Prescribed fire effects on mixed conifer forest structure at Crater Lake, Oregon

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Received October 16, 1985[2]

Accepted May 27, 1986

THOMAS, T. L., and J. K. AGEE. 1986. Prescribed fire effects on mixed conifer forest structure at Crater Lake, Oregon. Can. J. For. Res. **16**: 1082–1087.

Prescribed fire was applied to a mixed conifer forest in southern Oregon, part of which was selectively logged in the 1930's. Structural effects were measured over a 4-year postfire period. Initial tree mortality was concentrated in small diameter and height classes of *Abies concolor* (Gord. and Glend) Lindl., *Pinus lambertiana* Dougl., and *Pinus ponderosa* Dougl. Most mortality in all three species after the 1st year was associated with bark beetles. Mortality after 1 year for *Abies concolor* remained primarily in smaller tree classes, while both small and large pines were killed. Implications for restoring natural conditions in these ecosystems include recognizing structural as well as process goals, while reintroducing fire, and recognizing the significance of available prescription variables in the prediction of fire effects.

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On a brûlé expérimentalement une forêt mixte de conifères, dont une portion avait été exploitée par coupe sélective durant les années 1930 dans le sud de l'Orégon. Les effets structuraux furent mesurés durant une période de 4 ans postérieure au brûlage. La mortalité initiale des arbres était concentrée dans les petites classes de diamètre et de hauteur de *Abies concolor* (Gord. and Glend) Lindl., *Pinus lambertiana* Dougl. et *Pinus ponderosa* Dougl. La plus grande partie de la mortalité chez les trois essences après la 1re année était associée aux coléoptères de l'écorce. Après 1 an, la mortalité d'*Abies concolor* demeurait concentrée dans les petites classes, tandis que les pins morts se retrouvaient dans toutes les classes d'arbres. Les implications pour restaurer les conditions naturelles dans ces écosystèms consistent à reconnaître les objectifs aussi bien structurels que décisionnels lorsqu'on reintroduit le feu, et a reconnaitre la signification des variables permettant de prédire les effets du feu.

[Traduit par la revue]

Introduction

Fire has been widely recognized as a natural process that has a vital role affecting species composition, structure, and function in many ecosystems (Mooney *et al.* 1981). In areas managed primarily for natural values, it is important to allow fire to interact with the ecosystem. Where fire was historically frequent, as in the mixed conifer ecosystems of western North America, human suppression of natural fires for many decades has frequently resulted in important changes: species composition has shifted to more shade-tolerant species, structure of the forest has been altered by the addition of a dense understory of trees, and fuels have built up to high levels (Biswell 1961; Parsons and DeBenedetti 1979). Prescribed fire has been introduced in some mixed conifer forests to begin the restoration of natural conditions (Kilgore 1973; van Wagtendonk 1974).

The mixed conifer forests of Crater Lake National Park, Oregon, are bounded by ponderosa pine (*Pinus ponderosa* Dougl.) forest at lower elevation and red fir (*Abies magnifica* Murr. var. *shastensis* Lemn.) – lodgepole pine (*Pinus contorta* Doug. var. *murryana* Grev. and Balf.) forest at higher elevation. Fire frequency from the ponderosa pine zone into the red fir zone was reported to be 9–42 years (McNeil and Zobel 1980), with a fire-free interval using tree clusters of 12–24 years at 4 km from the present study site in a similar plant community. Fire-free intervals of this length allow young white fir to develop some fire resistance and increase survival probability from the next fire. Effective fire suppression has removed approximately five cycles of fire from these ecosystems.

Restoration of pristine or presettlement conditions in the mixed conifer forests at Crater Lake National Park is complicated by past selective logging in some areas that were later added to the park. Ponderosa pine and sugar pine (*Pinus lambertiana* Dougl.) were both removed from some areas in the 1930's, leaving unnaturally pure stands of white fir (*Abies concolor* (Gord. and Glend.) Lindl.). The objective of the study was to evaluate the degree to which a single prescribed fire could reduce density of white fir, while maintaining density of both ponderosa pine and sugar pine, which are important structural elements of the prefire-suppression era.

