Research Article

Fire History and Forest Structure along an Elevational Gradient in the Southern Cascade Range, Oregon, USA

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ABSTRACT

We examined stand structure, demography, and fire history using tree cores and fire scar data across an approximately 7000-hectare study area over an elevational gradient in the southern Cascade Range, Oregon, USA. Our plots were located in mountain hemlock (*Tsuga mertensiana* [Bong.] Carr), red fir (*Abies magnifica* A. Murr.), lodgepole pine (*Pinus contorta* Loudon), and mixed conifer forest types. Stand demography from high elevation mountain hemlock forests showed continuous regeneration since the early 1600s and no fire scars present. Red fir forests showed both continuous and episodic regeneration over the past several centuries, providing evidence for a mixed-severity fire regime. Lodgepole pine stands were even-aged with no fire scar evidence and likely established following high severity fire events. Mixed conifer forests were uneven-aged. The majority of trees that we sampled established between 1880 and 1920. Interpretation of our data is limited by a

RESUMEN

Examinamos la estructura, demografía, e historia del fuego usando datos provenientes del barrenado y cicatrices de fuego en árboles en un área de estudios de aproximadamente 7000 ha sobre un gradiente de elevación en la cordillera Cascade en Oregon, EEUU. Nuestras parcelas estaban ubicadas en bosques de tsuga (*Tsuga mertensiana* [Bong.], Carr), abeto rojo (*Abies magnifica* A. Murr.), pino contorta (*Pinus contorta* Loudon), y otros tipos de bosques de coníferas mixtos. La demografía de los rodales de los bosques altos de tsuga mostró regeneración continua desde principios del año 1600 y no presentaron cicatrices de fuego. Los bosques de abeto rojo mostraron tanto regeneración continua como episódica en las últimas centurias, lo que proveyó de evidencias de un régimen de fuegos de severidad mixta. Los rodales de pino contorta eran todos coetáneos, sin evidencias de cicatrices de fuego y probablemente establecidos luego de eventos de fuego de alta severidad. Los bosques de coníferas mixtos fueron todos disetáneos. La mayoría de los árboles que muestreamos se habían establecido entre 1880 y 1920. La interpretación de nuestros datos está limitada por un bajo número de cicatrices de fuego y un tasmall number of fire scars and relatively small sample size. However, our study highlights the spatial complexity of forest types and concomitant fire regimes on this landscape.

maño de muestras relativamente pequeño. Sin embargo, nuestro estudio refleja la complejidad espacial de los tipos forestales y concomitantemente de los regímenes de fuego en este paisaje.

Keywords: Crater Lake National Park, fire regimes, landscape ecology, lodgepole pine (*Pinus contorta*), mountain hemlock (*Tsuga mertensiana*), red fir (*Abies magnifica*), subalpine forest

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INTRODUCTION

The use of dendrochronology to characterize the fire history in coniferous forests in the Pacific Northwest has advanced our understanding of the importance of fire (Agee 1993, Falk *et al.* 2011, Perry *et al*. 2011). This has been particularly true in low elevation pine-dominated and mixed conifer forests in which evidence of past fires is recorded in fire scarred trees (Farris *et al*. 2010, Falk *et al.* 2011, Perry *et al.* 2011). There have been fewer published fire histories from upper elevation coniferous forests (dominated by mountain hemlock, *Tsuga mertensiana* [Bong.] Carr; red fir, *Abies magnifica* A. Murr.; and lodgepole pine, *Pinus contorta* Loudon), in which fire is relatively infrequent, with fire-free intervals ranging from several decades to centuries (Agee 1993, Bekker and Taylor 2010). In these forests, stand age structures are important in determining historical patterns of fire occurrence (e.g., Taylor and Halpern 1991, Taylor 1993, Bekker and Taylor 2010).

Stand age and establishment age of tree cohorts identifies patterns of past natural disturbances, including windstorms (Taylor and Halpern 1991) and fire severity (Bekker and Taylor 2010). However, many trees have been harvested over the nineteenth and twentieth centuries and many fire scars and tree age records have been lost (Hessburg and Agee 2003; but see Taylor (1993) for use of tree stumps), highlighting the importance of old-growth forests in providing insight into forest dynamics. Further, the effects of fire exclusion have not been well characterized in many upper elevation conifer forests; a better understanding of these effects could help identify future strategies in fire management. Future climate change may further alter fire and forest dynamics in this region and has important implications for land management given the temporal extent of fire in these systems (Taylor 1995).

