Final Project Report: CA CESU Task Agreement J8C07070009 Submitted February 2012
Funded through the NPS Fuels Research Reserve Fund

Mixed Severity Fire Regimes & Forest Structure at Crater Lake National Park, Oregon, USA

Alison Forrestel and Scott Stephens
Department of Environmental Science, Policy and Management
University of California, Berkeley

Introduction

The west side forests of Crater Lake National Park (CLNP) are unique in that they represent one of the few places in the Cascade Range where an elevational gradient from mixed conifer to high elevation forests remains intact and has never been logged. The fire history along this gradient is not well documented or understood. Park management documents, including the Fire Management Plan, describe the fire regime of these forests as ranging from mixed severity (mean fire return interval of 40-70 years) in mid-elevation red fir forests to a low frequency, high severity regime (mean fire return interval greater than 100 years) for high elevation mountain hemlock forests (National Park Service 2007). However, both the patch mosaic structure of these forests as well as the fire behavior and fire effects in recent wildland fires in this region suggest that the fire regimes may be more mixed in severity and that fire return intervals may be shorter than previously thought. In addition, there may be potential for fire spread from lower to higher elevation forests that is absent in more fragmented ecosystems.

Along the western slope of Mount Mazama, at CLNP, a gradient of forest types are found. At the highest elevations, from 1800 to 2300 meters, forests are dominated by open stands of mostly pure mountain hemlock. As elevation decreases, forests are dominated by a mix of red fir and mountain hemlock. The lowest elevations, ranging from 1500 to 1700 meters, are dominated by mixed conifer forests which are comprised of Douglas-fir, white fir, incense-cedar, western hemlock and western white pine. Lodgepole pine forests are found across the elevational gradient within the study area, primarily on flat cold air drainages with poor soils (Zeigler 1978). Figure 1 shows typical stands of each of the major forest types in the study. CLNP was established in 1902 and most of the forests within the park boundary, including all of the forests in the study area, have never been logged.

Prior to this study, there have been few published fire histories that include these forest types at CLNP. There is published fire history information from other forest types within CLNP and from these forest types in other parts of the Cascades or Sierra Nevada ranges (see Table 1). One study, in the Panhandle region of CLNP, reported fire return intervals of nine to forty-two years in ponderosa pine forest (McNeil 1975). Another study, that used a combination of stumps on an

Figure 1. Typical stands of mountain hemlock (a), red fir (b), lodgepole pine (c) and mixed conifer species (d) at Crater Lake National Park, OR, USA.

(a)

(b)

(c)

(d)

area owned by the Winema National Forest adjacent to CLNP and cores from a burned area within park boundaries, reported a fire return interval of thirty-nine years in red fir forests (Chappell 1991). Other studies of fire history in red fir forests south of CLNP report fire return intervals ranging from twenty to close to one hundred years (Pitcher 1987, Chappell 1991, Taylor and Halpern 1991, Taylor 2000, Bekker and Taylor 2001, Taylor and Solem 2001, Scholl and Taylor 2006). The fire history of subalpine mountain hemlock forests is not well documented but these forests are thought to have fire free intervals of hundreds of years (Agee 1993). Bekker and Taylor (2001, 2010) found fire return intervals of 20 years (based on direct analysis of fire scars) and 100 years (based on fire extent maps using the same set of scars) for red fir – mountain hemlock forest in the southern Cascades. They found that moderate and high severity fires occurred in this forest type, but they were not able to detect impacts of fire on forest composition or structure (Bekker and Taylor 2010).

Table 1. Published fire histories for Crater Lake National Park and similar forest types in Oregon and California.

Forest Type	**Location**	**FRI (years)**	**Analysis Unit for FRI**	**Citation**
Red Fir	Sequoia National Park, CA	78	plot (.25-.5 ha)	Pitcher (1987)
Red Fir	Crater Lake National Park, OR	39	plot (.5 ha)	Chappell (1991)
Red Fir	Swain Mtn Experimental Forest, CA	40-42	plot (.5 - 1 ha)	Taylor & Halpern (1991)
Red Fir-Western White Pine	Lassen Volcanic National Park, CA	70 (26-109)	point	Taylor (2000)
Red Fir-Western White Pine	Caribou Wilderness, CA	66	plot (.04-.1 ha)	Taylor & Solem (2001)
Red Fir-Western White Pine	Lake Tahoe, CA	76 (25-175)	point	Scholl & Taylor (2006)
Red Fir-Mtn Hemlock	Thousand Lakes Wilderness, CA	20 (9-91)	point	Bekker & Taylor (2001)
Red Fir-Mtn Hemlock	Thousand Lakes Wilderness, CA	100	point	Bekker & Taylor (2010)
Lodgepole Pine	Caribou Wilderness, CA	67	plot (.04-.1 ha)	Taylor & Solem (2001)
Lodgepole Pine	Thousand Lakes Wilderness, CA	47 (28-54)	point	Bekker & Taylor (2001)
Lodgepole Pine	Thousand Lakes Wilderness, CA	50-76.5	point	Bekker & Taylor (2010)
Ponderosa Pine	Crater Lake National Park, OR	9-42	2 trees	McNeil (1975)

In addition to evidence for mixed severity fire regimes from similar systems, recent wildfires at CLNP have been mixed in severity. For example, the 2006 Bybee Fire burned over 1100 ha of lodgepole pine, red fir and mountain hemlock forests within the study area. Burn severity, based on data obtained through the Monitoring Trends in Burn Severity program, was mixed within the Bybee Fire and areas of both high and low severity occurred across all three forest types (Eidenshink et al. 2007).

Although mixed severity fire regimes are likely widespread throughout the western United States, they are poorly documented (Perry et al. 2011). In addition, the term mixed severity has

not been well defined in the literature. Agee (1993) defines mixed severity as those fire regimes where more than 20% but less than 70% of the tree basal area is killed by a typical fire. Other defining characteristics of mixed severity regimes are patchiness across the landscape at scales of 1-100's of ha and temporal variation in the proportion of high versus low severity patches (Perry et al. 2011).

Understanding the fire regimes of the mixed conifer, lodgepole pine, red fir and mountain hemlock forests at CLNP is important for a variety of reasons. First, a clear understanding of fire history is important to guide the management of wildfires and prescribed fires into the future. Second, documentation of a mixed severity fire regime in a system such as this that has never been logged is useful in understanding the fire regimes elsewhere. This study uses stand structural and fire scar data to document fire history and forest successional trajectories across the gradient of forest types on the west side slopes of Crater Lake National Park. Specifically, we hypothesized that fire return intervals in red fir and mixed conifer forest types would be similar to those documented in similar forest types in surrounding areas and that fire return intervals in mountain hemlock forests would be similar to those found in red fir forests.