Methods

The study area is located near Sun Creek within Crater Lake National Park, Oregon (Fig. 1). All plots are within the *Abies concolor* series, so in the absence of disturbance, white fir dominates the tree reproduction. A ponderosa pine – white fir and sugar pine – white fir community type were selected for study. Both community types are dominated by pine but have a substantial component of white fir in the overstory, a species mix maintained by the presence of frequent, low-intensity fires before this century. *Ceanothus velutinus* is a common invading shrub when sites are disturbed by logging. Within each community type a representative logged and unlogged plot was subjectively located to represent average conditions and to minimize fire-line construction. On each 50 × 50 m plot, all trees less than 5.5 cm diameter at breast height (dbh) were recorded by species and height. Trees above 5.5 cm dbh were tagged and increment cored to determine age; species, dbh, and height were determined. Increment cores were mounted and sanded, and rings were counted under a dissecting scope. Ages were adjusted if

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[2]Revised manuscript received May 22, 1986.

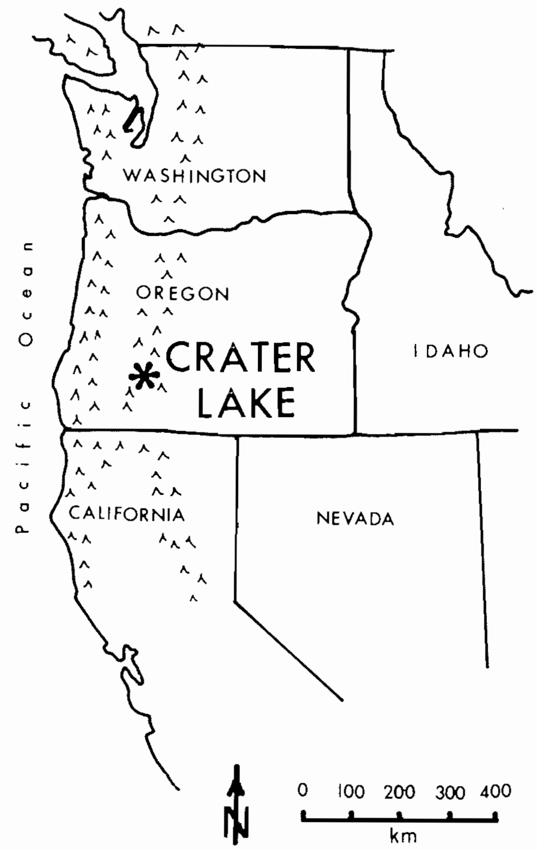

FIG. 1. Location of study area in the southern Oregon Cascades.

the core missed the pith slightly and to correct for age at core height to determine germination date. Since the minimum age cohort for analysis was 20 years wide, such corrections had insignificant bias on the data.

Spatial pattern of each major tree species in a 10- to 20-ha area around each plot was measured using the nonarea analytic technique (Bray 1962). This technique provides a measure of species pattern relative to other species present, but does not allow quantification of the size of the pattern. Each sample point was separated from the next by approximately 20 m and, at each point, the four nearest individuals were recorded by species. In addition, the four nearest individuals at least 100 years old (including dead trees or stumps that were judged to have been alive 100 years ago) were also recorded by species to evaluate historical species patterns.

Fuels were measured by the planar intersect method (Brown 1974) along a continuous line 5 m inside the edge of the plot and along two lines bisecting the plot center. A total of 25 litter–duff depth samples were measured on each plot. Depths were converted to loading using regression equations (Agee 1973); 15 m of 1-h time lag (0–0.62 cm diameter) fuel transect, 30 m of 10-h (0.63–2.54 cm diameter) and 100-h time lag (2.55–7.62 cm diameter) fuel transect, and 240 m of >100-h time lag (>7.62 cm diameter) fuel transect were also measured.

