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# Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, Southern Cascades, California, USA

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## Abstract

**Aim** In this study, we evaluated the fire-forest mosaic of a mixed conifer forest landscape by testing the hypothesis that pre-fire suppression fire regime parameters vary with species composition (tree species), and environment (i.e. slope aspect, slope position, elevation).

**Location** Our study was conducted in the 1587 ha Cub Creek Research Natural Area (CCRNA), Lassen National Forest, CA, USA.

**Methods** We quantified the return interval, seasonal occurrence, size, rotation period, and severity of fires using dendroecology.

**Results** Slope aspect, potential soil moisture, forest composition, and fire regime parameters in our study area co-vary. Median composite and point fire return intervals (FRI) were longest on higher, cooler, more mesic, north-facing (NF) slopes covered with white fir (*Abies concolor*), Douglas fir (*Pseudotsuga menziesii*)–white fir, and red fir (*A. magnifica*)–white fir forests, shortest on the dry, south-facing (SF) slopes covered with ponderosa pine (*Pinus ponderosa*)–white fir forests and intermediate on west-facing slopes dominated by white fir–sugar pine (*P. lambertiana*)–incense cedar (*Libocedrus decurrens*) forests. The spatial pattern for length of fire rotation (FR) was the same as that for FRI. Fires in CCRNA mixed conifer forests occurred mainly (90%) in the dormant season. Size of burns in CCRNA mixed conifer forests were generally small (mean = 106 ha), however, during certain drought years widespread fires burned across fuel breaks and spread throughout the watershed. Fire severity was mainly high on upper slopes, low on lower slopes and moderate and low severity on middle slopes. Patterns of fire severity also varied with slope aspect. Fire frequency decreased dramatically in CCRNA after 1905.

**Conclusions** In CCRNA, fire regime parameters [e.g. FRI, fire extent, FR, fire severity] varied widely with species composition, slope aspect and slope position. There was also temporal variation in fire extent with the most widespread fires occurring during drought years. The important contributions of topography and climate to variation in the fire regime indicates that exogenous factors play a key role in shaping the fire-forest structure mosaic and that the fire-forest structure mosaic is more variable, less predictable and less stable than previously thought. Finally, some characteristics of the fire regime (i.e. fire severity, season of burn) in CCRNA are different than those described for other mixed conifer forests and this suggests that there are geographical differences in mixed conifer fire regimes along the Pacific slope.

**Keywords**
Fire regimes, mixed conifer forest, dendroecology, disturbance, California.

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## INTRODUCTION

Species distribution and abundance patterns in forested landscapes are strongly influenced by both site conditions (e.g. soils, temperature, moisture) (e.g. Whittaker, 1956) and the type severity, and extent of natural disturbances (e.g. White, 1979). Disturbances such as fire (e.g. Romme & Knight, 1981), windstorms (e.g. Foster, 1988; Foster & Boose, 1992), and debris flows (e.g. Parker, 1993) are all known to affect vegetation patterns at landscape scales. Moreover, disturbance and disturbance effects on community dynamics are strongly influenced by current vegetation patterns which are, in part, an artefact of the history of disturbance. Feedbacks between vegetation structure and composition and the frequency, spread, and severity of disturbance have been documented (e.g. Harmon *et al.*, 1983; Foster & Boose, 1992; Miller & Urban, 2000a; Taylor, 2000) and appear to play a key role in shaping community structure in some forests such as the fire-prone mixed conifer forests of California (e.g. Bonnicksen & Stone, 1981, 1982). In these forests, frequent (e.g. median fire interval = 3–20 years) low intensity surface fires create fine-grained multi-aged stands (e.g. Kilgore & Taylor, 1979; Caprio & Swetnam, 1995; Skinner & Chang, 1996). Burns influence the spatial patterns of future fires by temporarily reducing fuels in the burn patch (e.g. van Wagtendonk, 1995; Miller & Urban, 2000b; Minnich *et al.*, 2000) and the forest pattern resulting from this process has been described as a shifting mosaic steady-state (e.g. Bormann & Likens, 1979) at the landscape scale with patch sizes of < 0.2 ha (e.g. Bonnicksen & Stone, 1981, 1982). The fire-forest structure mosaic is potentially self-organizing (e.g. Holling *et al.*, 1996) and time-dependent because of the period needed for sufficient fuel to accumulate to carry the next fire. Recent research, however, suggests that fire regimes (i.e. frequency, extent, and severity) in mixed conifer forests are also strongly influenced by exogenous factors such as variation in weather (e.g. Miller & Urban, 2000b; Bekker & Taylor, in press), climate (e.g. Swetnam, 1993), or topography (e.g. Taylor & Skinner, 1998; Taylor, 2000). Consequently, the fire-forest mosaic may be more variable, less predictable, and less stable than previously thought, and a non-equilibrium view (e.g. Botkin, 1990; Sprugel, 1991) of mixed conifer forest dynamics may be more appropriate.

Mixed conifer forests cover 1,642,500 ha (Franklin & Fites-Kaufman, 1996) of the mid-montane zone (900–2200 m) in the Sierra Nevada and Cascade Ranges of California (Barbour, 1988). Any of the six conifer species (ponderosa pine (*Pinus ponderosa* Dougl.), Douglas fir [*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco], incense cedar (*Calocedrus decurrens* Torr. Florin), sugar pine (*P. lambertiana* Dougl.), Jeffrey pine (*P. jeffreyi* Grev. & Balf. in A. Murr), and white fir (*Abies concolor* Gord. and Glend.) may co-occur and share dominance in a stand depending on site conditions, latitude, and stand history (Parker, 1995; Barbour, 1988). Mixed white fir and red fir (*A. magnifica* A. Murr) forests occur above the mixed conifer zone (Parker, 1995). Tree cover in the mixed conifer zone is often interrupted by patches of montane chaparral. Chaparral shrubs are usually less than 2 m tall and the most common shrubs are green-leaf manzanita (*Arctostaphylos patula* Greene), California lilac (*Ceanothus* spp.) and dwarf oak (*Quercus* spp.). Montane chaparral species are fire adapted (i.e. post-fire regeneration from fire-scarified seed, or from sprouts) (Kauffman, 1990) and chaparral appears to occupy sites that have experienced severe fire or are too poor to support trees (Wilken, 1967; Rundel *et al.*, 1977; Weatherspoon, 1988; Bolsinger, 1989).