Methods

Study area

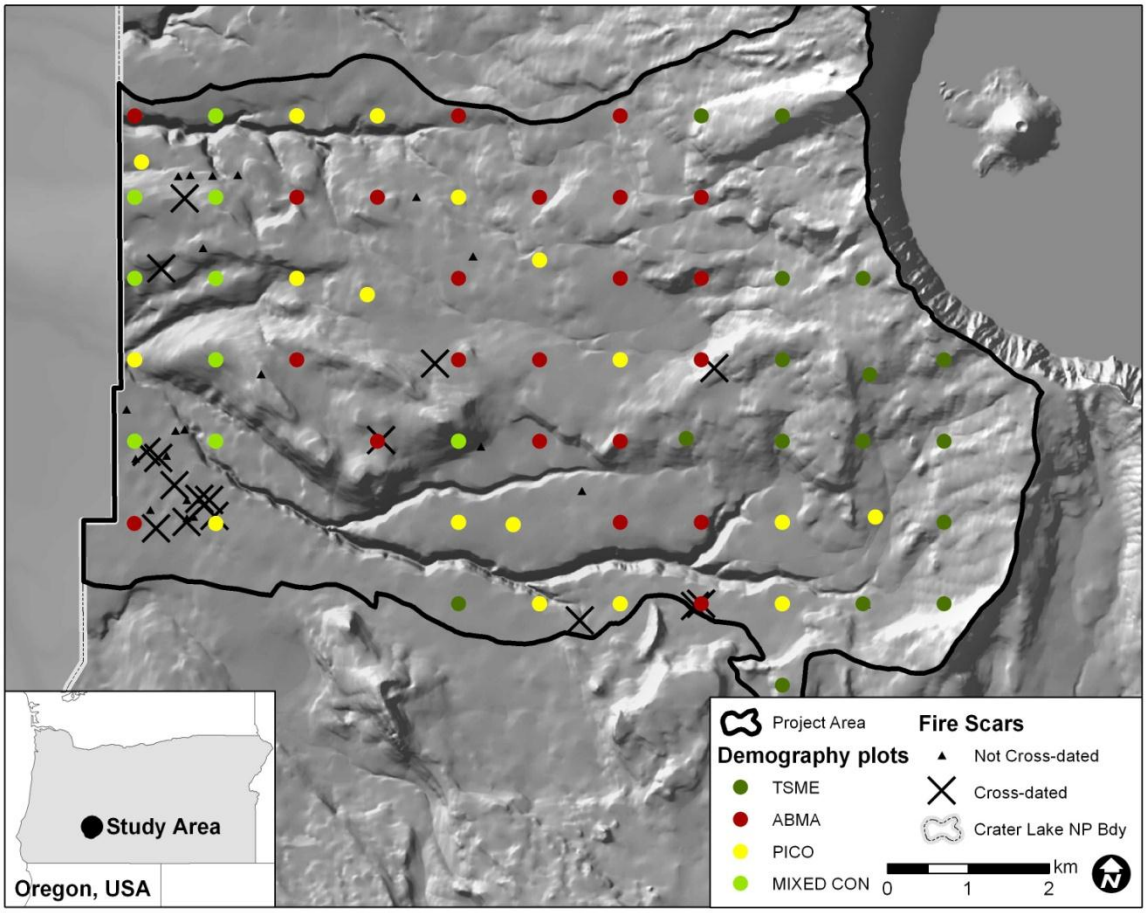
Field work was conducted at Crater Lake National Park. CLNP is located in the Southern Cascade Mountains of Oregon and covers more than 74,000 hectares. Specifically, this study focused on the mountain hemlock, red fir, lodgepole pine, and mixed conifer forests on the west side of the Cascade crest within CLNP. The study area is two subwatersheds of the Upper Rogue River watershed encompassing 7,031 ha (Figure 2). This area covers an elevational gradient from 1500 to 2300m. The climate in the study area is characterized by long, snowy winters and short, dry summers. Mean annual precipitation is 168cm, most of which falls in the form of snow. The mean maximum July temperature is 20 C and the mean minimum January temperature is -8 C (Western Regional Climate Center 2008). Soils in the study area are volcanic and originated with the eruption of Mount Mazama approximately 6600 years ago (Williams 1942).

Plot selection and sampling

Sixty-four stand demography plots were established within the study area using a 1km grid with a random starting point (Figure 2). Plots were located using a GPS and were rejected if the selected location was non-forested. Stand demography data were collected using variable radius circular plots. At each plot, the 20 closest trees to plot center with a diameter at breast height (DBH) of 10cm or greater were identified and species, DBH, status (live versus dead) and canopy class were recorded. Each tree was cored at 15 cm above the ground or lower and core height was recorded. The distance to the furthest tree from plot center was recorded. The tree closest to plot center was tagged at breast height with a numbered tag facing plot center. The distance and azimuth from plot center of the tagged tree were recorded. Plot level data were collected at each plot including aspect, slope, dominant canopy species, ocular estimates of canopy cover and dominant shrub and herbaceous species. Four photographs were taken at each plot, one in each cardinal direction. Within each plot, no more than five trees with a DBH less than 20cm were cored. If more than five such trees were present in a plot, the plot was expanded

to include larger trees and trees less than 20cm were measured and identified, but not cored. This ensured that older trees were adequately sampled, but also biased our results such that recent recruits were less likely to be captured.

Figure 2. Study area and plot locations



Fire scars were sampled opportunistically throughout the study area from both living and dead trees. Such targeted sampling has been shown to yield comparable results to random or grid-based sampling (Van Horne and Fule 2006). Partial cross-sections were removed from visible scars using a chain saw. Intact fire scars were extremely rare within the project area; the majority of scars we encountered were rotten, presumably because firs and hemlocks, the dominant species in the study area, do not hold scars well or tend to heal over so that scars are not visible (Pitcher 1987, Taylor 1993) and due to the heavy snow pack in the study area. For each fire scar that was sampled, we recorded the location of the scar using a GPS as well as the species, status (live versus dead) and DBH.

Cores and fire scars were sanded using progressively finer sandpaper. We cross-dated scars and cores using standard methodology as described in Stokes and Smiley (1968). Cross-dating used several published master chronologies from nearby sites (NOAA 2011, Table 2). For cores that

did not intersect the pith, but were within an estimated ten years of the pith, we estimated the pith date based on the curvature of the innermost rings (Applequist 1958). We did not adjust for the number of years it took for trees to reach core height, but because our analysis is based on ten year bins of establishment dates, we expect this source of error to be relatively unimportant.

Table 2. Master chronologies used in cross-dating cores and fire scars.

Site Name	Location	Elevation (m)	Species	Time Period	Number of Cores	Series Intercorr -elation	Mean Sensitivity	Contributor
Mt. Ashland	42.07°N 122.72°W	1860	Abies magnifica	1739-1983	22	0.606	0.182	Briffa, K., F.H. Schweingruber
Crater Lake	42.97°N 122.17°W	1752	Tsuga mertensiana	1564-1983	23	0.735	0.284	Briffa, K., F.H. Schweingruber

Data analysis

Each plot was assigned to a forest type based on the species with the maximum basal area in that plot. For mixed conifer plots, the maximum basal area was comprised of species other than mountain hemlock, red fir or lodgepole pine. We summarized the size class distribution of each major species within each forest type. We used regression analysis to examine relationships between tree age and tree size for each major species. Using our demography data, we summarized stand age structure by species. We also summarized the stand age structure of each species broken down by forest type. Fire scars were analyzed with FHAES software (USDA Forest Service 2011). All statistical analyses used R statistical software version 2.11.1 (R Development Core Team 2010).

Results

Stand Demography, Forest Composition and Structure

Four primary forest types were sampled in the stand demography phase of this study: mountain hemlock, red fir, lodgepole pine and mixed conifer. Dominant species in mixed conifer plots included white fir, western hemlock, western white pine, Douglas-fir, and incense-cedar. A total of 1,025 trees were cored across the study area. Approximately 23% of cores were excluded from further analysis because they could not be cross-dated or were too far from the pith to estimate a pith date.

Table 3 shows the number of plots and average stand characteristics for each of the forest types sampled. These results are shown graphically in Figure 3. Figure 4 shows the distribution of basal area amongst canopy classes within each forest type. Figure 5 illustrates the distribution of species, by stem count, within the mixed conifer forest type.

Although understory characteristics were not measured quantitatively, they were described qualitatively. More than half of the plots had little or no shrub or herbaceous layer; this open, litter-dominated understory was particularly prevalent in the red fir forest type. Only seven plots, which were distributed relatively evenly among forest types, had a shrub dominated understory. This shrub layer was dominated by low-growing species (<0.5m), primarily huckleberry and manzanita. An herbaceous understory was found on approximately one third of plots and was somewhat more common in lodgepole pine stands.

Table 3. Average stand characteristics by forest type, Crater Lake National Park, OR, USA

Forest Type	Mountain hemlock (TSME)	Red fir (ABMA)	Lodgepole pine (PICO)	Mixed conifer
Number of Plots	16	22	17	9
Elevation (m)	1975	1752	1688	1595
Total Basal Area (m^2/ha)	87.3	136.1	42.8	94.7
Total Stem Density (stems/ha)	591	986	779	841
TSME Basal Area (m^2/ha)	68.5	19.1	0.4	8.6
ABMA Basal Area (m^2/ha)	11.0	105.1	5.9	12.1
PICO Basal Area (m^2/ha)	6.9	3.3	34.3	2.1
Other Basal Area (m^2/ha)	0.9	8.5	1.9	71.9
TSME Stem Density (stems/ha)	457	321	12	193
ABMA Stem Density (stems/ha)	65	536	88	123
PICO Stem Density (stems/ha)	67	39	636	25
Other Stem Density (stems/ha)	2	90	44	500

Figure 3. Total basal area and total stem density for red fir, mountain hemlock, lodgepole pine and mixed conifer forest, Crater Lake National Park, OR, USA