Burning prescriptions (Table 1) were developed to produce a low-intensity surface fire that would selectively reduce white fir density. All plots were ignited during the summer dry season from July through September, with subsequent smoldering that lasted from 7 days to 1 month after ignition, typical of prescribed fires at Crater Lake National Park. Actual fire behaviour was variable because of fuel variations and weather changes over this period (Table 2). The unlogged ponderosa pine plot was ignited as part of a larger 2-ha block. Ignition began in a strip head fire pattern; a passing weather front caused humidity to increase and limited precipitation fell before the fire reached the plot. Subsequent spread was defined by diurnal wind patterns and fuel moisture. This resulted in a fire of low fire-line intensity that burned slowly creating a mosaic of burned and unburned patches. The remaining fires were ignited with strip head fires and burned with higher fire-line intensities. No fire burned all of any plot and variable proportions of each plot burned after the main fire front had passed; therefore, the average values in Table 2 have wide variations. Some variables, such as scorch height, could be measured only where low branches existed and are biased towards values in understory thickets of brush or trees.

Tree mortality was measured 3 times after the plots burned: year 1 (at the end of the first dry season following the fires), year 2, and year 4 (during middle to late summer). Fuel transects were remeasured in year 1 only.

TABLE 1. Fire prescription used for the prescribed fires

Weather or behaviour variable	Desired average or range
Wind (m/s)	0–4.5
Relative humidity (%)	20–70
Air temperature (°C)	15–21
Fuel moisture (%)	
1-h TL[a] fuels	6–14
10-h TL fuels	8–15
100-h TL fuels	12–17
1000-h TL fuels	14–18
Fire-line intensity (kW/m)	<300
Scorch height (m)	6–7
Ignition pattern	Strip head fire; depth of strip determined while firing

[a]TL, time lag.

TABLE 2. Weather and fire behaviour characteristics of the four prescribed fires during the period of main fire spread

Weather or fire behaviour characteristic	Sugar pine		Ponderosa pine	
	Unlogged	Logged	Unlogged	Logged
Windspeed (m/min)	<134	<134	<134	<134
Day temperature (°C)	11–21	22–23	11–24	25–28
Relative humidity (%)	15–56	23–34	22–72	30–34
10-hr TL[a] moisture (%)	12	12	16	9
Area burned (%)	65	70	55	80
Mean fire-line intensity (kW/m)	37	32	8	48
Median scorch height (m)	6.1	4.6	0.3	9.1

NOTE: Fire behaviour was less intense after the period of main fire spread.
[a]TL, time lag.

Results

Prefire species composition and structure

All plots were dominated by white fir before burning. Tree basal area on the logged plots was 45–60% of that on the unlogged plots with almost all the basal area in white fir (Table 3). White fir also made up more than 50% of the basal area on unlogged plots and remained dominant even when trees older than 100 years were analyzed separately. These study areas appear to have had a significant component of white fir even in presettlement times. McNeil and Zobel (1980) reported fire-free intervals near this area sufficiently long to allow young white fir to develop some fire resistance and increase survival probability from the next fire.

Tree diameter distribution on each plot shows the predominance of white fir in all size classes but particularly the smaller

TABLE 3. Species basal area on each plot before (1980) and after (1984) burning

	Basal area (m^2/ha)		Basal area change	
	1980	1984	Actual	%
Unlogged sugar pine plot				
Ponderosa pine	1.74	1.74	0	0
Sugar pine	7.65	5.47	−2.18	−28.5
White fir	11.75	9.90	−1.85	−15.7
Logged sugar pine plot				
Ponderosa pine	1.97	1.95	−0.02	−1.0
Sugar pine	0.35	0.18	−0.17	−48.5
White fir	7.12	6.49	−0.63	−8.8
Unlogged ponderosa pine plot				
Ponderosa pine	6.45	6.27	−0.18	−2.8
Sugar pine	2.13	2.13	0	0
White fir	10.27	9.60	−0.67	−6.5
Logged ponderosa pine plot				
Ponderosa pine	0.02	0.02	0	0
Sugar pine	0.02	0.02	0	0
White fir	11.28	7.63	−3.65	−32.3

size classes of trees (Fig. 2). The stand structure on the logged ponderosa pine plot is an all-sized stand of almost pure white fir. In contrast, the logged sugar pine plot has abundant pine reproduction and some large residual ponderosa pines.