The westside forests of Crater Lake National Park (CLNP) in the southern Cascade Range, Oregon, USA, are unique in that they represent one of the few places where an elevational gradient from low elevation mixed conifer to high elevation mountain hemlock forests remains intact and has never been logged. At the highest elevations, from 1800 m to 2300 m, forests are relatively dense, pure mountain hemlock with a sparse understory. Mountain hemlock is a long-lived, slow growing species that is adapted to long winters and short growing seasons (Taylor 1995, Bekker and Taylor 2010). As elevation decreases, forests transition to a mix of red fir and mountain hemlock. Red fir exhibits a dual strategy of both extensive post-fire regeneration and shade-tolerant establishment in areas that have not burned recently (Taylor and Halpern 1991, Taylor 1993, Scholl and Taylor 2006). The lowest elevations, ranging from 1500 m to

1700 m, are dominated by mixed conifer forests composed of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), white fir (*Abies concolor* [Gord. Glend.] Lindl.), incense-cedar (*Calocedrus decurrens* [Torr.] Florin), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), ponderosa pine (*Pinus ponderosa* Laws), and western white pine (*Pinus monticola* Dougl.). Lodgepole pine forests are found across the elevational gradient within the study area, primarily on flat cold-air drainages with poor soils (Zeigler 1978). 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 post-fire stand density is related to the proximity of these seed trees (Zeigler 1978, Pierce and Taylor 2011, Heyerdahl *et al.* 2014).

While there is fire history information for other forest types within CLNP and for similar forest types in other parts of the Cascades and Sierra Nevada ranges (Table 1), fire history along a gradient of forest types such as in this study is not well documented or understood. The CLNP 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 to 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, observed fire behavior and effects in recent managed fires in this region suggest that fires may be more mixed in severity (Agee 1993, Chappell and Agee 1996, McNeil and Zobel 1980, Perry *et al.* 2011, Heyerdahl *et al.* 2014; C. Farris, National Park Service, Klamath Falls, Oregon, USA, personal communication). 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 remotely sensed data obtained through the Monitoring Trends in Burn Severity program, was mixed and areas of both high and low severity occurred across all 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, Heyerdahl *et al.* 2014, Hessberg *et al.* 2016). In addition, the term "mixed severity" has not been well defined in the literature. Agee (1993), for example, defines mixed severity as those fire regimes in which 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 one to hundreds of hectares, and variation between fires in the proportion of high severity versus low severity patches due to small-scale variation in fuel conditions and shifting weather conditions (Perry *et al*. 2011).

Understanding fire regimes of mixed conifer, lodgepole pine, red fir, and mountain hemlock forests at CLNP is important for both management and ecological reasons. First, a clear understanding of fire history is important to guide management of wildfires and prescribed fires into the future. Second, documentation of fire regimes in this landscape is useful in understanding mixed-severity fire regimes in similar forest types. Specifically, our study addresses the following hypotheses: 1) The fire regime in red fir and mountain hemlock forests is mixed severity with episodic tree establishment and fire return intervals of 40 to 70 years; 2) The fire regime in lodgepole pine forests is low frequency and high severity with even-aged stands; and 3) The fire regime in mixed conifer forests is high frequency and low severity, with uneven-aged stands without peaks of establishment and fire intervals less than 40 years.

Table 1. Fire histories for forests in Crater Lake National Park, Oregon, USA, and similar forest types in Oregon (OR) and California (CA), USA. FRI = fire return interval. Ranges are shown in parentheses.

Forest type	Location	FRI (yr)	Analysis unit for FRI	Sample size	Citation
Red fir	Sequoia National Park, CA	78	plot (0.25 ha to 0.5 ha)	16	Pitcher 1987
Red fir	Crater Lake National Park, OR	39	plot (0.5 ha)	11	Chappell and Agee 1996
Red fir	Swain Mountain Experimental Forest, CA	40 to 42	plot (0.5 ha to 1 ha)		Taylor and Halpern 1991
Red fir	Swain Mountain Experimental Forest, CA	16 to 19	plot (3 ha)		Taylor 1993
Red fir-mountain hemlock	Thousand Lakes Wilderness, CA	20 (9 to 91)	point	6	Bekker and Taylor 2001
Red fir-mountain hemlock	Thousand Lakes Wilderness, CA	100	point		Bekker and Taylor 2010
Red fir-lodgepole pine	Mammoth Lakes, CA	25 (13 to 38)	plot (2 ha)	10	Stephens 2001
Red fir-western white pine	Lassen Volcanic National Park, CA	70 (26 to 109)	point	41	Taylor 2000
Red fir-western white pine	Caribou Wilderness, CA	66	plot (0.04 ha to 0.1 ha)		Taylor and Solem 2001
Red fir-western white pine	Lake Tahoe, CA	76 (25 to 175)	point		Scholl and Taylor 2006
Lodgepole pine	Caribou Wilderness, CA	67	plot (0.04 ha to 0.1 ha)		Taylor and Solem (2001)
Lodgepole pine	Thousand Lakes Wilderness, CA	47 (28 to 54)	point	6	Bekker and Taylor 2001
Lodgepole pine	Thousand Lakes Wilderness, CA	(50 to 76.5)	point		Bekker and Taylor 2010
Lodgepole pine	Deschutes National Forest, OR	(26 to 82)	plot (0.1 ha to 0.5 ha)	30	Heyerdahl *et al.* 2014
Ponderosa pine	Crater Lake National Park, OR	(9 to 42)	2 trees	48	McNeil and Zobel 1980
Ponderosa pine-white fir-mountain hemlock	Cherry Creek Research Natural Area, OR	(4 to 146)	plot (0.2 ha)	35	Foster 1998