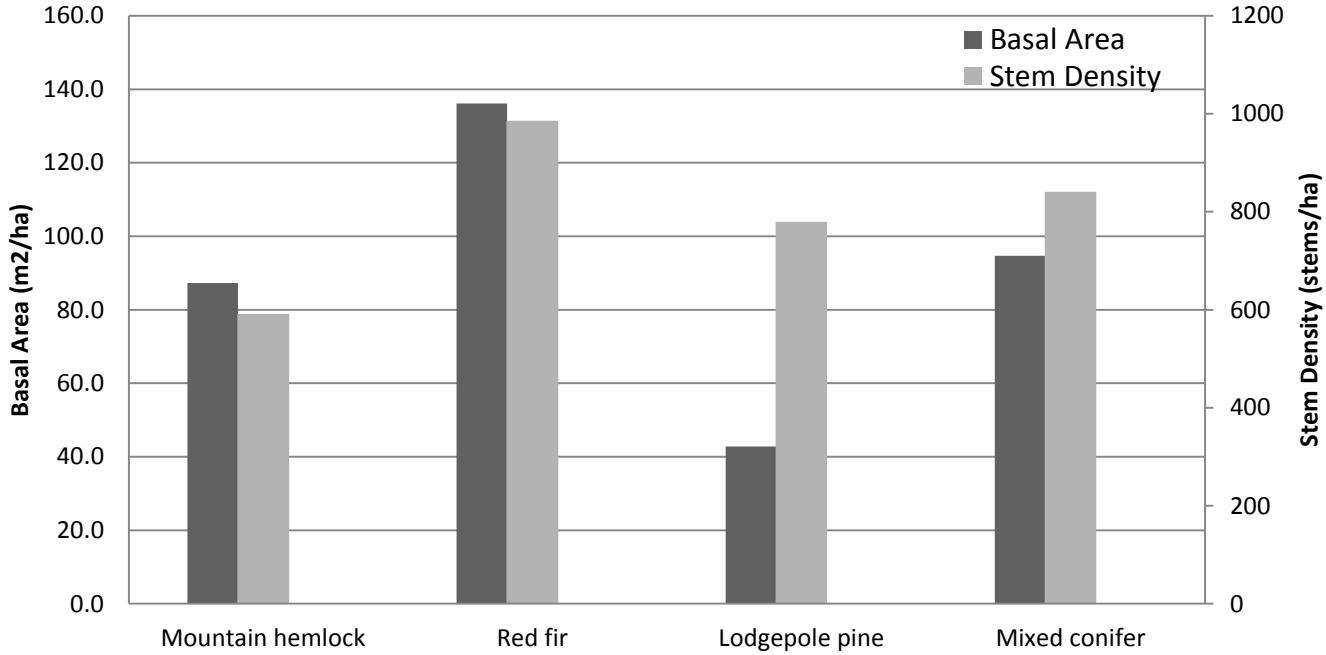


Figure 4. Total basal area by canopy class for red fir, mountain hemlock, lodgepole pine and mixed conifer forest, Crater Lake National Park, OR, USA

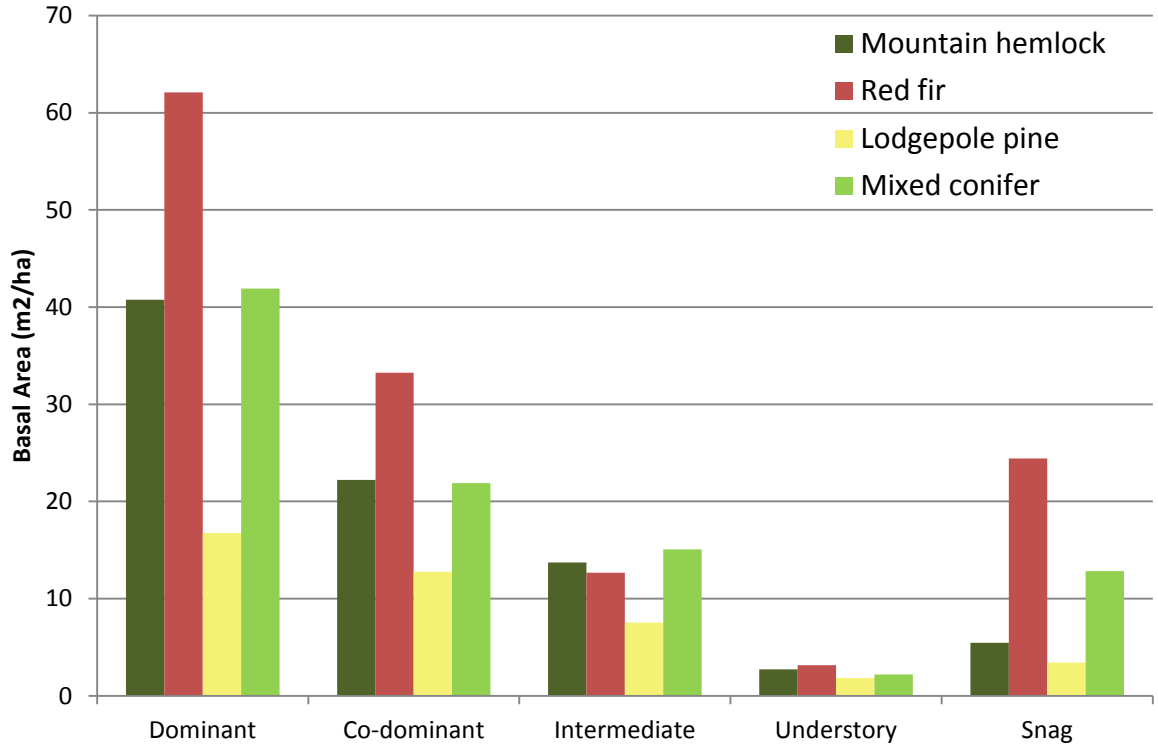


Figure 5. Distribution of stems amongst species in mixed conifer forest plots, Crater Lake National Park, OR, USA

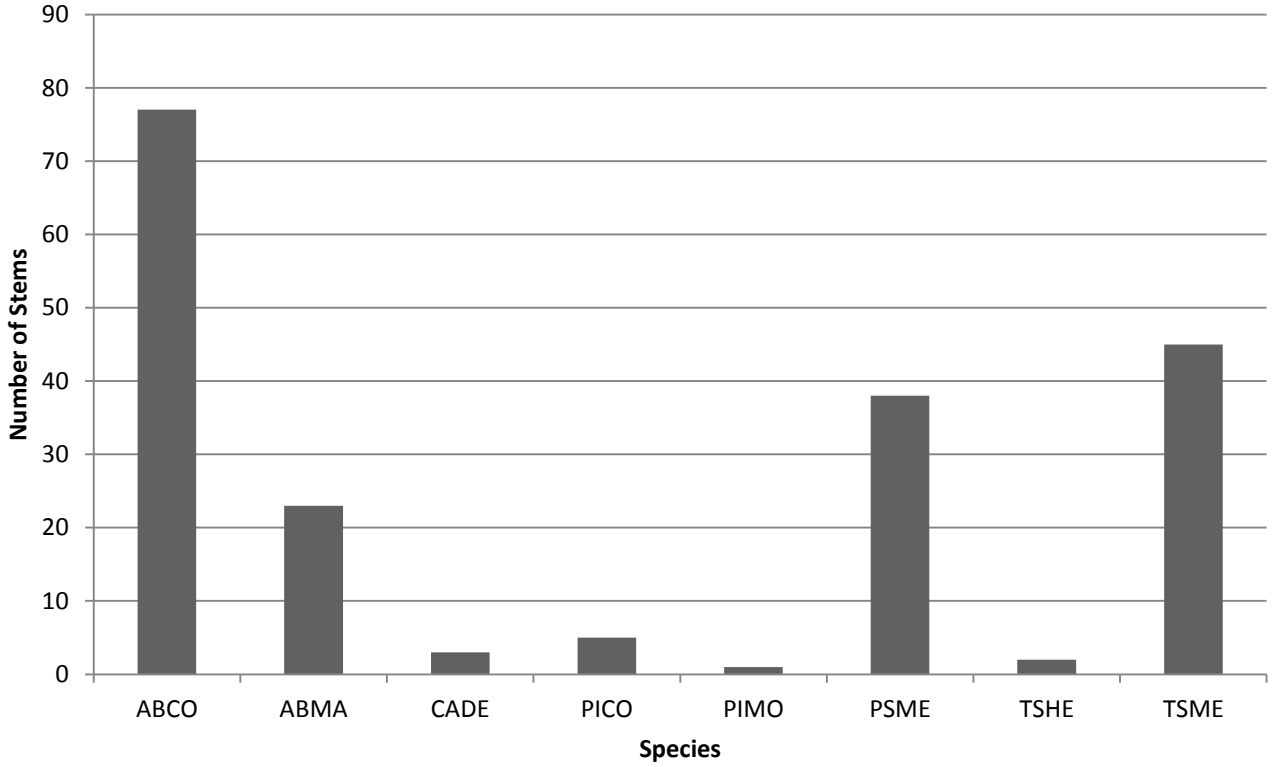


Figure 6 shows the relationship between size and age for the three major species in the study area. Red fir and mountain hemlock both had much stronger size-age relationships than lodgepole pine.