Each tree species is distributed contagiously relative to the other species in the area (Table 4). The pines tend to be found in pure groups, as does white fir. All species on the unlogged plots have retained this relative contagious pattern over the fire-suppression period. In the logged ponderosa pine area, there is not enough ponderosa pine remaining to test the pattern statistically; in the logged sugar pine area, sugar pine has tended to regenerate in clumps and maintain the relative contagious pattern.

Species mortality over time

In a silvicultural sense, fire reduces stand stocking from below and mortality should be concentrated in the smaller size classes. Mortality in the 1st year was concentrated in the smaller size classes for all three species, with some larger white fir also dying the 1st year (Fig. 3). Absolute numbers of dead white fir exceeded those for ponderosa pine and sugar pine in part because there were so many more small fir before the fire. The proportion of total trees killed per size class also was higher for white fir, which generally is regarded as having less fire resistance in the sapling stage than either sugar pine (Mason 1955) or ponderosa pine (Minore 1979). Reduction of white fir with dbh > 5.5 cm was 34% on the unlogged sugar pine plot, 45% on the unlogged ponderosa pine pine plot, 31% on the logged sugar pine plot, and 46% on the logged ponderosa pine plot. Most of the trees that died the 1st year were killed as a direct result of the fire: total crown scorch, girdled stems from cambial heating, or root damage from soil heating.

All three species suffered significant mortality the 2nd year after the fire and between the 2nd and 4th year after burning. Roughly two-thirds of total white fir mortality over the 4 year period occurred in year 1; one-third occurred in years 2–4. For the pines, one-third of total mortality occurred in year 1; the remaining two-thirds occurred in years 2–4. Some larger trees also died in years 2–4, primarily sugar pines. For all species, insects were important causes of death after year 1.