METHODS

Study Area

Field work was conducted at CLNP, which 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 (Figure 1) on the west side of the Cascade crest, within two sub-watersheds of the Upper Rogue River watershed encompassing 7031 ha (Figure 2). This area covers an elevational gradient from 1500 m to 2300 m. The climate in the study area is characterized by long, snowy winters and short, dry summers. Mean annual precipitation is 168 cm, most of which falls in the form of snow. The mean maximum July temperature is 20 °C and the mean minimum January tem-

Figure 1. Typical stands within each forest type in the study area at Crater Lake National Park, Oregon, USA. (A) Mountain hemlock forest, (B) lodgepole pine forest, (C) red fir forest, and (D) mixed conifer forest.

perature 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). The 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. The CLNP practiced full fire suppression from the inception of the CLNP (1902) until management-ignited fires began in the 1980s.

Plot Selection and Sampling

To characterize stand structure, 64 stand demography plots were established within the study area using a 1 km grid with a random starting point (Figure 2). Plots were located using a GPS. Data collected at each plot included the following: aspect, slope, elevation, several measurements from the dominant canopy species, ocular estimates of canopy cover, and cover of dominant shrub and herbaceous species. Elevation assigned to each plot was divided into three categories: low, which included those plots in the lower third of elevations (<1684 m); moderate, which included plots between the thirty-third and sixty-sixth percentile (1684 m to 1818 m); and high, which included all plots in the upper third of elevations (>1818 m). Stand demography data were collected using variable radius circular plots (Speer 2009). At each plot, the 20 closest trees to plot center with a diameter at breast height (DBH) of 10 cm or greater were identified, and species, DBH, status (live or dead), and canopy class (dominant, co-dominant, intermediate, or understory) were recorded. Each tree was cored at a maximum of 15 cm above the ground and core height was recorded. Occasionally trees had to be cored higher than 15 cm due to obstacles at the base of the tree or to accommodate boring equipment. Distance of the farthest tree from the plot center was also recorded. No more than five trees with a DBH less than 20 cm were cored. If more than five trees less than 20 cm were present, the plot radius was expanded to include larger trees and trees less than 20 cm were measured (DBH) and recorded, but not cored. This ensured that older trees were adequately sampled, and also balanced our results such that recent recruits were less likely to be captured. Plots were rejected only if they were non-forested (<10 trees ha^{-1}).

Fire scars were sampled opportunistically throughout the study area from both living and dead trees. Intact fire scars were extremely