Although fire is considered a key disturbance process that regulates mixed conifer forest dynamics there has been little research that quantifies spatial and temporal variability in pre-fire suppression fire regimes (e.g. seasonal timing, return interval, rotation period, extent, severity) in the Sierra Nevada or Cascade Ranges, especially at landscape scales (Skinner & Chang, 1996). Determining how fire regime characteristics vary is essential for identifying the role of fire in the long-term dynamics of mixed conifer forest ecosystems. Limited tree-ring evidence of fire mainly from the southern and central Sierra Nevada suggest that fire return intervals (FRI) may be longer on north vs. south slopes, at high vs. low elevations, on fir vs. pine dominated sites, on shallow vs. deep soils, and in the fire suppression vs. pre-fire suppression period (e.g. Kilgore & Taylor, 1979; Caprio & Swetnam, 1995; Fites-Kaufman, 1997; Bekker & Taylor, in press). There are no data on mixed conifer fire regimes for the southern Cascades (Skinner & Chang, 1996) and only the fire return interval and season of burn have been quantified elsewhere in the mixed conifer zone. Regional differences in precipitation and species dominance between the central Sierra Nevada and the southern Cascades (e.g. Parker, 1995; Skinner & Chang, 1996) may be sufficient to lead to geographical differences in fire regimes within the mixed conifer forest type. Geographical variation in disturbance regimes have been identified in several widespread forest types and this variation contributes to regionally distinct vegetation patterns at landscape scales (e.g. Spies & Franklin, 1989; Shinneman & Baker, 1997; Taylor & Skinner, 1998).

In this study, we evaluate the efficacy of the mixed conifer fire-forest mosaic model by testing the hypothesis that pre-fire suppression fire regime parameters vary with species composition (tree species), and environment (i.e. slope aspect, slope position, elevation) in a mixed conifer forest landscape. Our premise is that a spatially variable fire regime leads to a more variable, less predictable, and less stable fire-forest mosaic and therefore to a non-equilibrium explanation for mixed conifer forest dynamics. For this study, we quantified the return interval, seasonal occurrence, size, rotation period and severity of fires using dendroecology.

## STUDY AREA

Our study was conducted in the 1587 ha Cub Creek Research Natural Area (CCRNA), Lassen National Forest, CA, USA (Fig. 1). Elevations range from 1136 to 2044 m. The climate

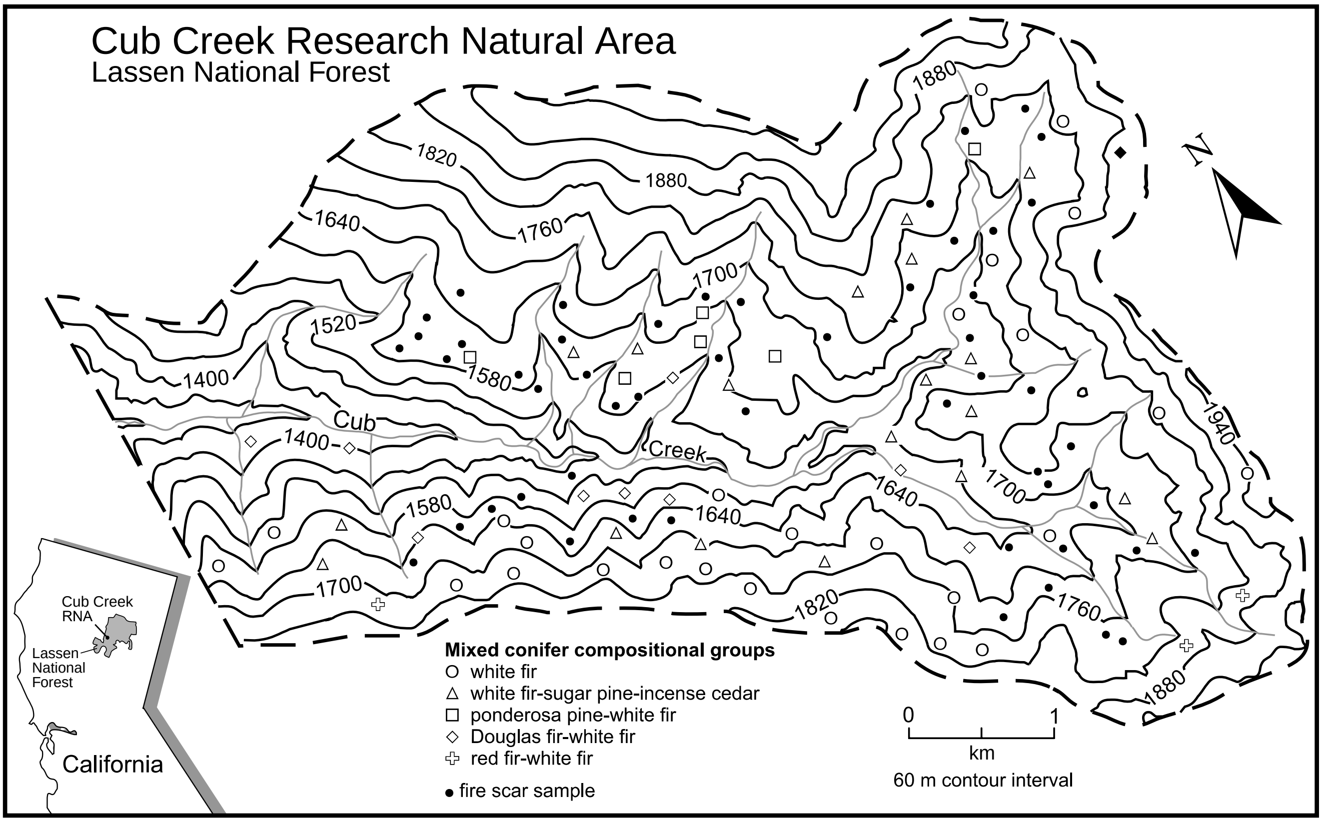

**Figure 1** Location of study area, forest sample plots, and fire scar samples in the Cub Creek Research Natural Area (CCRNA), Lassen National Forest, CA, USA. The different symbols represent ponderosa pine–white fir (PP–WF), Douglas fir–white fir (DF–WF), white fir–sugar pine–incense cedar (WF–SP–IC), red fir–white fir (RF–WF), and white fir (WF) forests (see Table 1).