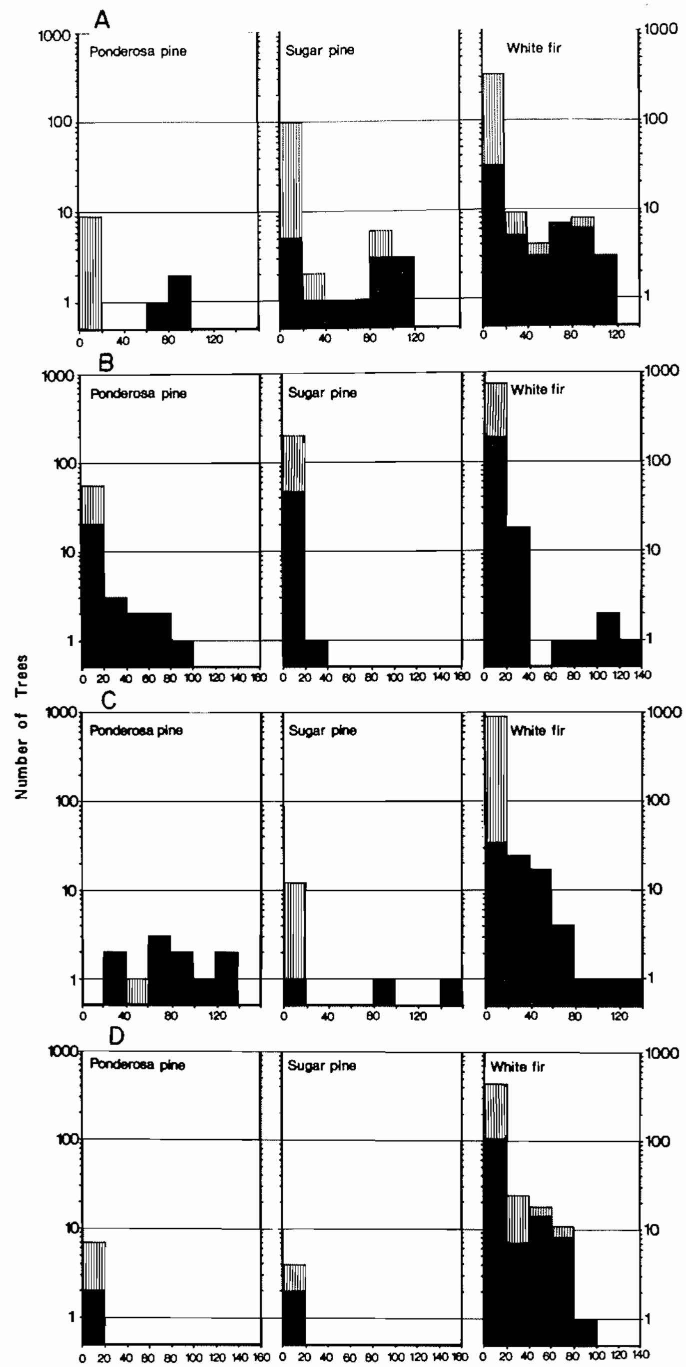

FIG. 2. Diameter distribution of each species on study plots: A, unlogged sugar pine; B, logged sugar pine; C, unlogged ponderosa pine; D, logged ponderosa pine. ■, residual trees; ▥, trees killed by year 4.

White fir was attacked by the fir engraver beetle (*Scolytus ventralis* LeConte). Because most of the very small white fir were killed initially by the fire, fir engraver attacks were most common on trees ≥5 cm dbh. Some trees were attacked only on one side of the stem and have survived, which is common for fir engraver attacks (Furniss and Carolin 1977). On small white firs with bark thickness generally 2–3 mm thick, an unknown insect with galley patterns very similar to those of *Pityophthorus pseudotsugae* Swaine appeared to be a primary attacker.

Ponderosa pine was relatively resistant to insect attack on the plots, although in surrounding areas and on past fires in the park

TABLE 4. Relative dispersion by species around the four study plots

	Ponderosa pine				Sugar pine			
	Unlogged		Logged		Unlogged		Logged	
Species	1880	1980	1880	1980	1880	1980	1880	1980
White fir	+	+	+	+	+	+	+	+
Ponderosa pine	+	+	+	ID	+	ID	ID	NS
Sugar pine	ID	ID	ID	ID	+	+	+	+

NOTE: All significant results are at the 95% level.
+, significantly different from random relative dispersion; in all cases, the relative dispersion was contagious; ID, insufficient data for analysis; NS, not significantly different from random relative dispersion.

TABLE 5. Mortality (per ha) of each species by height class over time

Species	Height class (m)	No. before fire	Mortality Year 1	Mortality Year 2	Mortality Year 4	Residuals at year 4	% mortality
Ponderosa pine	0–10[a]	79	—[b]	—	—	15	81
	0–10[c]	17	2	2	2	11	35
	10.1–30	10	0	0	0	10	0
	>30	11	0	0	1	10	9
	Total	117				46	61
Sugar pine	0–10[a]	266	—	—	—	41	85
	0–10[c]	43	9	12	5	17	60
	10.1–30	3	1	0	0	2	33
	>30	14	0	2	2	10	29
	Total	326				70	79
White fir	0–10[a]	1974	—	—	—	281	86
	0–10[c]	362	156	31	35	140	61
	10.1–30	139	27	11	5	96	31
	>30	68	5	5	0	58	15
	Total	2543				575	74

[a]Trees less than 5.5 cm dbh.
[b]No yearly mortality available for trees in this class except total after year 4.
[c]Trees greater than 5.5 cm dbh.

some mortality from insects has occurred. The California five-spined ips (*Ips paraconfusus* Lanier) killed two small trees, a beetle with a gallery pattern similar to *Pityogenes* sp. killed one tree, and one large ponderosa pine (47 cm dbh) broke off in a storm; the breakage apparently was unrelated to the fire.