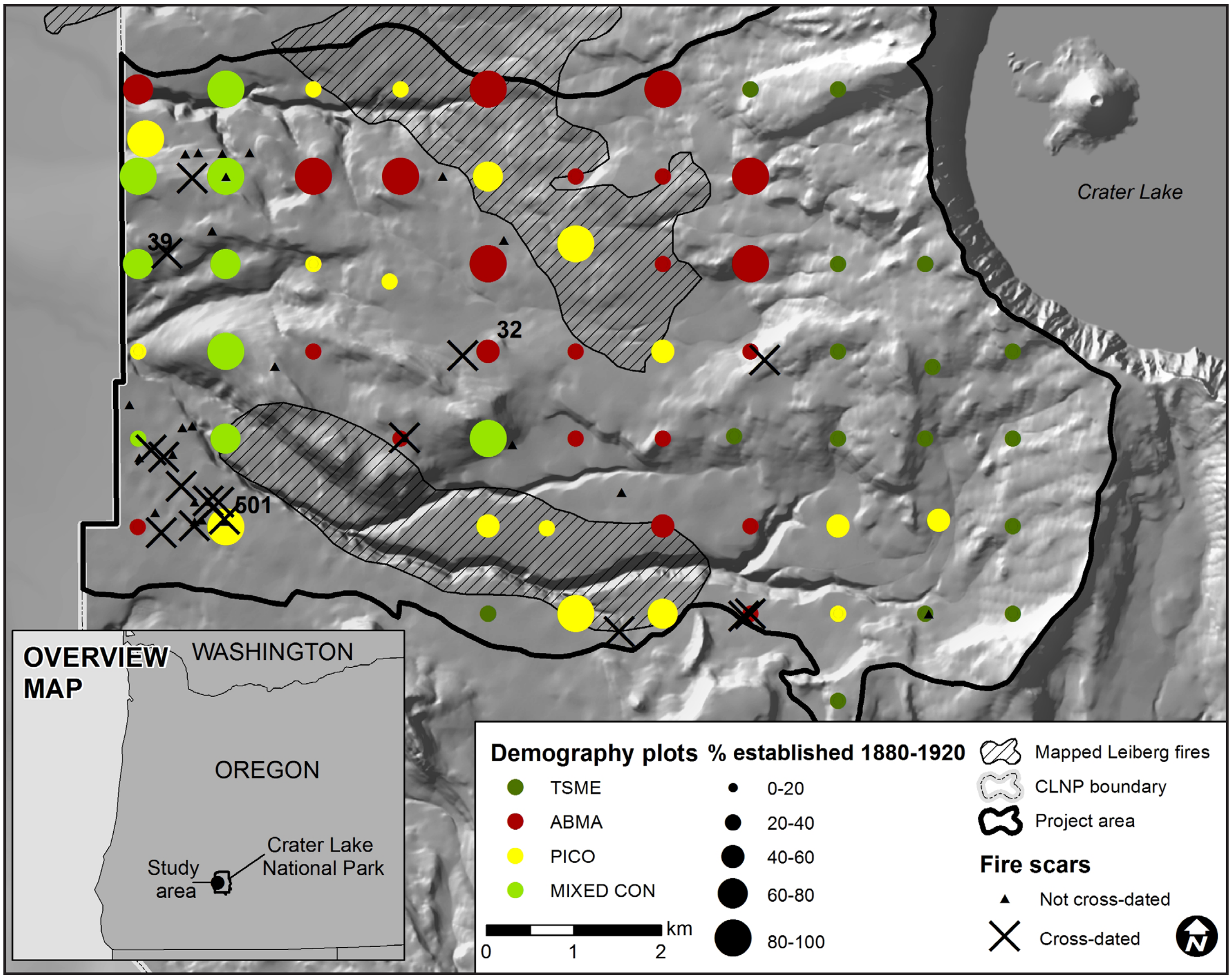

Figure 2. Location of study site in Crater Lake National Park, Oregon, USA. Plot locations are shown with colored dots that correspond with the forest type of each plot (TSME = mountain hemlock, ABMA = red fir, PICO = lodgepole pine, MIXED CON = mixed conifer), and dot size corresponds with the percent of trees in each plot that established between 1880 and 1920. Fires mapped around the turn of the twentieth century are also shown (Leiberg 1900).

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 preserve scars well or tend to heal over between fires (Pitcher 1987, Taylor 1993). Using a chain saw, partial cross-sections were sampled from a total of 35 trees with visible scars, primarily from the mixed conifer forest areas (low elevation). For each fire scar that was sampled, we recorded the location of the scar using a GPS as well as the species, status (live or dead), and DBH.

Tree cores and fire scars were sanded using progressively finer sandpaper, and cross-dated using standard methodology (Stokes and Smiley 1968) coupled with several published master chronologies from nearby sites (NOAA 2011, Table 2). For cores that did not intersect the pith and 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. Our analysis was based on 10-year bins of establishment dates, so we expected that this source of error would be relatively unimportant.

Table 2. Master chronologies used in cross-dating cores and fire scars (NOAA 2011) at Crater Lake National Park, Oregon, USA. Both master chronologies were contributed by Briffa, K., and F.H. Schweingruber.

Site	Location	Elevation (m)	Species	Time period	Cores (*n*)	Series intercorrelation	Mean sensitivity
Mt. Ashland	42° 4′ 12″ N, 122° 43′ 12″ W	1860	*Abies magnifica*	1739 to 1983	22	0.606	0.182
Crater Lake	42° 58′ 12″ N, 122° 10′ 12″ W	1752	*Tsuga mertensiana*	1564 to 1983	23	0.735	0.284

Data Analysis

Each plot was assigned a forest type—mountain hemlock, red fir, lodgepole pine, or mixed conifer—based on the species with the maximum basal area in that plot. For mixed conifer plots, the species with the maximum basal area was Douglas-fir, white fir, incense-cedar, western hemlock, or western white pine. Using our demography data, we summarized stand age structure by forest type and elevation, and then compared age distributions between species using Kolmogorov-Smirnov two-sample tests with Bonferroni corrections for multiple comparisons. Although it would have been preferable to analyze data at the plot level, it was necessary to analyze data summarized by forest type and elevation because of our limited sample size.

We used both land use history and reconstructed drought information to aid in interpreting age structure data. Specifically, for land use history, we used forest survey maps developed by the US Geologic Survey around the beginning of the twentieth century that included perimeters of recently burned areas (Leiberg 1900). We related reconstructed Palmer Drought Severity Index (PDSI; grid point 4)—an indicator of past climate and seasonal drought (Cook *et al.* 1999)—to tree establishment dates. Negative PDSI indicates drier than average conditions, and positive PDSI indicates wetter than average conditions (Palmer 1965). We averaged PDSI over 10-year periods to correspond to the tree establishment bin size (10 years) for a more accurate comparison. Summary statistics from fire scars were obtained using FHAES software (USDA Forest Service 2011). All fire scars were analyzed together and interpreted cautiously due to the small sample size. All statistical analyses used R statistical software version 2.11.1 (R Development Core Team 2010).

RESULTS

Stand Demography, Forest Composition, and Structure

We cored 1025 trees across the study area. Approximately 23% of cores were excluded because of rotten tree centers or because intact wood was too far from the pith to estimate an establishment date (Table 3). Of the entire sample, 45% of trees were established during the 40-year period centered around 1900. Separated by forest type, this was the dominant age cohort in lodgepole pine and mixed conifer stands in which more than half of the trees we cross-dated were established during that 40-year time period (1880 to 1920; Table 3; Figure 3). This cohort was also pronounced at lower elevations (Figures 2 and 4) and in areas mapped as recently burned around the beginning of the twentieth century (Figure 1; Leiberg 1900). Eleven of our 64 plots (17%) and 1312 ha (19%) of the total study area fell within the mapped Leiberg fire (Figure 2).