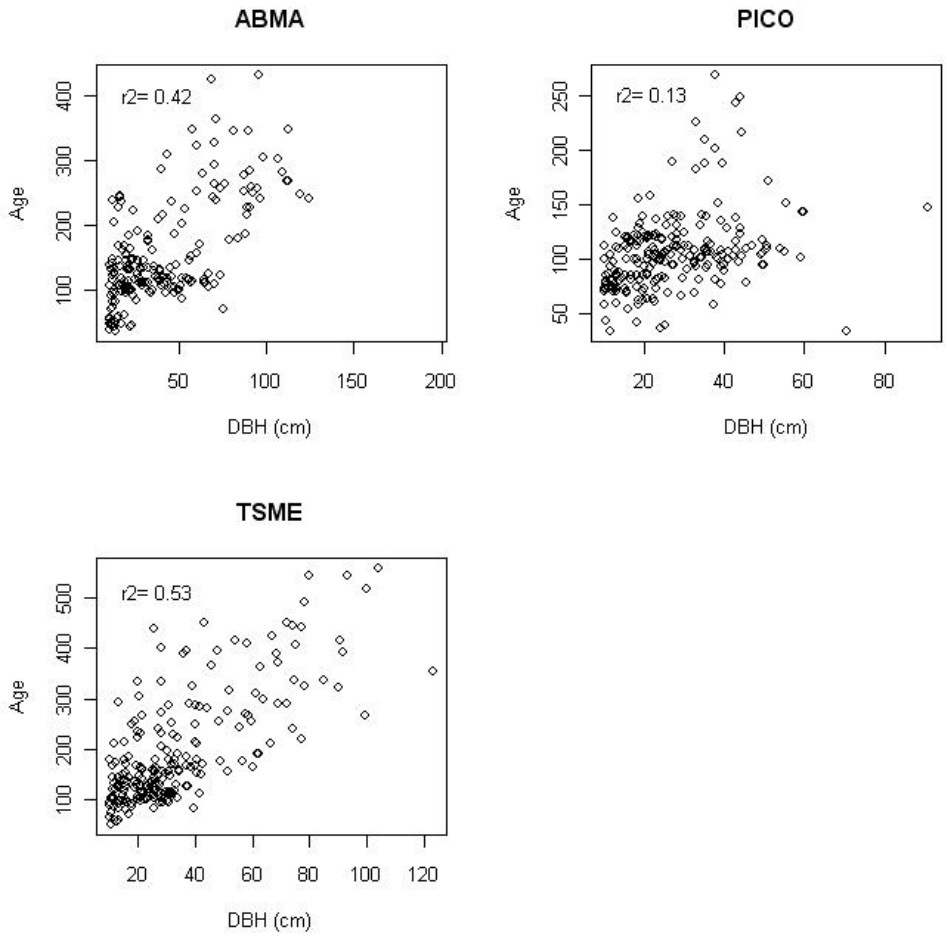


Figure 6. Diameter versus age for red fir, mountain hemlock and lodgepole pine, Crater Lake National Park, OR, USA

Figure 7 shows the establishment date by species across all plots as well as reconstructed Palmer Drought Severity Index (PDSI) (Cook et al. 2004). Mountain hemlock exhibited the widest range of establishment dates with a substantial proportion of individuals establishing prior to 1800. Lodgepole pine and the mixed conifer forest dominants exhibited the opposite pattern with very few individuals with establishment dates prior to 1800. The majority of lodgepole pine and mixed conifer species established in the decades around 1900. Red fir establishment dates exhibited a pattern intermediate between mountain hemlock and lodgepole pine with a sharp peak of establishment around 1900 but with substantial establishment occurring prior to 1800. Table 4 shows the number of individuals cored and dated by species as well as the proportion of each species established before 1800 and between 1880 and 1920. Of the entire sample, 45% of trees established during the forty year period centered around 1900. 54% and 79% of the lodgepole pine and mixed conifer dominants, respectively, were established during this same time period.

Table 4. The number of cores and individuals established in various time periods by species, Crater Lake National Park, OR, USA.

	All Trees	TSME	ABMA	PICO	Other
# Cored	1025	328	280	281	136
# Dated	787	242	209	231	105
% Established <1800	18.7	36.0	24.4	2.2	3.8
% Established 1880-1920	45.2	26.9	40.2	53.7	79.0

Figure 7. Age class distribution of red fir, mountain hemlock, lodgepole pine and other species (primarily Douglas-fir, white fir, western white pine and western hemlock) across all plots, as well as the Palmer Drought Severity Index (PDSI),Crater Lake National Park, OR, USA. Establishment dates are grouped into ten year bins.