Sugar pine was proportionately most susceptible to postfire insect attack. Mountain pine beetles (*Dendroctonus ponderosae* Hopkins) killed 25% of the sugar pines above 20 cm dbh. The California five-spined ips concentrated on trees in the 10–20 cm dbh range. The *Pityogenes*-like beetle killed trees generally less than 10 cm dbh and trees attacked were small with very thin bark.

Mortality by height class was very similar to that by diameter: shorter trees were killed more than taller ones (Table 5). Nearly 75% of all trees on the plots were killed by the fire, primarily in 0–10 m class trees with dbh <5 cm. Overall percent mortality by height class was very similar for sugar pine and white fir; ponderosa pine mortality was less, particularly in the taller height categories.

Age-class analysis (Fig. 4) indicated that younger trees were more fire susceptible than older ones, generally because they were smaller. No trees over 200 years old were killed by the fire. Of the prefire suppression age cohort (older than 80 years), 11% of the ponderosa, 20% of the sugar pine, and 40% of the white fir were killed by year 4. Most of these were in the smaller tree diameter classes; for example, two-thirds of such mortality in white fir occurred in the 81- to 120-year age-class with average dbh in the 20–40 cm range.

Surface fuel reduction

Dead and down fuels were significantly reduced by the fire (Table 6). Absolute reductions of fuel loads were greatest in those fuel categories where fuel loads were highest before burning: >100-h time lag fuels and litter–duff layers. Reduction of total dead and down fuel was 44% for the logged ponderosa pine plot, 68% for the unlogged ponderosa pine plot, 69% for the logged sugar pine plot, and 73% for the unlogged sugar pine plot. Litter–duff fuels were reduced an average of 86%; percent reduction of the other fuel categories was lower.

The mortality of understory trees will result in additions to dead and down fuel loads in the next 5–10 years. These fuel additions were estimated by applying allometric equations (Gholz *et al.* 1979; Agee 1983) to individual trees killed by year 4. The 1-h time lag fuel category additions assume these aerial fuels were not consumed by the fire, which is largely true but results in some overestimation. Some of these fuels are also double counted, as some had fallen by the time the year 1 fuel measurements were made. An immediate reduction of 67% of dead and down fuels resulted from the fire and even if all dead fuels created by tree mortality are added in, total dead and down

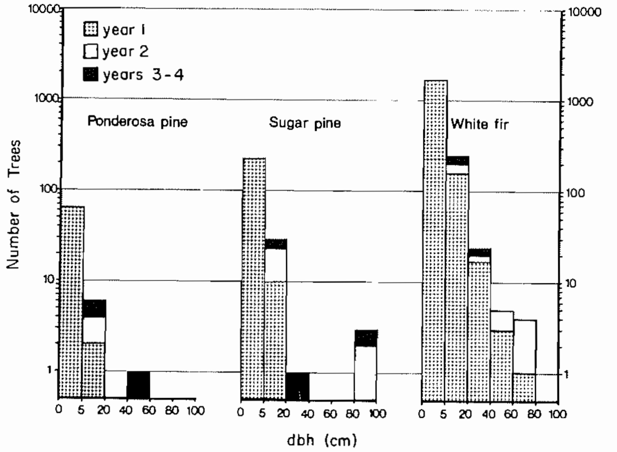

FIG. 3. Species mortality by diameter class over time. For trees in the 0–5 cm dbh class, the year 1 totals represent mortality over the 4-year postfire period.