Tree establishment dates varied by forest type at CLNP (Figure 3). Mountain hemlock forests exhibited a pattern of continuous establishment since the early 1600s (Figure 3). Red fir forests showed continuous establishment since the mid- to late-1600s with a peak of in-

Table 3. Trees cored and individuals established by time periods and species, Crater Lake National Park, Oregon, USA. SE = one standard error.

	All trees	Mountain hemlock	Red fir	Lodgepole pine	Other
Trees cored (*n*)	1025	328	280	281	136
Average DBH (cm) (SE)	33.6 (0.7)	33.3 (1.2)	40.2 (1.7)	26.9 (0.7)	33.5 (0.7)
Number cross-dated	787	242	209	231	105
Established pre-1800 (%)	18.7	36	24.4	2.2	3.8
Established 1880 to 1920 (%)	45.2	26.9	40.2	53.7	79

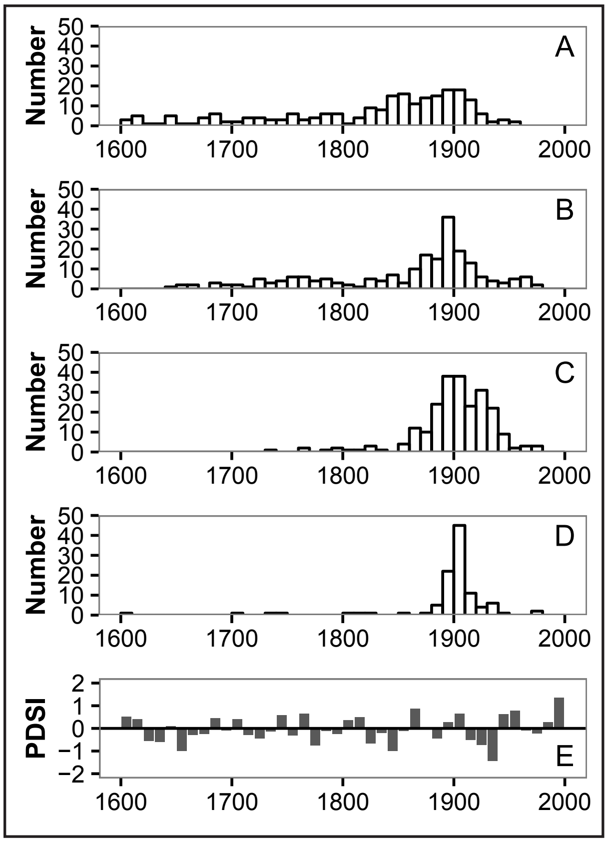

Figure 3. Age class distributions of mountain hemlock (A), red fir (B), lodgepole pine (C), and other species (D: primarily Douglas-fir, white fir, western white pine, and western hemlock) across all plots at Crater Lake National Park, Oregon, USA, as well as the closest Palmer Drought Severity Index (E; grid point 4). Establishment dates are grouped into 10-year bins, and PDSI was averaged over 10-year periods that match the establishment bins.

creased establishment around 1900. Lodgepole pine and mixed conifer forests both exhibited a distinct peak of establishment around 1900 with very little establishment prior to 1850. These patterns were characteristic for each forest type rather than each species. For example, mountain hemlock individuals found in lodgepole pine or mixed conifer forest types showed the same 1900 establishment peak characteristic of those forest types. Reconstructed PDSI does not explain peak patterns of establishment in the study area (Figure 3).

We compared the age distribution between species using Kolmogorov-Smirnov two-sample tests with Bonferroni corrections for multiple comparisons. Excluding the mixed conifer group (because it includes multiple species), age structures were significantly different between mountain hemlock and red fir ($P \leq 0.005$), red fir and lodgepole pine ($P \leq 0.005$), and mountain hemlock and lodgepole pine ($P \leq 0.005$). We also compared the age distribution between elevation groups using the same method. Age structures were significantly different between elevation zones (high to moderate elevation $P \leq 0.005$; high to low elevation $P \leq 0.005$; moderate to low elevation $P \leq 0.005$).

More than half of the plots had little or no shrub or herbaceous layer; this forest-litter-dominated understory was particularly prevalent in the red fir forest type. Only seven plots (11 %), which were distributed among all forest types, had a shrub-dominated understo-