is characterized by warm, dry summers and cold, wet winters. Mean monthly temperature at Mineral, California (1478 m), 20 km north of CCRNA, ranges from –0.8 °C in January to 17.2 °C in July, and annual precipitation averages 134 cm with most (81%) falling as snow between November and April. Forests grow on soils derived from Tertiary (Pliocene) aged volcanic rocks and the landscape has been deeply incised by fluvial erosion. Slopes are steep (25–30°) except for a flat bench adjacent to the north side of Cub Creek that occurs in the lower third of the drainage. Cub Creek runs southeast to northwest so the dominant slope aspects in the study area are northeast and southwest. Cliffs and rock outcrops occur throughout the watershed separating areas of continuous vegetation. These barren areas may serve as fuel breaks that retard the spread of fire.

People have influenced fire regimes in CCRNA in known and unknown ways. Fire is known to have been used by the native Yana tribe to drive game and encourage certain plants used for food and fibre (Schulz, 1954), but there is no direct evidence that they set fires in the watershed (Taylor & Randall, 1979). Euro-americans entered the Lassen region in 1849 with the opening of the Noble and Lassen trails north of the study area (Amesbury, 1967; Strong, 1973; Calhoon & Eaton, 1987). Livestock grazing and forest burning by herders affected fire regimes in nearby areas (McKelvey & Johnston, 1992), but we do not know if these activities occurred in the CCRNA. In 1905, the Lassen National Forest Reserve was established and a policy of fire suppression was implemented (Strong, 1973).

## METHODS

### Forest composition

Variation in forest composition by slope aspect and slope position in CCRNA was determined by first stratifying the study area by forest cover type (forest cover type map), elevation, and aspect (topographic map), and then sampling forests using 400 m$^2$ plots ($n = 66$). Plots were placed in strata that were homogenous in species composition, structure, and environment and the location of each plot was determined with a global positioning system (GPS) and then placed on a 1 : 24,000 topographic map. In each plot, all stems > 5.0 cm diameter at breast height (d.b.h.) were measured and the elevation, slope aspect, slope configuration, and topographic position of each plot was recorded. The last four variables were used to calculate each plot's Topographic Relative Moisture Index (TRMI), a measure of potential soil moisture based on topography that ranges from 0 (xeric) to mesic (60) (Parker, 1982).

We identified forest compositional groups using cluster analysis. First, we calculated species importance values (IV) as the sum of relative basal area (BA) and relative density (range 0–200). Secondly, we clustered species IV using relative Euclidean distance and Ward's method. Ward's clustering method minimizes within group variance relative to between group variance (Gauch, 1982; van Tongeren, 1995). We then identified variation in species composition (IV) and environment (TRMI, elevation) among compositional groups by comparing values for each group using a distribution free Kruskal–Wallis *H*-test (Sokal & Rohlf, 1995).

### Fire regimes

Fire regime parameters (i.e. return interval, season, extent, rotation, severity) were quantified using four types of data: (1) written fire records (1905–97); (2) fire scars in partial wood cross-sections removed from fire scarred trees; (3) radial growth changes in trees; and (4) age-class distribution of trees in plots (e.g. Arno & Sneck, 1977; Barrett & Arno, 1988). One hundred and fifteen fire scarred trees were located within CCRNA but only fifty-six were collected. The following criteria were used in choosing samples: (1) location in the watershed (i.e. forest cover type, aspect and elevation strata), (2) number of external fire scars and (3) sample integrity (i.e. decay). Many fire scarred trees were too decayed to sample. Samples were removed by cutting a partial cross-section from each tree with a chain saw (e.g. Arno & Sneck, 1977) and the location of each sample was then determined with a GPS and recorded on the topographic map. Fire dates in each cross-section were identified by first sanding wood samples to a high polish and then cross-dating (e.g. Stokes & Smiley, 1968) the annual growth rings with a nearby tree-ring chronology (Holmes *et al.*, 1986). The calendar year of the tree-ring with a fire scar was then recorded as the fire date. Fire history data were analysed using FHX2 software (Grissino-Mayer, 1996).

The season in which a fire occurred was identified by recording the position of each fire scar within an annual growth ring. Scar positions were assigned to one of five categories (cf. Baisan & Swetnam, 1990): (1) early (first one-third of earlywood), (2) middle (second one-third), (3) late (last one-third), (4) latewood (in latewood) or (5) dormant (at ring boundary). In northern California, dormant season fires represent fires that burn in late summer or fall after trees stop growing for the year (e.g. Caprio & Swetnam, 1995).

Fires can initiate distinct age-classes in forest stands, so we aged a sub-sample of trees in each plot to identify fire related cohorts (Arno & Sneck, 1977). We cored an average of fifteen trees (range, six to twenty-one) at 30 cm above the ground in each plot; trees > 1.0 m d.b.h. were cored at 1.0 m. Tree ages were then determined by sanding each core to a high polish, cross-dating the annual growth rings, and then determining the year of the innermost ring. Distinct pulses of recruitment lasting at least 10–30 years were deemed fire related if the onset of recruitment corresponded to the date of a fire in a nearby fire scar sample.

Fires that injure but do not scar trees can cause sudden changes in the radial growth of trees (Arno & Sneck, 1977; Barrett & Arno, 1988; Means, 1989; Brown & Swetnam, 1994). Consequently, we used variation in radial growth suppressions or releases (200% change in radial growth for 5 years compared with the previous 5 years) to identify fire occurrence in cross-sections and cores that did not have a fire scar in them. Dates of radial growth changes were determined to be fire-related if a nearby fire scar sample recorded a fire in the same year.