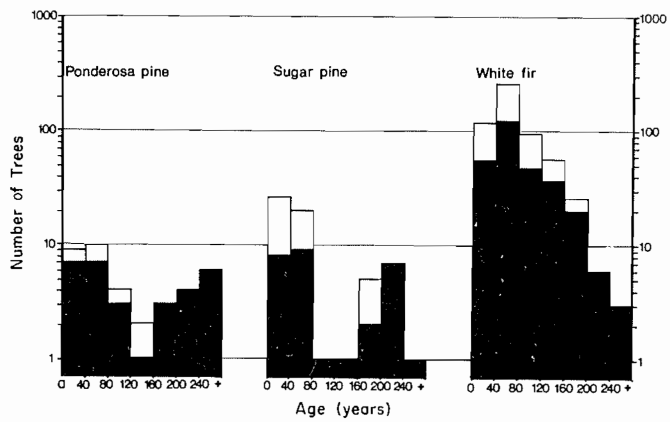

FIG. 4. Species mortality by age-class: □, dead by year 4; ■, residuals. Trees with dbh < 5 cm were not aged and are excluded from the analysis; they would be almost completely within the 0- to 80-year class.

TABLE 6. Fuel reduction (kg/ha) by burning and potential additions due to tree mortality

Fuel time lag category	Before fire	After fire (year 1)	Near future additions	Near future totals
1-h	3 470	1 455	4 615	6 070
10-h	3 290	2 277	4 761	7 038
100-h	6 160	2 940	12 683	15 623
>100-h	67 285	38 067	43 190	81 257
Litter–duff	92 130	12 525	——[a]	12 525
Total	172 335	57 264	65 249	122 513

[a]Litter additions from trees killed by fire are included in the 1-h timelag category. Duff additions are assumed to be negligible in the short run. Annual litter additions from the residual stand are not included.

fuel loads were reduced by 29%. The quantities of most fuel size categories will increase in the near future as dead understory fuels fall to the ground.

Postfire species composition and structure

White fir maintained basal area and density dominance on all plots 4 years after the fire (Table 3, Fig. 2). The largest plot basal area change was a decrease of 16 m^2/ha on the unlogged sugar pine plot, where insect attacks killed several large sugar pines. The largest species basal area change was 15 m^2/ha for white fir on the logged ponderosa pine plot. The overall basal area reduction across all plots averaged 15%.

The most significant changes were in the small size classes of trees, so that a much more open understory has been created. For trees smaller than 5 cm dbh, no apparent differential survival by species was evident.

Discussion

The general objective of prescribed fire use in the mixed conifer ecosystems of Crater Lake National Park is to reduce unnatural fuel accumulations while retaining structural elements that remain from the prefire suppression era. Although the list of structural elements could be extensive, the most dominant elements are trees and, in this case, those that germinated before 1900. These objectives are intermediate between those of Bonnicksen and Stone (1982) and Parsons *et al.* (1986). Bonnicksen and Stone (1982) suggest that the presettlement state of the ecosystem should be structurally defined and then simulated through time in the presence of simulated fire to a hypothetical desired present state. This present state should be the restoration goal to be achieved in present or near future time. Parsons *et al.* (1986) argue that the uncertainties in such an approach are significant enough that introduction of prescribed fire is generally sufficient to reduce fuels and allow future natural fires to help define successional and structural attributes of the system. Both agree that once restoration is achieved, either planned or unplanned ignition prescribed fires are an essential process in future management of these natural areas.

Fires of low intensity but long duration can be of high severity because of heat input to soil from smoldering duff or logs. Most forests at Crater Lake have developed on very coarse-textured soils derived from glowing avalanche or pumice deposits from Mount Mazama. Nearby lodgepole pine forests on pumice deposits are very shallow rooted. The trees are easily scarred or killed from low-intensity, smoldering fires along logs typical of this particular type of lodgepole pine forest (Gara *et al.* 1986). Prescribed fire of low intensity in ponderosa pine forests in Washington has been associated with fine root mortality (S. Milne and C. Grier, College of Forest Resources, University of Washington, personal communication). If concentrated surface rooting in mixed conifer forest occurs at Crater Lake, root damage, and subsequent moisture stress and insect attack may be likely. Ferrell (1978) found that the moisture stress threshold for susceptibility of white fir to fir engraver beetles was about −2 MPa; this level was apparently reached by many of the white fir trees in this study that died between years 1 and 4 from insect attack. A similar process may be responsible for mortality in large pines. A survey of pine mortality was conducted along transects inside and outside of burned areas in year 4 to determine if there was a difference in mortality between areas. The proportion of beetle-killed pines above 70 cm dbh was higher inside burned areas (including but not limited to the study plots) than outside (n = 166) for both sugar pine ($p<0.005$) and ponderosa pine ($p<0.001$); mortality within the burned areas does not appear to be simply a random effect of endemic beetle populations.