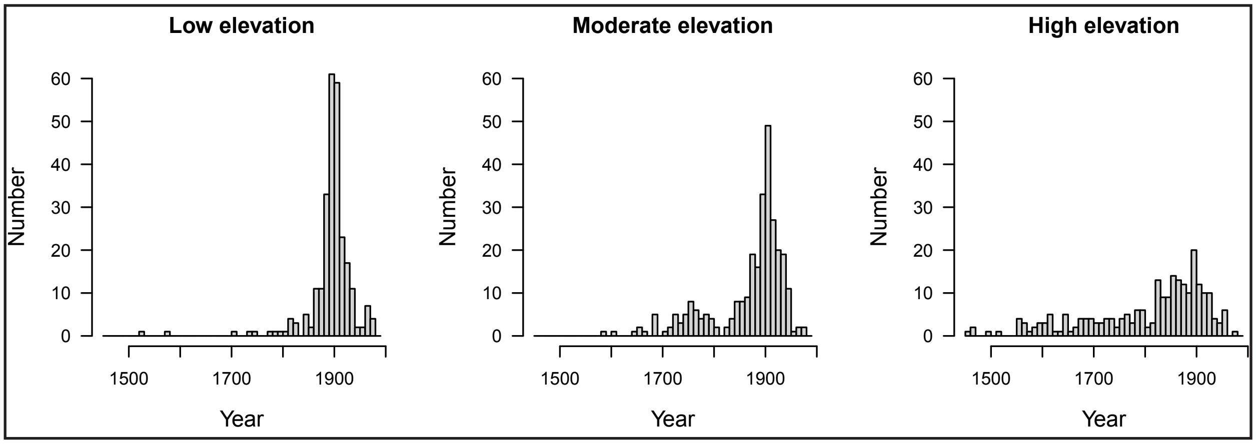

Figure 4. Tree establishment dates by elevation, Crater Lake National Park, Oregon, USA (low includes plots less than 1684 m, moderate includes plots between 1684 m and 1818 m, and high includes plots above 1818 m).

ry consisting of low-growing species (<0.5 m in height), primarily huckleberry (*Vaccinium* spp.) and manzanita (*Arctostaphylos* spp.).

Fire History

We were able to cross-date fire scars on 16 of the samples collected (Figures 2 and 5). Successfully dated scars were collected at lower to middle elevations in red fir and mixed conifer forests; no fire scars were collected in lodgepole pine, higher elevation red fir, or mountain hemlock forests. We dated a total of 32 scars, which was insufficient size to compute meaningful fire return intervals. In only three of nine cases in which fire scar samples were collected within 500 m of the stand demography plots in red fir and mixed conifer forests did scars roughly correspond with (i.e., immediately pre date) a peak in establishment (Figure 6).

DISCUSSION

Stand demography data indicate that each forest type in the study area has a somewhat different fire ecology. This is corroborated by fire scar data for mixed conifer and lower elevation red fir forest. Mountain hemlock forests tended to occur at higher elevation and exhibited continuous establishment over the last four centuries. Contrary to our hypothesis, this suggests that, at the scale of our study area, high severity fires are rare in this forest type. High or moderate severity fires may occur in this forest type, but we were unable to find any fire scars in this forest type to corroborate our stand demography data, either because fire is relatively rare or because fire scars rarely form, heal over, or tend to rot in these forests. Because mountain hemlock forests are covered in snow for much of the year, there is a narrow window during which wildfires can occur. When they do occur, fires may burn as low severity surface fires with small pockets of higher severity, such as observed in the 2006 Bybee Fire. 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 forests in the southern Cascades. They found that moderate and high severity fires occurred in this forest type, but they were unable to detect impacts of fire on forest composition or structure (Bekker and Taylor 2010). Gardner and Whitlock (2001) found that 75% of the 3700 ha burned by the 1996 Waldo Fire in the northern Cascades of Oregon experienced >90% mortality, providing further evidence