Spatial variation in FRI in CCRNA was determined by comparing both point and composite FRI for different slope aspect and forest composition groups. Composite FRI include all recorded fires in a slope aspect or forest compositional group, including small spot fires, and they tend to shorten as sample areas increase (e.g. Arno & Petersen, 1983). Point FRI, or the record of successive fires in single samples, in contrast, are longer and reflect the time dependence of fire occurrence associated with fuel accumulation at a single point (Dieterich, 1980; Kitzberger & Veblen, 1997). Group composite and group point FRI were compared using a distribution free Kruskal–Wallis *H*-test (Sokal & Rohlf, 1995). Composite FRI of more widespread fires were also compared by slope aspect group by calculating FRI for fires that scarred 25% or more of the samples in each group (Grissino-Mayer, 1996).

We identified variation in fire occurrence that may be related to land use change by comparing composite FRI for the pre-settlement (1700–1849), settlement (1850–1904), and fire suppression (1905–97) periods using a *t*-test. The composite FRI for the entire watershed was used for the temporal comparisons because composite FRIs are more sensitive to change in fire occurrence related to land use change than are point FRI (Dieterich, 1980).

Fire extent was estimated using fire boundary maps (cf. Taylor, 2000). Maps were produced by drawing boundaries on the topographic map around groups of three or more sites (i.e. fire scars, radial growth changes) that recorded a fire in a given year. Boundaries were drawn equidistant between points with and without evidence of a fire, except when breaks in the continuity of fuels (e.g. cliffs, rock outcrops, perennial streams) occurred between points. When fuel breaks were present, boundaries were placed along the fuel break. Fuel breaks were identified using aerial photographs (1941, 1993). The extent of each fire was then estimated using a dot-grid overlay. Some fires extended beyond the study area boundaries but these areas were not measured as part of a fire.

The fire rotation (FR; Heinselman, 1973), or the time (years) needed for an area equal in size to the study area to burn given the extent of burning over a specified period, was calculated by each aspect and forest composition group and for the entire study area using the burn area maps. FRS were calculated separately for the pre-settlement (1700–1849), settlement (1850–1904), and fire suppression (1905–97) periods because of potential differences in burning rates during these periods.

Spatial variation in fire severity in CCRNA was determined by identifying the cumulative area burned at high, moderate, or low severity using tree age data from plots and forest patch characteristics evident on 1941 and 1993 aerial photographs. Our analysis only characterizes the cumulative pattern of fire severity for fires between 1883 and 1926 because evidence of fire severity for earlier burns is erased by more recent events (Taylor & Skinner, 1998). Stands were grouped into three fire severity classes based on the density of different tree height classes evident on the aerial photographs: (1) high severity < 10 emergent stems ha$^{-1}$, (2) moderate severity = 10–20 emergent stems ha$^{-1}$ and (3) low severity > 20 emergent stems ha$^{-1}$ (cf. Taylor & Skinner, 1998). This approach assumes that stands with mainly older and taller trees experienced only low or moderate severity fires while stands with young short stems that are similar in height experienced high severity fire. Stands of montane chaparral present on both the 1941 and 1993 aerial photographs were excluded from the fire severity analysis because they may not have originated after severe fire (Rundel *et al.*, 1977; Weatherspoon, 1987; Bolsinger, 1989). Tree age and size data from the plots were also used to confirm fire severity class membership. Spatial patterns of fire severity were then identified by calculating the percentage of area burned by high, moderate, and low severity burns by slope position (low, middle, high) and slope aspect.

## RESULTS

### Forest composition

Five forest compositional groups were identified based on cluster analysis of species IV and they are segregated by slope aspect, elevation and potential soil moisture (Kruskal–Wallis *H*-test, $P < 0.05$) (Table 1). The white fir (WF) group ($n = 28$) is strongly dominated by white fir and is concentrated on mesic, northeast- and northwest-facing slopes; Douglas fir and sugar pine are important associates in sheltered coves. The white fir–sugar pine–incense cedar (WF–SP–IC) group ($n = 19$) is compositionally variable and occupies drier west-facing slopes. The Ponderosa pine–white fir (PP–WF) group ($n = 6$) occupies dry mid-elevation (1600–1770 m) sites on southwest-facing slopes and it is strongly dominated by ponderosa pine; incense cedar and Douglas fir are common associates. The Douglas fir–white fir (DF–WF) ($n = 8$) and red fir–white fir (RF–WF) groups ($n = 5$) occupy low (1370–1635 m) and high (>1850 m) elevation sites on northeast-facing slopes, respectively (Table 1).

### Fire regimes

Slope aspect, potential soil moisture, and forest composition in our study area co-vary (Table 1). Consequently, we compared fire regime characteristics for the following slope aspect groups: (1) south-facing (SF), (2) northern headwaters (NHW), (3) southern headwaters (SHW), and (4) north-facing (NF).

**Table 1** Mean importance value (IV, maximum 200), basal area (BA) (m$^2$ ha$^{-1}$) and density (ha$^{-1}$) of trees (>5.0 cm d.b.h.) and environmental characteristics of forest types identified by cluster analysis of species importance values (IV) in Cub Creek Research Natural Area (CCRNA). Forest types are ponderosa pine–white fir (PP–WF), Douglas fir–white fir (DF–WF), white fir–sugar pine–incense cedar (WF–SP–IC), red fir–white fir (RF–WF), and white fir (WF). $n$ = Number of samples in each forest type. TRMI varies between 0 (xeric) and 60 (mesic)