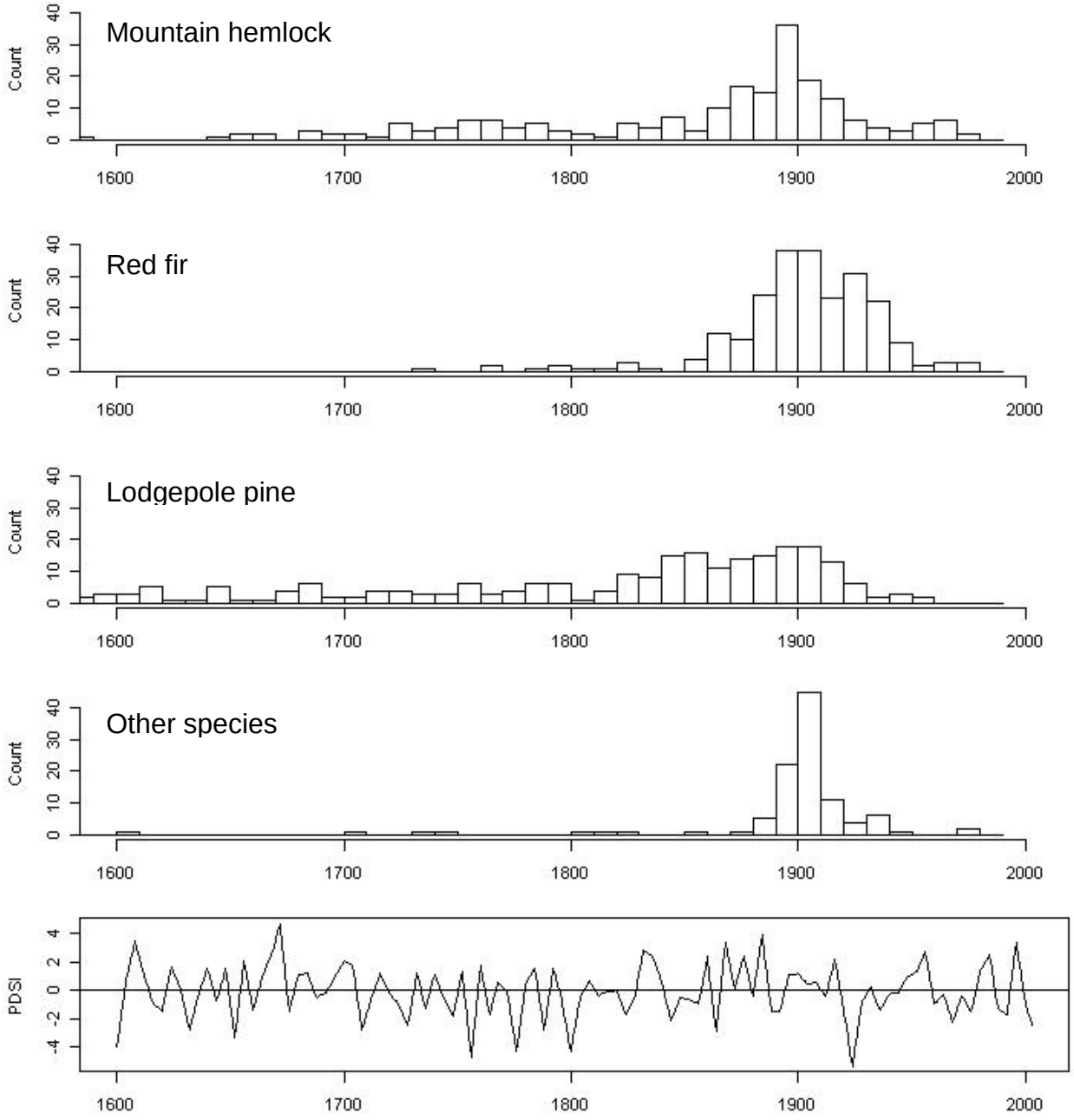


Figure 8a shows how different the establishment pattern for a given species, mountain hemlock, is between forest types. In the case of mountain hemlock, establishment is almost continuous in mountain hemlock dominated forests. In red fir-dominated forest, however, establishment of mountain hemlock individuals dropped off prior to 1700. Mountain hemlock individuals growing in lodgepole pine and mixed conifer forest show a distinct pattern of establishment peaking around 1900 and being rare or non-existent prior to that. Red fir exhibits a similar pattern of establishment across forest types as mountain hemlock (see Figure 8b). However, in both red fir and mountain hemlock forests, red fir shows a stronger peak in establishment around 1900 than mountain hemlock. Similarly to mountain hemlock, in lodgepole and mixed conifer forests, red fir shows little to no establishment prior to 1900. Figure 8c shows that the vast majority of lodgepole pine encountered in the study was in lodgepole pine forest and was established around 1900. There were few lodgepole pine in red fir or mountain hemlock forest and those that were sampled tended to be older than the lodgepole pine sampled in lodgepole pine forest. Figure 9 shows the establishment dates for all species stratified by elevation. Elevation was broken into low, moderate and high classes where low elevation included those plots in the lower third of elevations present in the study area (<1684m), moderate elevation included all plots between the 33th and 66th percentile (≥ 1684m; <1818m) and high elevation included all plots in the upper third of elevations (>1818m). Figure 10 illustrates the spatial distribution of the 1880-1920 cohort across the landscape overlaid with the Leiberg fire polygons from the same period (Leiberg 1900). Symbol colors correspond to forest type and symbol size corresponds to the percent of trees in that plot that established during the period from 1880 to 1920.

Figure 8a. Mountain hemlock establishment dates in different forest types, Crater Lake National Park, OR, USA.

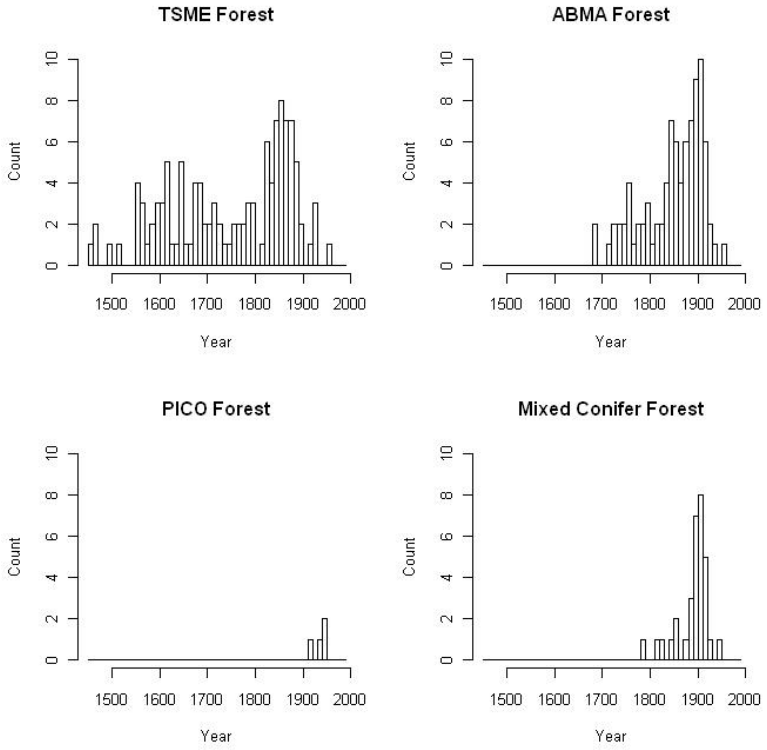


Figure 8b. Red fir establishment dates in different forest types, Crater Lake National Park, OR, USA.

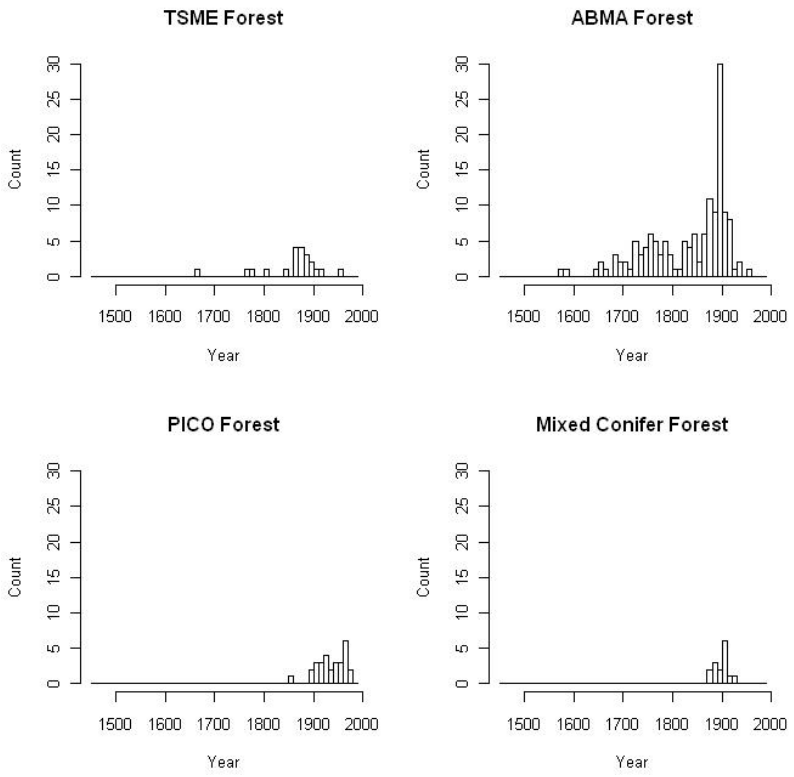


Figure 8c. Lodgepole pine establishment dates in different forest types, Crater Lake National Park, OR, USA.

