 1854, 1886, 1897, 1924, and 1938. The 1924 fire scoured the most trees (17) followed by fires in 1886 (12), 1854 (10), 1897 (9), and 1938 (8) (Table 3).

**Fire – age structure relationships**

Establishment dates of trees in each plot could not be estimated by adding a simple correction factor to stump ages. Heights of aged stumps varied (10–140 cm), as did their patterns of initial radial growth. In plot 1, 50% of the stumps had rapid initial growth, 33% were intermediate, and 17% were slow. In plot 2, only 13% of the stumps had rapid initial growth, 41% were intermediate, and 46% were slow. Furthermore, ages of uncut trees in each plot were estimated from age–diameter regressions, and small stems were not aged because they were not present. Despite these limitations, pulses of regeneration followed some fires in the plots.

In plot 1, dominant red fir were concentrated in the 145- to 194-year age-classes, and the oldest stem in the plot was 232 years. A fire in 1740 was recorded in two stumps adjacent to plot 1, suggesting that fire in the mid-1700s initiated this stand. White fir are concentrated in the 115- to 154-year age-classes, and four fires occurred in plot 1 between 1836 and 1867.

In plot 2, red fir were concentrated in the 135- to 184-year age-classes, and fires occurred in or adjacent to plot 2 in 1828 and 1836. Age and scar data do not suggest that trees in plot 2 initiated after a stand-replacing fire.

Fire regimes in red fir forests are dominated by low- and moderate-intensity fires (Kilgore 1971, 1973; Agee 1990). Low-severity fires consume surface fuels, expose mineral soil, and thin patches of seedlings and saplings (Kilgore 1971). Fire-scar data from Swain Mountain are consistent with these observations of fire behaviour. Most fires scarred few trees, suggesting that they were of low severity. Moreover, large post-fire cohorts did not develop after most fires, suggesting that regeneration was in small patches.

Moderate- and high-severity fires that initiated large patches of regeneration do occur in red fir forests (Pitcher 1981, 1987; Taylor and Halpern 1991). Dominants in plot 1 (>75 cm DSH) established after a stand-replacing fire in the mid-1700s, as did a nearby stand (<200 m) (Taylor and Halpern 1991), suggesting that this severe fire burned at least 5.0 ha.

Small, patchy, low-severity fires probably contribute to the clumped distribution of younger red fir age-classes. Red fir establishes better on mineral soil than on forest litter (Gordon 1970) in shaded, cool, microsites (Ustin et al. 1984; Selter et al. 1986). Older red fir were less intensely clumped, which is the result of thinning by competition and (or) fire (Pitcher 1981; Taylor and Halpern 1991).

**General discussion**

Fire history data from other red fir forests to compare with those from this study are scarce. Pitcher (1987) and Taylor and Halpern (1991) report average fire-free intervals of 65 years (range 5–126 years) and 41 years (range 5–65 years) from small plots in the Sierra Nevada and on Swain Mountain. Estimates of fire-free intervals are sensitive to the size of the sample unit (i.e., single tree with scars vs. many scar samples over a wide area), so intersite comparisons should use the
same sampling unit. Pitcher (1987) sampled multiple-scared trees \( n = 16 \) in red fir forests, yielding a mean 65-year fire-free interval. Multiple-scared stumps from this study \( n = 19 \) found over a similar area had a mean fire-free interval of 47 years (range 14–127 years), shorter than for southern Sierra Nevada stands. Fires that scarred two or more trees in the southern Sierra Nevada occurred every 73 years (range 38–108 years). Fires represented by three or more scars on Swain Mountain stumps occurred every 30 years (range 14–46 years). These data indicate that fires burned more frequently in red fir stands on Swain Mountain than in the southern Sierra Nevada during the past 250 years.

Fire-free intervals varied by historical period on Swain Mountain. The fire-free interval during the presettlement period (1740–1850), when lightning and Native American ignitions prevailed (Schulz 1954), was 21.4 years, similar to the interval for the fire-suppression period (1935–1983) (Taylor 1990), 17.3 years. During the settlement – pre-fire-suppression period (1851–1934), fire-free intervals were shorter (7.9 years). Large numbers of livestock grazed Lassen National Forest, which surrounds Swain Mountain, until the mid-1920s (Taylor 1990). Stockmen, settlers, and timber owners frequently burned forests in the late 1800s and early 1900s in California to manipulate forage and stand structure (Vankat 1977; Pyne 1982). The shorter fire-free intervals during the settlement period are probably in part the result of fires set by Europeans. Fire-free intervals in southern Sierra Nevada forests did not shorten with European settlement. Instead, aboriginal fire frequencies were extended by Europeans until the fire suppression period (Vankat and Major 1978; Kilgore and Taylor 1979).

Forest structure and composition in lower montane conifer forests in the Cascades and Sierra Nevada have been altered by fire suppression since the early 20th century (Vale 1977; Vankat and Major 1978; Parsons and DeBenetti 1979; Kilgore and Taylor 1979; McNeil and Zobel 1980). Stand density has increased and compositional shifts to more fire intolerant species such as white fir have occurred as a result of elimination of several fire cycles. Density increases in red fir stands have also been reported in the southern Sierra Nevada (Vankat and Major 1978). Fires were frequent in red fir stands on Swain Mountain and they probably thinned seedling and sapling populations. As fire-free intervals lengthen with fire suppression, red and white fir densities will increase, changing both the vertical and horizontal components of red fir forests.

Acknowledgements

This project was funded by the USDA Forest Service (cooperative agreement PSW-90-0018 C.A) and was completed with the cooperation of many individuals. G. Everest, S. Pierce, N. Prest, C. Simpson, and D. Winters assisted with fieldwork. K. O’Brien, M. Peoria, B. Powers, and S. Ralston helped with data compilation. C. Skinner provided insights on fire behavior and fire history in red fir forests elsewhere in California. This project would not have been possible without the enthusiastic support of J. Laaekte. M. Barbour, C. Halpern, J. Laaekte, R. Martin, C. Skinner, and two anonymous referees provided helpful comments on an earlier draft of this paper.