| | PP–WF ($n = 6$) | | | DF–WF ($n = 8$) | | | WF–SP–IC ($n = 19$) | | | RF–WF ($n = 5$) | | | WF ($n = 28$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | IV | BA | Density | IV | BA | Density | IV | BA | Density | IV | BA | Density | IV | BA | Density |
| White fir* | 85.1 | 14.1 | 620.8 | 99.4 | 38 | 753.1 | 117.3 | 58 | 694.7 | 120.4 | 60.6 | 605 | 189.4 | 92.9 | 1278.7 |
| Red fir* | | | | | | | 1.9 | 1.2 | 6.6 | 76.6 | 36.3 | 580 | 0.3 | 0.3 | 1.9 |
| Bigleaf maple* | | | | 4.2 | 1.3 | 43.8 | | | | 2.5 | 0.1 | 30 | 0.1 | 0 | 0.9 |
| Incense cedar* | 16.3 | 13.5 | 70.8 | 13.9 | 2.4 | 153.1 | 30.7 | 18.9 | 213.2 | | | | 1 | 0.4 | 5.6 |
| Pacific dogwood* | | | | 6.9 | 0.4 | 90.6 | 1.7 | 0.1 | 18.4 | | | | | | |
| Jeffrey pine | | | | | | | 3.7 | 2.6 | 3.9 | | | | 0.4 | 0.1 | 1.9 |
| Sugar pine* | 1.7 | 0.1 | 16.7 | 18.6 | 18.8 | 62.5 | 39.8 | 35.5 | 52.6 | | | | 6.4 | 4.2 | 22.2 |
| Western white pine* | | | | | | | | | | 0.5 | 0.1 | 10 | | | |
| Ponderosa pine* | 93.1 | 86.9 | 112.5 | 3.5 | 2.6 | 9.4 | 3.8 | 3.1 | 3.9 | | | | 0.1 | 0.1 | 0.9 |
| Douglas fir* | 3.8 | 0.2 | 37.5 | 52.8 | 49.2 | 65.6 | 0.1 | 0 | 1.3 | | | | 2.2 | 0.8 | 13 |
| Canyon live oak | | | | 0.2 | 0 | 3.1 | 0.2 | 0 | 2.6 | | | | 0.1 | 0 | 0.9 |
| | Mean | SD | | Mean | SD | | Mean | SD | | Mean | SD | | Mean | SD | |
| Elevation (m)* | 1657 | 61.8 | | 1548 | 112 | | 1661 | 57 | | 1856 | 89 | | 1731 | 81 | |
| Aspect* | SW | – | | NE | – | | W | – | | NE | – | | N | – | |
| TRMI* | 27.2 | 3.8 | | 36.3 | 7.4 | | 33 | 6.3 | | 35 | 4.7 | | 36 | 5.7 | |

Values for variables with an asterisk were significantly different among forest types ($P < 0.05$, Kruskal–Wallis *H*-test).

**Table 2** Characteristics of the fire record and sample areas in CCRNA. Time period spans between the earliest fire and data collection. Slope aspect groups are NF = north face, SHW = southern headwaters, NHW = northern headwaters, and SF = south face. See Table 1 for description of forest types

| Slope aspect group | Area (ha) | Dominant aspect | Dominant forest type | Number of samples | Time period | Number of fire scars | Number of years with fire scars |
|---|---|---|---|---|---|---|---|
| NF | 105.4 | NE | WF/DF–WF | 8 | 1616–1997 | 17 | 6 |
| SHW | 87 | W | WF–SP–IC | 14 | 1642–1997 | 29 | 8 |
| NHW | 101.5 | W | WF–SP–IC/WF | 15 | 1795–1997 | 50 | 17 |
| SF | 133.5 | SW | PP–WF | 19 | 1714–1997 | 160 | 28 |
| All | 427.4 | – | – | 56 | 1616–1997 | 256 | 59 |

*Fire record*

A total of fifty-nine fires were recorded in the fifty-six samples between 1616 and 1926, but the number of samples, the length of the fire record and the number of fires in each slope aspect group varies (Table 2, Fig. 2). SF had the most fires (twenty-eight) and the longest fire record (1616–1997) while seventeen fires were recorded in NHW between 1642 and 1997. There were fewer fires and shorter fire records for SHW and NF. Between 1795 and 1997 SHW had eight fires while NF had six fires between the years 1714 and 1997.

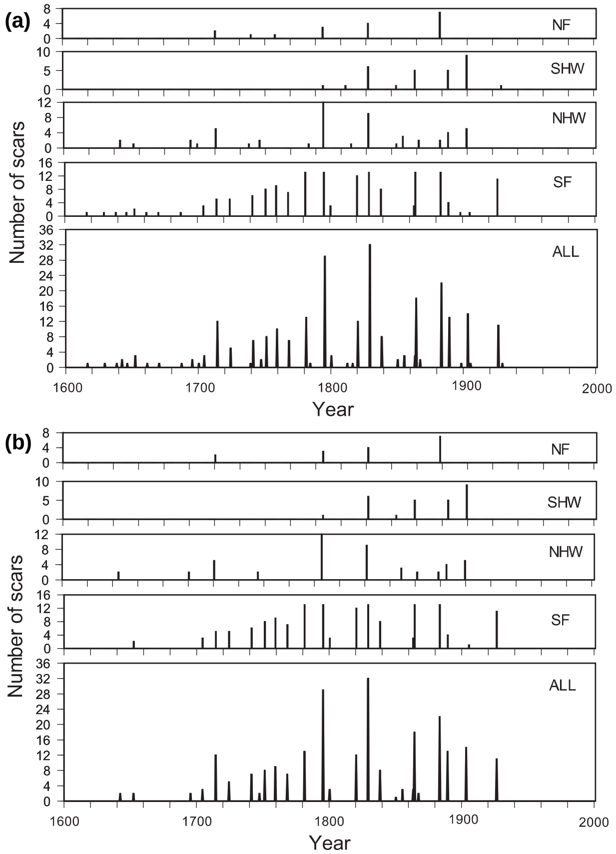

**Figure 2** Composite fire chronology for (a) all scarred and (b) >25% scarred samples by slope aspect group for Cub Creek Research Natural Area (CCRNA).

*Season of fire occurrence*

Fire scar positions within annual growth rings indicate that fires mainly (90.3%) burned in the dormant season after trees stopped growth for the year. However, there was some spatial variation in burn season by slope aspect (Table 3). NF experienced only dormant season fires, while SF experienced some (13%) growing season burns. Percentage of growing season burns was intermediate for SHW (7.1%) and NHW (3.7%).

*Fire return intervals*

The median and mean composite FRI for all fires in the study area were 7 and 7.6 years (range, 1–21), respectively (Table 4). The median for the composite FRI for more widespread events (i.e. 25% scarred) was longer at 14.2 years.