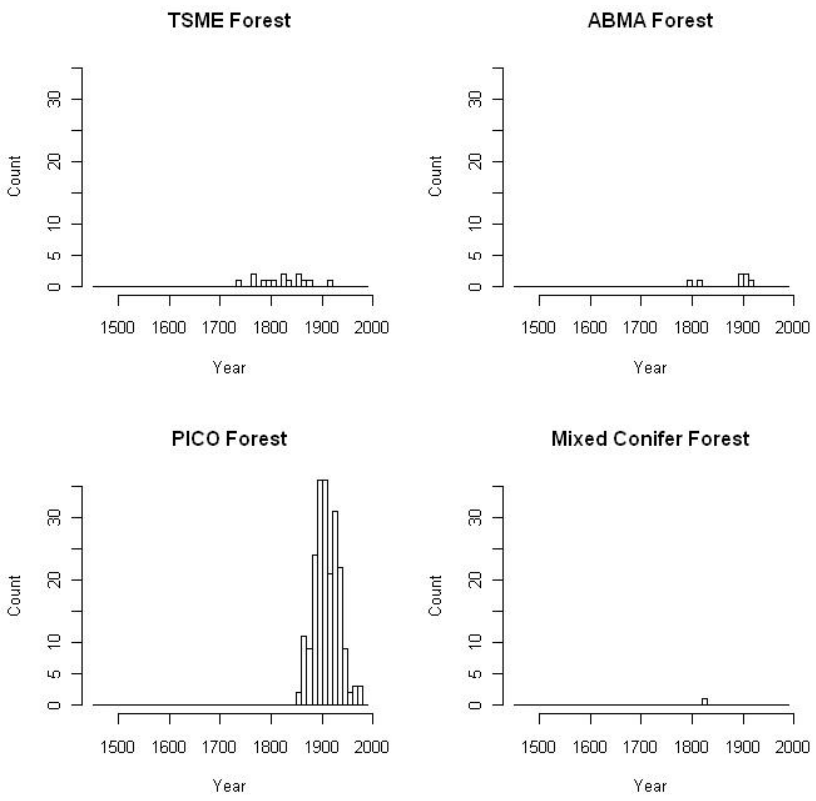
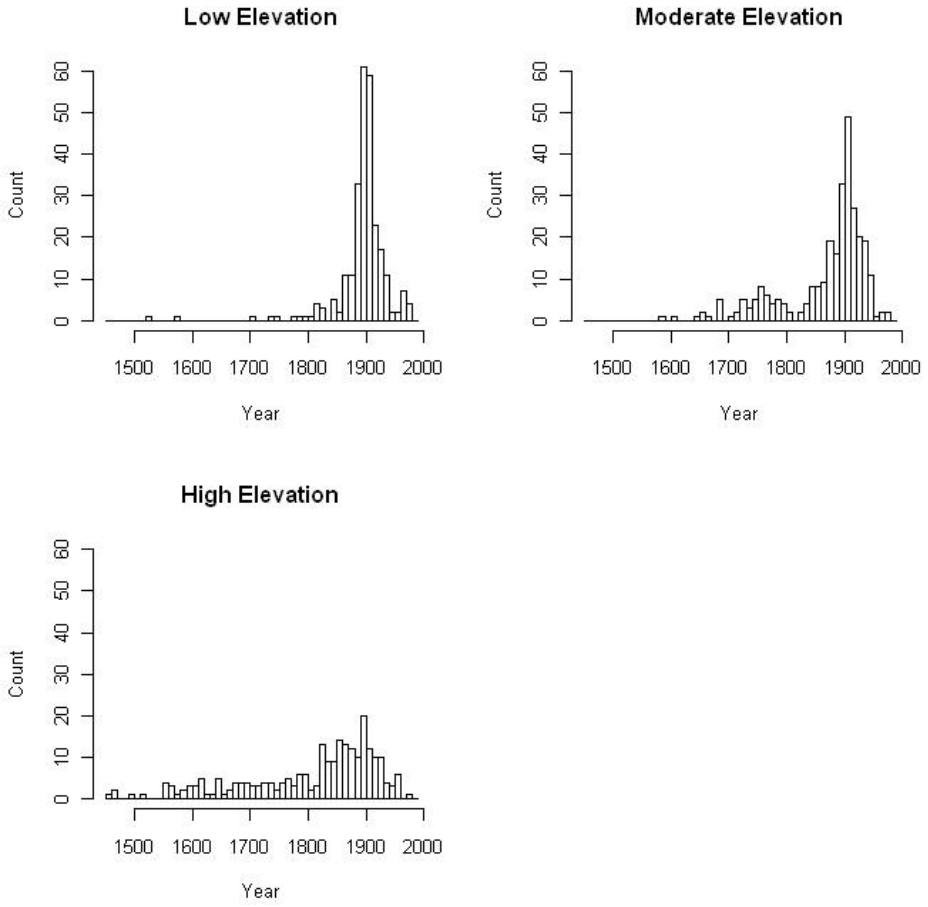


Figure 9. Establishment dates by elevation, Crater Lake National Park, OR, USA (Low includes plots less than 1684m, moderate includes plots between 1684m and 1818m and high includes plots above 1818m).



We compared the age distribution between species using Kolmogorov-Smirnov two-sample tests with Bonferroni corrections for multiple comparisons. Based on this analysis, which excluded the mixed conifer group, age structures were significantly different between lodgepole pine, mountain hemlock and red fir lumped across all forest types (ABMA-TSME p=.0015; ABMA-PICO p<<0.0; TSME-PICO p<<0.0).

Fire History

Cross-sections were sampled from a total of 35 scarred trees, primarily from mixed conifer forest areas. Of these, we were able to cross-date scars on 16 samples. A total of 32 scars were dated and the median point fire return interval was 37.5 years. (see Table 5). All of scars that were sampled and successfully dated were collected at lower to middle elevations in red fir or mixed conifer forests. Figure 11 shows the fire history for sampled scars.

There were ten instances where fire scars were collected and dated near (<500m) a stand demography plot. In most of these cases, scar dates did not correspond with a peak in establishment. However, in four plots, there were such peaks (Figure 12).

Figure 10. Plot locations and Leiberg fire polygons, Crater Lake National Park, OR, USA. Symbol colors correspond with the forest type of each plot and symbol size corresponds with the percent of trees in each plot established between 1880 and 1920. Leiberg fire polygons were mapped as recently burned in 1900.

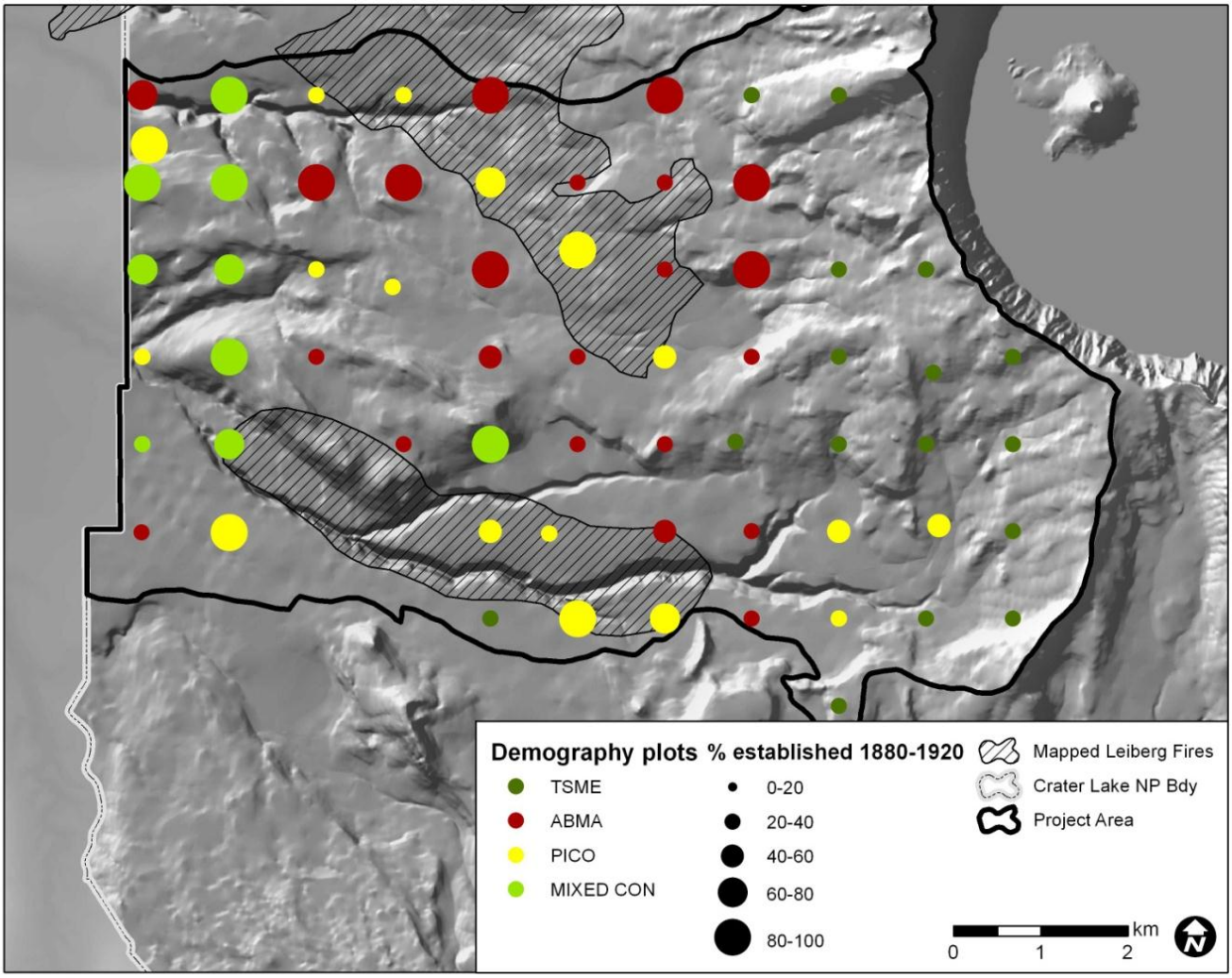


Table 5. Fire history summary statistics, Crater Lake National Park, OR, USA

Number of samples	16
Number of scars	32
Number of intervals	16
Median point interval (range)	37.5 (12-82)*

** Most samples are from mixed conifer forest; interval is representative of fire in this forest type only.*

Figure 11. Fire history, scars sorted from high (top) to low (bottom) elevation, Crater Lake National Park, OR, USA. Composite filter shows years with at least two scarred trees.