These large pines are structurally important as a codominant prefire suppression element of the ecosystem and are important as future seed sources. If group of pines die as a result of an initial prescribed fire, understory fir density is high enough to capture the growing space and potentially eliminate pine from the area. Careful application of fire will be necessary to preserve the large pine component of these forests. Fires will need to be of low duration to minimize root and root collar heating. Mechanical applications such as scraping some bark and needle accumulations away from the bases of some larger trees may be needed. Risk rating by age-class and vigor class (Keen 1943) may also be appropriate to identify particularly susceptible pines. Where edaphic conditions are responsible for shallow rooting patterns, attention to forest structure as well as process is necessary to restore natural conditions in these forests (Agee and Huff 1986).

The logged ponderosa pine plot is analogous to a so-called climax stand, with the potential dominant, white fir, occupying the growing space at all structural levels. While the fire effectively reduced white fir density, there was no change in relative density after the fire. Further density reduction followed by cluster planting of ponderosa pine will be needed to restore a mimic of natural conditions to this and similar sites. In the logged sugar pine plot, pine regenerated after logging; it was substantially thinned by the fire. Sufficient stock remains to restore a natural balance of pine and fir, but less mortality of pine can be tolerated from the next fire.

Because the restorative process will require several fires and an indication that limited pine regeneration is successful, it cannot yet be concluded that fire can be used as a sole restorative tool in the Crater Lake mixed conifer ecosystems. The postfire suppression era white fir cohort greater than 40 cm dbh cannot be removed by low-intensity, long-duration fires without causing significant mortality in important, not easily replaced prefire-suppression structural elements of the ecosystem. Accepting this white fir cohort may continue the dominance of white fir in regeneration dynamics because of additional forest floor shading.

To assure survival of large pines, fire prescriptions and monitoring techniques need to continually refined. The fire needs to be prescribed such that it maximizes the effectiveness of fire-resistant characteristics of the large pines: high resistance to crown scorch because the trees are tall and moderate resistance to cambial heating because of thick bark. Differential species resistance to heating of roots appears to be low at Crater Lake on these volcanic soils. The type of fire best meeting these criteria is one of low to moderate fire-line intensity (<300 kW/m) and low duration. Weather conditions for this type of fire will most commonly be found in late spring when soil and duff are wet but surface fuels can support moderate fire-line intensity.

Actual duff or soil moisture could be used as a prescription variable, but is awkward to measure. The 1000-h time lag fuel moisture from the National Fire-Danger Rating System appears to have some utility in estimating duff moisture (Sandberg 1980; Brown *et al.* 1985) and research is currently proposed to evaluate its utility in predicting local duff moisture at Crater Lake. Predictions of fire severity would be improved by incorporating 1000-h time lag fuel moisture into fire prescriptions.

Monitoring of tree mortality and fuel changes as a result of fire should occur over several years to fully evaluate fire effects. Significant underestimation of tree mortality would have occurred if predictions of fire effects had been based only on 1st-year results. For trees with dbh >5 cm, one-third of white fir mortality and two-thirds of pine mortality occurred after the 1st year. Similarly, fuel reduction must consider the contribution from standing dead trees killed by the fire. Since accurate tree mortality estimates take several years, accurate fuel estimates also will require measurement after several years. In this study, contributions from standing dead trees will increase fine fuel loads above preburn levels; timing of such inputs will be erratic as larger snags may stand for some time.

Acknowledgment

This research was conducted under National Park Service contract CX-9000-1-E002, Pacific Northwest Region, Seattle, WA.

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