*Spatial patterns*

The composite FRI for all fires and widespread fires (>25% scarred) and point FRI varied by slope aspect group ($P < 0.05$, Kruskal–Wallis *H*-test) (Table 4). Median composite FRI were shortest on SF (9 years) and NHW (13.5 years) and longer on SHW (17 years) and NF (34 years). Overall, median point FRI were longer than composite FRI but the pattern of spatial variation was the same. Point FRI were shortest on SF (19 years) and NHW (34 years) and longer on SHW (37 years) and NF (54 years). Composite FRI for widespread fires (>25% scarred) were shortest on SF (10 years) and SHW (17 years) and longer on NHW (29.5 years) and NF (34 years). The composite FRI for widespread fires on NF may be underestimated because of the relatively small number of samples ($n = 8$) in this group.

*Temporal patterns*

Composite FRI varied by time period (Table 5). The mean composite FRI was similar ($P > 0.05$, *t*-test) in the settlement (6.6 years) and pre-settlement (7.7 years) period, but longer ($P < 0.05$, *t*-test) in the fire suppression period (after 1905). Only two fires occurred in the study area between 1905 and 1997.

*Fire extent*

Fire extent varied by year and by slope aspect (Fig. 3). The average extent of a fire between 1704 and 1926 ($n = 23$) was 106 ha (range, 7–379 ha) and most fires burned only one or

**Table 3** Position of fire scars within annual growth rings by slope aspect group in CCRNA

| Slope aspect group | *n* | Undetermined | Scar position<br>Middle (%) | <br>Latewood (%) | <br>Dormant (%) |
|---|---|---|---|---|---|
| NF | 18 | 5 | – | – | 100 |
| SHW | 29 | 15 | – | 7.1 | 92.9 |
| NHW | 54 | 27 | – | 3.7 | 96.3 |
| SF | 160 | 60 | 6 | 7 | 87 |
| All | 261 | 107 | 5.8 | 5.8 | 90.3 |

two slopes. Large ( > 150 ha) fires did burn throughout the study area. Six large burns that burned three or more slopes occurred in 1714, 1795, 1829, 1883, and 1889. Average fire sizes were largest on NF (80 ha, range, 37–120 ha) and SF (75 ha, range 21–105 ha) and smaller on NHW (40 ha, range 7–48 ha) and SHW (73 ha, range 36–106 ha).

### *Fire rotations*

Fire rotations also varied by slope aspect (Table 6). Pre-fire suppression FR was longest (42.5 years) for NF, shortest (17.4 years) for SF, and intermediate for NHW (27.2 years) and SHW (37.2 years). The overall pre-1905 FR was 28.2 years. In contrast, the suppression period FR for the whole study area was 406 years.

### *Fire severity*

The cumulative area (%) burned at low, moderate, and high severity varied by topographic position and slope aspect (Table 7). Fire severity was mainly high (85.7%) on upper slopes, low (60%) on lower slopes and moderate and low severity (46.8% and 29.9%) on middle slopes. SF and NF had similar fire severity patterns with mainly ( > 60%) low and moderate severity burns while NHW and SHW experienced mainly ( > 60%) high severity burns (Table 8).

**Table 4** Fire return intervals (FRI) (years) by slope aspect groups in CCRNA

| Slope aspect group | Mean | Median | Range | SD | Skewness | Number of intervals |
|---|---|---|---|---|---|---|
| *Composite fire return intervals, all scarred* | | | | | | |
| NF | 33.8 | 34 | 18–54 | 13.3 | 0.42 | 5 |
| SHW | 19.1 | 17 | 14–26 | 4.95 | 0.33 | 7 |
| NHW | 16.3 | 13.5 | 5–43 | 11 | 1.12 | 16 |
| SF | 11.5 | 9 | 1–25 | 5.58 | 0.63 | 27 |
| All | 7.6 | 7 | 1–21 | 4.7 | 0.83 | 30 |
| *Point FRI, all scarred* | | | | | | |
| NF | 54.3 | 54 | 34–88 | 19.4 | 0.59 | 9 |
| SHW | 39.4 | 37 | 14–74 | 20.6 | 0.74 | 14 |
| NHW | 37.8 | 34 | 8–108 | 24.9 | 1.06 | 35 |
| SF | 21.6 | 19 | 5–61 | 12.1 | 0.78 | 139 |
| All | 27.2 | 25 | 5–108 | 18.1 | 1.51 | 185 |
| *Composite FRI, 25% or more scarred* | | | | | | |
| NF | 33.8 | 34 | 18–54 | 13.3 | 0.42 | 5 |
| SHW | 21.6 | 17 | 14–35 | 8.5 | 0.73 | 5 |
| NHW | 26.1 | 29.5 | 5–48 | 14.7 | –0.02 | 10 |
| SF | 13.5 | 10 | 6–37 | 7.5 | 1.16 | 23 |
| All | 14.2 | 11.5 | 6–35 | 7.8 | 1.46 | 14 |

## DISCUSSION

Mixed conifer forests in CCRNA varied widely in composition. Species distribution and abundance patterns were controlled by slope aspect, topographically influenced patterns of soil moisture and elevation. Elevation, slope aspect and soil moisture, are all recognized as important determinants of regional species abundance patterns in the southern Cascades (e.g. Taylor, 1990; Parker, 1991, 1992, 1995; Bekker & Taylor, in press) and the central and southern Sierra Nevada (Parker, 1989). In CCRNA, these same variables strongly influence species distribution patterns at more local and landscape scales.