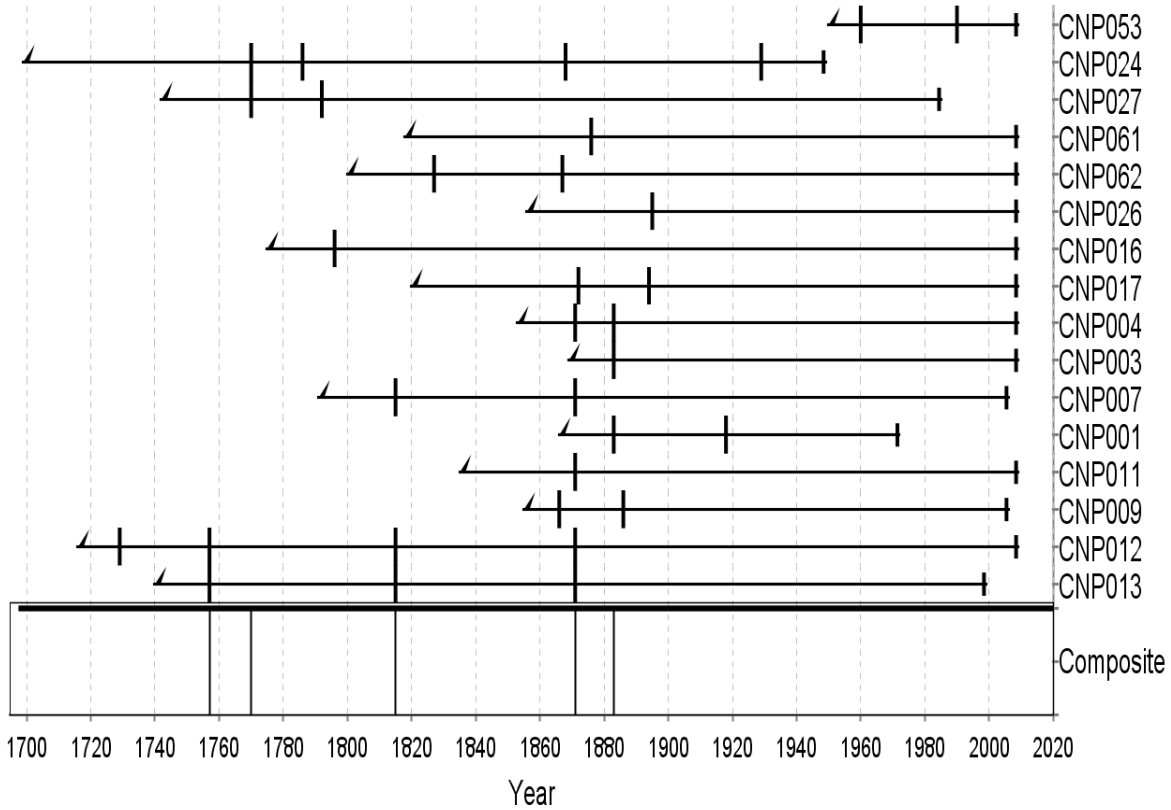
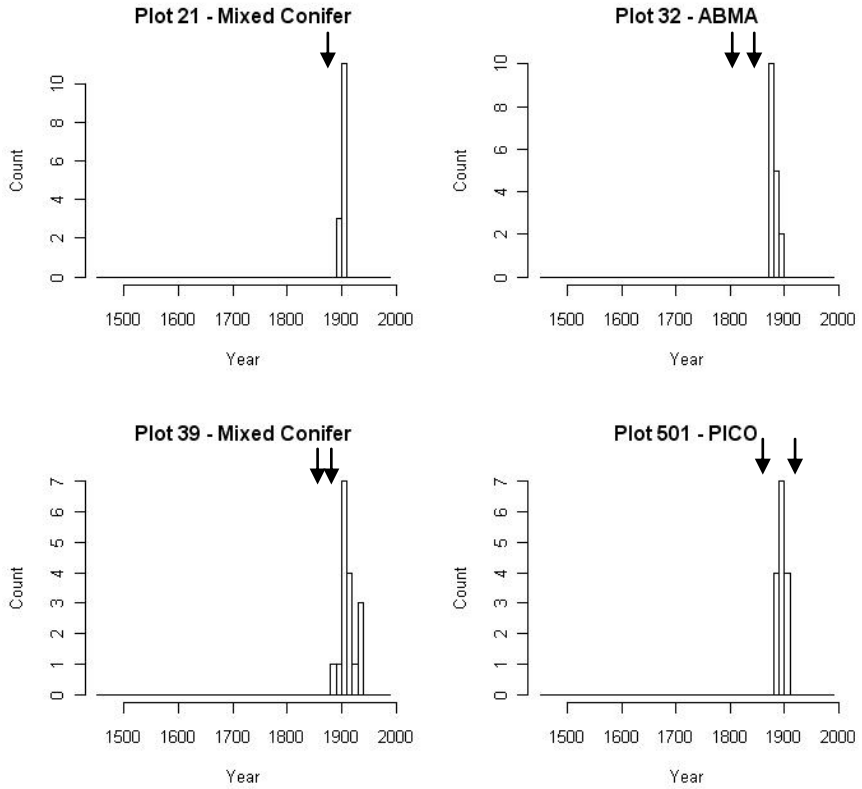


Figure 12. Plots where peaks in establishment correlated with fire dates. Fire dates are indicated by arrows.



Discussion & Conclusions

Stand structures observed in this study are typical for these forest types. Among the forest types considered, red fir forests stand out as having substantially higher basal area. This may be because red fir are long lived and become quite large and also grow at relatively high stem densities. Mountain hemlock individuals are also often large and long lived, but these higher elevation forests tend to be more open and had substantially lower stem densities than the other forest types studied.

Age-to-size relationships were much stronger for red fir and mountain hemlock than they were for lodgepole pine. This likely reflects the reproductive strategy of lodgepole pine which regenerates in largely mono-dominant stands. These stands tend to be close to even-aged with size differences likely determined more by microsite and genetic differences than by age.

There is a marked difference in the age structure between major species across the study area. Across the study area, mountain hemlock has the flattest age structure distribution. Individuals that established from 1600 through 1800 have a relatively even representation across plots with more individuals present that established between 1800 and the present. The mixed conifer species represent the opposite end of the spectrum with almost all individuals present with an establishment date close to 1900. Lodgepole and red fir forests fill in the continuum between these extremes. Reconstructed PDSI does not appear to explain patterns of establishment in the study area.

In addition to differences in age structures between species, the demographics of each species vary depending on the forest type where it is found. Mountain hemlock, for example, has fairly continuous establishment in mountain hemlock forests yet exhibits a peak of more recent establishment in other forest types. A similar, somewhat less pronounced pattern is present in red fir forests. Both lodgepole pine and mixed conifer forest species have a strong peak of establishment around 1900 regardless of forest type. Lodgepole pine with older establishment dates were found predominately in stands with a significant component of red fir and mountain hemlock, rather than in mono-specific stands.

When the data are stratified by elevation, the same pattern emerges, with more continuous establishment in older age classes at high elevations and a stronger peak of recent establishment at moderate and low elevation. One possible explanation for the pattern of more continuous establishment over the last several centuries in high elevation plots is that less disturbance at high elevations allows older trees to survive to the present.

The peak in establishment around 1900 observed in this study has been observed in similar forest types in other locations (Taylor 1995, Bekker and Taylor 2010). This may be the result of a warm mesic period in the region around this time (Taylor 1995). However, if climate is a factor in this peak in establishment, it is not captured in PDSI. Land use and fire history may also be factors; forest survey maps produced for this region in 1900 show approximately 25% of the study area as recently burned (Leiberg 1900). This peak in forest establishment appears to be spread fairly evenly across the landscape. Other than the absence of the establishment peak at the highest elevations, this turn of the century cohort does not appear to be associated exclusively

with fires mapped around the same period or to be otherwise spatially aggregated.