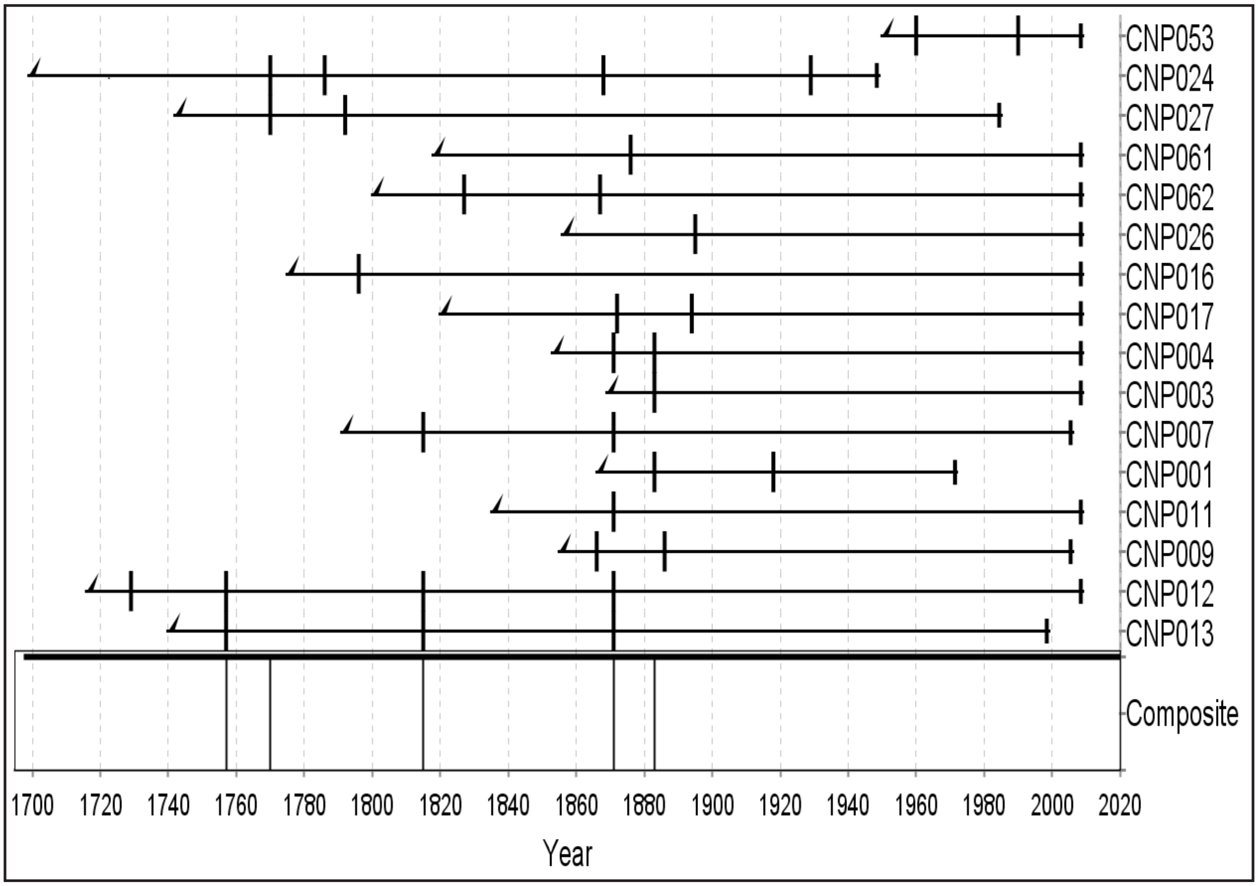

Figure 5. Fire history, scars sorted from high (top) to low (bottom) elevation, Crater Lake National Park, Oregon, USA. Horizontal lines represent the age of each fire scar sample, with the vertical lines representing fire events. Each fire scar is labeled "CNP" plus the scar number (e.g., CNP001). The record labeled "Composite" represents years with at least two scarred trees.

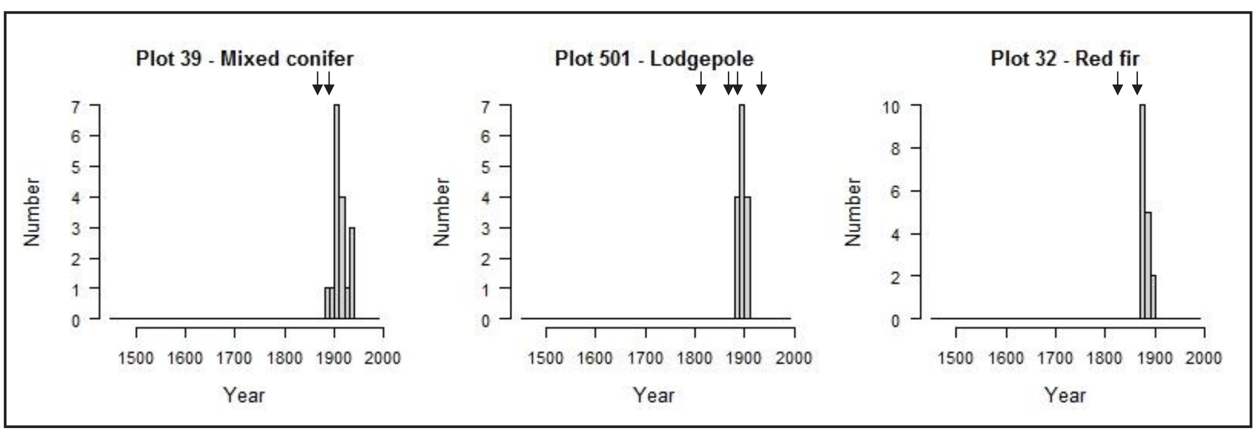

Figure 6. Plots in which peaks in tree establishment were correlated with fire dates from conifer forests at Crater Lake National Park, Oregon, USA. Fire dates are indicated by arrows.

that high severity fire can be a component of this forest type.

The dual regeneration strategy of red fir is apparent in the demography data for this forest type, which shows both continuous establishment for the last several centuries at the landscape scale, and peaks of establishment that are roughly associated with fire events at the plot scale. Although our fire scar analysis combined red fir and mixed conifer forests, the results are inconclusive given the small sample size, but are consistent with other studies documenting the difficulty of determining fire return intervals in mixed fire severity regimes (e.g., Pitcher 1987, Taylor and Halpern 1991, Taylor 1993, Chappell and Agee 1996, Taylor 2000, Bekker and Taylor 2001, Taylor and Solem 2001, Scholl and Taylor 2006). Regardless, fire years were generally not synchronous across the study area, which suggests that fires were likely smaller in extent or that the tree species were poor fire recorders; more recent fires could have also erased the evidence of past fires.