Fire regime parameters also varied with forest composition and environmental setting (i.e. slope aspect, slope position, elevation). Median composite and point FRI were longest on higher, cooler, more mesic, NF slopes covered with WF, DF–WF, and RF–WF forests, shortest on the dry, SF slopes covered with PP–WF forests and intermediate on west-facing slopes dominated by WF–SP–IC forests. The spatial pattern for length of FR was the same as that for FRI. Actual FRI may be shorter than our tree ring derived FRI estimates. Low intensity fires may not scar trees because of thick bark (Agee, 1993; Taylor, 1993; Taylor & Skinner, 1998). Variation in FRI with slope aspect, slope position, elevation, and species dominance has also been identified in several fire history studies in mixed conifer forests in the Sierra Nevada (e.g. Kilgore & Taylor, 1979; Caprio & Swetnam, 1995; Fites-Kaufman, 1997) and the spatial

**Table 5** Composite fire return intervals (FRI) (years) for the pre-settlement (1700–1849), settlement (1850–1904), and fire suppression (1905–97) periods in CCRNA. There was no difference in the mean fire return interval between pre-settlement and settlement period, but it was longer ($P < 0.05$, *t*-test) during the suppression period

| | Time period | Mean | Median | Range |
|---|---|---|---|---|
| Pre-settlement | 1700–1849 | 7.7 | 8.5 | 2–15 |
| Settlement | 1850–1904 | 6.6 | 5.5 | 1–16 |
| Suppression | 1905–97 | 30.7 | 21 | 3–68 |

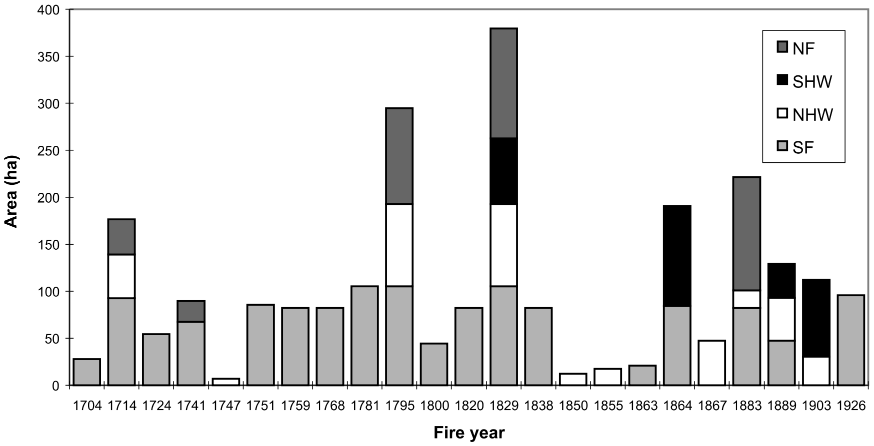

**Figure 3** Fire extent by slope aspect in Cub Creek Research Natural Area (CCRNA). NF = north face, SHW = southern headwaters, NWH = northern headwaters, and SF = south face. The fire record for SHW does not extend before 1795.

patterns of FRI, we identified in CCRNA are similar. Moreover, our point and composite estimates for pre-fire suppression FRI are in the range of values for mixed conifer forests in the southern Cascades (Bekker & Taylor, in press; Norman & Taylor, in press), the Klamath Mountains (Taylor & Skinner, 1998), the Sierra Nevada (Kilgore & Taylor, 1979; Caprio & Swetnam, 1995; Fites-Kaufman, 1997), the San Bernardino range (McBride & Lavin, 1976) and the San Pedro Mártir in Baja California (Burk unpublished in Savage, 1997). All of these studies underscore the importance of frequent fire in mixed conifer forest development.

Spatial variation in pre-fire suppression FRI is probably the result of several factors related to species composition and slope aspect that affect flammability of fuels. First, forest litter from species with long needles (i.e. ponderosa pine, sugar pine) is less dense than from species with short needles (i.e. Douglas fir, white fir, red fir) (e.g. Albini, 1976; van Wagtendonk, 1998) and fire intensity and spread are greater in lower density fuel beds (Albini, 1976; Rothermel, 1983; Fonda *et al*., 1998). Secondly, fuels are dry enough to burn for a longer period each year on SF slopes compared with NF ones and this increases the probability of an ignition turning into a fire (Agee, 1993). Finally, fine fuel production is greater in pine vs. fir dominated mixed conifer forests (e.g. Agee *et al*., 1978; Stohlgren, 1988; J. van Wagtendonk pers. comm.) so fires can burn again sooner in WF–PP than in WF forests.

FRI increased dramatically in CCRNA after 1905 because of a federal management policy of suppressing fires and similar declines in fire occurrence are characteristic of mixed conifer forests in the Cascade, Klamath and Sierra Nevada Mountains (Vankat, 1977; Vankat & Major, 1978; Kilgore & Taylor, 1979; Taylor, 2000; Bekker & Taylor, in press; Norman & Taylor, in press). The increase in length of FR from 28 to 407 years underscores the decline in the importance of fire in CCRNA. In some California mixed conifer forests an

**Table 6** Fire rotation (FR) by slope aspect group for the pre-suppression (1795–1904) and suppression (1905–97) periods in CCRNA

| | Fire rotation (years) | |
|---|---|---|
| Slope aspect group | Pre-suppression (1795–1904) | Suppression (1905–97) |
| NF | 42.5 | – |
| SHW | 37.2 | 37,352 |
| NHW | 27.2 | – |
| SF | 17.4 | 100.9 |
| All | 28.2 | 406 |

**Table 7** Percentage of area burned between 1883 and 1926 at low, moderate and high severity by topographic position in CCRNA

| | NF | SHW | NHW | SF | All |
|---|---|---|---|---|---|
| *Lower slopes* | | | | | |
| Low | 67.6 | 39.7 | 73.5 | 52.9 | 59.6 |
| Moderate | 31.8 | 36.2 | 11.8 | 46.1 | 34.6 |
| High | 0.6 | 24.1 | 14.7 | 1 | 5.8 |
| *Middle slopes* | | | | | |
| Low | 22.4 | 40.7 | 0 | 47.5 | 29.9 |
| Moderate | 48.5 | 37.3 | 45.6 | 47.5 | 46.8 |
| High | 29.1 | 22 | 54.4 | 5.2 | 23.4 |
| *Upper slopes* | | | | | |
| Low | 0.7 | 0 | 0 | 1.5 | 0.5 |
| Moderate | 28.4 | 2 | 0 | 29.4 | 13.8 |
| High | 70.9 | 98 | 100 | 69.1 | 85.7 |