Fire scar samples were collected only from middle and low elevation forests either because fire in high elevation forests is rare or because fire scars in high elevation forests rarely form, heal over or tend to rot. Within these mid to low elevation primarily mixed conifer forests, the median fire return interval was 37.5 years, which is comparable to fire return intervals observed elsewhere in Crater Lake and in similar forest types in other areas of the southern Cascades and Sierra Nevada (e.g. Chappell 1991, Taylor and Halpern 1991, Bekker and Taylor 2001). Fire years were generally not consistent across the study area. At the scale of 0.5km (50 ha), primarily in the southwest corner of the study area, we did sample multiple trees that had recorded the same fire years. There was an indication in stand demography, fire scar data, and forest survey maps of a relatively large area burned within the several decades around 1900.

Our data indicate that each forest type in the study has somewhat different fire ecology. At one end of the spectrum, mountain hemlock forests tend to be higher elevation and later successional. Contrary to our hypothesis at the outset of this study, the ongoing establishment of mountain hemlock observed in our data over the last four centuries suggests that high and even moderate severity fires are rare in this forest type. Because mountain hemlock forests are covered in snow for so much of the year, there is a narrow window when wildfires can occur. When they do occur, they likely burn as low severity surface fires with small pockets of higher severity such as observed in the Bybee Fire.

Red fir forests exhibit a dual strategy of both post-fire succession and shade-tolerant establishment in areas that have not burned recently (Taylor and Halpern 1991, Scholl and Taylor 2006). This is apparent in the demography data which shows both continuous establishment for the last several centuries and peaks of establishment associated with fire events. The fire regime of red fir forests is probably the most mixed in severity of the forest types considered in this study.

Lodgepole pine stands are characterized by even-aged establishment following high severity fire. Although lodgepole pine in the southern Cascade range is not serotinous, it establishes in high severity post-fire gaps via seed from surviving trees and stand density is related to the proximity of these seed trees (Zeigler 1978, Pierce and Taylor 2011). Lodgepole pine in the monospecific stands sampled in this study tended to have establishment dates in the last 100 to 150 years. Other studies have hypothesized that lodgepole pine follows two successional pathways following fire, where it is self-replacing on flat, cold air drainages with poor soils and succeeds to mountain hemlock and red fir forests on better sites (Zeigler 1978, Agee 1993). However, all of our plots dominated by lodgepole pine, including those on flat, poor sites, had an understory of mountain hemlock and red fir and it is likely that they would succeed to a red fir-mountain hemlock forest type in the absence of disturbance over several centuries.

The mixed conifer forests sampled have few older trees with most individuals established since 1900. This suggests that these forests may have burned with high severity around the turn of the twentieth century. This may reflect land use history, with increased fire associated with settlement and land use changes in southern Oregon during that period, particularly since the mixed conifer forests in the study area are near park boundaries and may have been more easily

impacted by human activities in surrounding areas. Typically, mixed conifer forest fire regimes in this region are high frequency and low to moderate severity, so high severity fire may be related to human influences (Agee 1993). Since the period around 1900, fires have been suppressed at Crater Lake. It is likely that large number of recruits since this time period also reflects fire suppression.

Overall, our results are consistent with studies of the fire ecology of these forest types in surrounding areas. Our fire scar data, which is primarily for lower elevation mixed conifer forests, supports the conclusion that this forest type has a relatively short fire return interval in relation to the period of fire suppression and may be in need of the most active management to restore fire as a natural process. The presence of mono-specific, even-aged stands of lodgepole pine, which are likely associated with past fire events, supports the conclusion that these forests are adapted to high severity, relatively low frequency fires. Our data suggest that red fir forests have the most mixed fire regime in the study area. Contrary to our hypothesis, our data did not support the idea that mountain hemlock forests in the study area had fire return intervals similar to red fir forests. Rather, continuous establishment in mountain hemlock forests over several centuries suggests that moderate to high severity fire is relatively unimportant or very infrequent in these forests.

References

Agee, J. 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, DC.

Applequist, M. B. 1958. A Simple Pith Locator for Use With Off-Center Increment Cores. Journal of Forestry **56**:141.

Bekker, M. F. and A. H. Taylor. 2001. Gradient analysis of fire regimes in montane forests of the southern Cascade range, Thousand Lakes Wilderness, California, USA. Plant Ecology **155**:15-28.

Bekker, M. F. and A. H. Taylor. 2010. Fire disturbance, forest structure, and stand dynamics in montane forests of the southern Cascades, Thousand Lakes Wilderness, California, USA. Ecoscience **17**:59-72.

Chappell, C. B. 1991. Fire ecology and seedling establishment in Shasta red fir (*Abies magnifica* var. *shastensis*) forests of Crater Lake National Park, Oregon. University of Washington, Seattle, Washington.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle. 2004. Long-Term Aridity Changes in the Western United States. Science **306**:1015-1018.

Eidenshink, J., B. Schwind, K. Brewer, Z. Zhu, B. Quayle, and S. Howard. 2007. A project for monitoring trends in burn severity. Fire Ecology **3**:3-21.

Leiberg, J. 1900. Cascade Range Forest Reserve, Oregon US Geological Survey, Washington, DC.

McNeil, R. 1975. Vegetation and Fire History of a Ponderosa Pine-White Fir Forest in Crater Lake National Park. Oregon State University, Corvallis, OR.

National Park Service. 2007. Crater Lake National Park Wildland Fire Management Plan. Crater Lake, Oregon.

NOAA. 2011. International Tree Ring Data Bank http://www.ncdc.noaa.gov/paleo/treering.html.

Perry, D., P. F. Hessburg, C. N. Skinner, T. A. Spies, S. L. Stephens, A. H. Taylor, J. F. Franklin, B. McComb, and G. Riegel. 2011. The ecology of mixed severity fire regimes in Washingon, Oregon and Northern California. Forest Ecology and Management **262**:703-717.

Pierce, A. and A. H. Taylor. 2011. Fire severity and seed source influence lodgepole pine (Pinus contorta var. murrayana) regeneration in the southern cascades, Lassen volcanic National Park, California. Landscape Ecology **26**:225-237.

Pitcher, D. C. 1987. Fire history and age structure in red fir forests of Sequoia National Park, California. Canadian Journal of Forest Research **17**:582-587.

R Development Core Team. 2010. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Scholl, A. and A. H. Taylor. 2006. Regeneration patterns in old-growth red fir–western white pine forests in the northern Sierra Nevada, Lake Tahoe, USA. Forest Ecology and Management **235**.

Stokes, M. A. and T. L. Smiley. 1968. An introduction to tree-ring dating. The University of Arizona Press, Tucson, AZ.

Taylor, A. H. 1993. Fire history and structure of red fir (*Abies magnifica*) forests, Swain Mountain Experimental Forest, Cascades Range, northeastern California. Canadian Journal of Forest Research **23**:1672-1678.

Taylor, A. H. 1995. Forest Expansion and C limate Change in the Mountain Hemlock (Tsuga mertensiana) Zone Lassen Volcanic National Park, California, USA. Arctic and Alpine Research **27**:207-216.

Taylor, A. H. 2000. Fire regimes and forest changes in mid and upper montane forests of the southern Cascades, Lassen Volcanic National Park, California, USA. Journal of Biogeography **27**:87-104.

Taylor, A. H. and C. B. Halpern. 1991. The structure and dynamics of *Abies magnifica* forests in the southern Cascades Range, USA. Journal of Vegetation Science **2**:189-200.

Taylor, A. H. and M. N. Solem. 2001. Fire regimes and stand dynamics in an upper montane forest landscape in the southern Cascades, Caribou Wilderness, California. Journal of the Torrey Botanical Society **128**:350-361.

USDA Forest Service. 2011. Fire History Analysis and Exploration System http://frames.nbii.gov/portal/server.pt/community/fhaes/355/about_fhaes/1607.

Van Horne, M. L. and P. Z. Fule. 2006. Comparing methods of reconstructing fire history using fire scars in a southwestern United States ponderosa pine forest. Canadian Journal of Forest Research **36**:855-867.

Western Regional Climate Center. 2008. Climate Summary for Crater Lake, 1931 - 2005.

Williams, H. 1942. The geology of Crater Lake National Park, Oregon. Carnegie Institute, Washington, DC.

Zeigler, R. 1978. The vegetation dynamics of Pinus contorta forest, Crater Lake National Park. Oregon State University, Corvallis, OR.