The methodology used to collect fire scars (see Van Horne and Fulé 2006) and the availability and type of fire scars available (i.e., stumps versus live trees and snags) may influence estimates of fire return intervals. Comparison of estimated fire return intervals at adjacent sites in fir forests in the southern Cascade Range based on fire scars collected from standing trees (Taylor and Halpern 1991) versus fire scars collected from stumps (Taylor 1993) suggests that scars may be lost to rot or may be healed over. Additionally, when sampling is limited to trees with visible scars, the resulting estimates of fire occurrence are likely conservative. In the intact, old-growth forests at CLNP, we were limited to sampling trees and snags with visible fire scars (no clear-cuts in the Park).

Lodgepole pine in monospecific stands that were sampled in this study tended to have establishment dates in the last 100 to 150 years. Although no direct fire scar evidence was found, these stands likely regenerated following stand-replacing fire. Several of the lodgepole pine stands we sampled did have establishment dates around 1900 and were located in or near mapped fire perimeters from the same time period (Leiberg 1900). Gara *et al*. (1985) and Heyerdahl *et al*. (2014) also found cohorts of lodgepole pine tree recruitment coincident with natural disturbance years (i.e., fire, windthrow, and beetle outbreak). However, their fire scar evidence suggested that high severity fire was spatially limited and low severity fire was more common across the study area (Heyerdahl *et al*. 2014). Some studies have hypothesized that lodgepole pine follows two successional pathways following fire: (1) self-replacement on flat, cold-air drainages with poor soils; and (2) succession to mountain hemlock and red fir forests on better sites (Zeigler 1978, Agee 1993). However, all of our plots that were dominated by lodgepole pine, including those on flat, poor sites, had an understory of mountain hemlock and red fir. It is likely that these stands will succeed to a red fir-mountain hemlock forest type in the absence of disturbance in the next several centuries (Figure 1).

The mixed conifer forests that we sampled had few older trees with most individuals having established since 1900. The lack of older trees has several possible explanations. One possibility is that these forests may have burned with high severity around the beginning 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. Alternatively, it is possible that this forest type had more of a mixed-severity fire regime with occasional moderate or high severity fires that killed older trees and led to the establishment of new cohorts. Mixed conifer forest fire regimes in this region are often described as high frequency and low to moderate severity (McNeil and Zobel 1980, Agee 1993), but the forests in our study area may represent a slightly different forest and fire regime type with more moisture and less frequent, higher severity fire such as that reported by Wills and Stuart (1994). Due to the relatively small number of fire scars in our study, it is not certain what the fire regime of mixed conifer forests might have been. This underscores the importance of careful evaluation of fire severity and monitoring of post-fire establishment when wildfires occur in this forest type in CLNP.

In interpreting the age-structure data from live trees, it is important to acknowledge that these data represent influences of establishment, survival, and mortality. It is not necessarily accurate that lodgepole pine and mixed conifer forests had little establishment prior to 1850; what the data demonstrate is that few establishment dates were recorded prior to 1850, or that only a small portion of the trees that established prior to 1850 survived to the present. The pulse in regeneration recorded in this study from 1880 to 1920 does not necessarily represent a favorable period for establishment; it may be that the lack of fires since that period due to fire suppression created favorable conditions for the survival of trees that established in that period.

The peak in establishment that we observed around 1900 has been detected in similar forest types in other locations (Taylor 1995, Bekker and Taylor 2010). Although our study did not find a strong relationship between PDSI and establishment, other studies suggest that this period of establishment may be the result of a warm, mesic period in the region (Taylor 1995). 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). However, our peak in forest establishment appears to be spread fairly evenly across the landscape; this turn-of-the-century cohort does not appear to be associated exclusively with fires that have been mapped around the same period (Figure 2). The CLNP's fire suppression policy in the early 1900s through the 1980s may also have contributed to this pulse in regeneration. Thus, further research needs to be done to determine the relative influence of climate, fire suppression, and land use history on fire regimes and tree establishment across the elevation range of this study (Chappell and Agee 1996). Although this study captured differences in fire ecology across an elevational gradient, future studies could target individual forest types or elevation zones over larger areas to elucidate the role of fire and climate in the historical landscape.

Overall, our results are not inconsistent with studies that found differences in fire ecology across elevational gradients or existing fire ecology studies in similar forest types. Because of our limited data, our results must be interpreted cautiously. However, our data are an important contribution to the body of knowledge about the relatively under-studied forests of the west side of the Cascade Range in Oregon. The presence of fire scars in the lower elevation mixed conifer forests supports the conclusion that this forest type has experienced repeated fire events in the past and that active management to restore fire as a natural process is most needed in this forest type. The presence of monospecific, even-aged stands of lodgepole pine, which are likely associated with past fire events, supports the conclusion that high severity, relatively low frequency fires have historically been present across large elevation ranges. Contrary to our hypothesis, our findings do not support the idea that mountain hemlock forests in the study area had fire return intervals similar to red fir forests. Rather, at the scale of our study area, continuous establishment in mountain hemlock forests over several centuries suggests that moderate to high severity fires have been relatively rare in these forests. Our study highlights the challenges of reconstructing fire history in these forest types and the importance of further research addressing these questions.

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