**Table 8** Percentage of area burned between 1883 and 1926 at low, moderate and high severity by slope aspect group in CCRNA

| | NF | SHW | NHW | SF |
|---|---|---|---|---|
| Low | 33.3 | 17.7 | 13.7 | 38.1 |
| Moderate | 35.8 | 17.4 | 16.4 | 43.9 |
| High | 30.9 | 64.9 | 69.9 | 18 |

earlier settlement period fire decline has been observed and attributed to reduction of grassy fuels by intensive livestock grazing in the mid to late nineteenth century (e.g. Caprio & Swetnam, 1995). There was no settlement period reduction in fire occurrence in CCRNA, or in other nearby mixed conifer (e.g. Norman & Taylor, in press) or mid- and upper-montane forests (Taylor, 2000; Bekker & Taylor, in press) suggesting there was little influence of grazing on pre-settlement period fire regimes at least in this part of the southern Cascades. Consequently, forests in CCRNA experienced a pre-settlement period fire regime until 1905 when fire suppression was implemented.

Season of burn has a strong influence on species response to fire (e.g. Kauffman & Martin, 1989; Kauffman, 1990) and burns in CCRNA mixed conifer forests occurred mainly (90%) in the dormant season. Fires in nearby (< 25 km) mixed conifer forests also mainly (80%) burned in the dormant season (Norman & Taylor, in press). Lighting activity peaks in July and August in the Lassen National Forest and ignitions are highest during this period (Hood, 1995). The positions of scars within growth rings in CCRNA are different than those reported for central Sierra Nevada mixed conifer forests. In the central Sierra Nevada, most (50%) scars occurred in latewood near the end of the growing season while only 30% occurred in the dormant season (Caprio & Swetnam, 1995). Geographical differences in season of burn are probably related to the south (early) to north (late) gradient for the onset of summer drought along the Sierra Nevada–Cascade axis (e.g. Major, 1977; Parker, 1994) which would influence how long fuels are dry enough each year to burn. These data suggest there is considerable variability in season of burn within mixed conifer forests and this variability may lead to regionally distinct vegetation responses to fire.

Sizes of burns in CCRNA mixed conifer forests were generally small (mean = 106 ha) and the average fire burned on only one or two slope aspects. Tree ring evidence of burns suggest that fire boundaries in most fire years were associated with breaks in the continuity of fuels such as along rock outcrops and stream courses. However, during certain years widespread fires burned across fuel breaks and spread throughout the watershed. Large fires occurred in 1795, 1829, 1883, 1889 and tree ring re-constructions of drought (e.g. GP-5, Palmer Drought Severity Index) show these as being dry or very dry years (Cook *et al.*, 1996). Widespread fires also occurred in dry or very dry years in 1829, 1841, 1846, 1864, 1883 and 1889 in nearby (< 50 km) mixed conifer and upper montane forests (e.g. Bekker & Taylor, in press; Norman & Taylor, in press). This suggests that regional scale climate variation, specifically drought, strongly influences the characteristics of mixed conifer forest fire regimes.

Fires in mixed conifer forests are described as being primarily low and moderate in severity (e.g. Kilgore & Taylor, 1979; Bonnicksen & Stone, 1982; Skinner & Chang, 1996) but in CCRNA high severity burns are an intrinsic part of the fire regime and burn severity varied with slope aspect and topographic position. The influence of topography on patterns of fire severity is poorly known but the fire severity/slope position gradient identified for mixed conifer forests in CCRNA is also present in Douglas fir forests growing on steep terrain in the Klamath Mountains (e.g. Taylor & Skinner, 1998). Higher fire induced tree mortality at mid and upper slope positions would occur because of higher fire line intensities at mid- and upper-slope positions caused by pre-heating of fuels (e.g. Rothermel, 1983). The fire severity/slope position association suggests that the interplay of topography and fire behaviour can lead to highly variable dynamics and structures in mixed conifer forests at both stand and landscape scales.

## CONCLUSIONS

Fires in mixed conifer forests have been previously described as being frequent and low to moderate in severity (e.g. Kilgore, 1973; Kilgore & Taylor, 1979; Agee, 1993). Low and moderate severity fires consume patches of fuel and kill mostly seedlings and saplings in the understory and occasionally small groups of main canopy trees (e.g. Kilgore & Taylor, 1979; Parsons & DeBenedetti, 1979; Skinner & Chang, 1996). This fire regime is purported to create a fine grained (< 0.2 ha) multi-aged forest with open and closed canopy conditions and heterogeneous fuels which impedes development of high severity fire and leads to a shifting mosaic steady-state forest at the landscape scale (e.g. Bonnicksen & Stone, 1982). The mixed conifer forest fire regime we quantified in CCRNA does not fit the fire-forest structure mosaic model developed mainly from mixed conifer forests in the central and southern Sierra Nevada. In CCRNA, fire regime parameters (e.g. FRI, fire extent, FR, fire severity) varied widely with species composition, slope aspect and slope position. Fine grained multi-aged forests were present in CCRNA, mainly at lower slope positions, but stands of even-aged forest that established after high severity fire were more widespread. There was also considerable temporal variation in fire extent with the most widespread fires occurring during drought years. The important contributions of topography and climate to variation in the fire regime indicates that exogenous factors play a key role in shaping the fire-forest structure mosaic and that the fire-forest structure mosaic is more variable, less predictable and less stable than previously thought. Finally, some characteristics of the fire regime (i.e. fire severity, season of burn) in CCRNA are different than those described for mixed conifer forests in the Sierra Nevada (Kilgore & Taylor, 1979; Caprio & Swetnam, 1995; Fites-Kaufman, 1997), the San Bernardino range (McBride & Lavin, 1976) and the San Pedro Mártir in Baja California (Savage, 1997; Minnich *et al.*, 2000), and this suggests that there are geographical differences in mixed conifer fire regimes along the Pacific slope. Geographical differences in disturbance regimes and species response to disturbance are known to contribute to structural and compositional diversity within widespread forest types (e.g. Spies & Franklin, 1989). Consequently, fire-forest structure mosaic models developed for one area should be extrapolated cautiously to other locations.

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