RESEARCH ARTICLE

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# Monitoring Postfire Tree Mortality in Mixed-Conifer Forests of Crater Lake, Oregon, USA

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**ABSTRACT**: Tree mortality after a prescribed fire was monitored four times in 13 years in a mixed-conifer forest at Crater Lake, Oregon, USA. Immediate postfire mortality was concentrated in smaller size classes for all species. Mortality of larger and older trees continued, with a peak for *Pinus ponderosa* Dougl. and *Pinus lambertiana* Dougl. in the 3–7 y period following fire, and a peak for *Abies concolor* (Gord. & Glend.) Lindl in the 8–13 y period. Monitoring mortality over long time periods showed that the burn objectives were achieved most closely immediately after the fire, but were compromised by subsequent mortality of large and older trees. This delayed mortality was probably linked to extended drought that also killed large trees in adjacent unburned areas. Further fuel reduction burns might reduce tree density below historic levels unless fires remain patchy. Melding structure and process goals will be essential for achieving resources management objectives in dry forests managed for natural values.

## Monitoreo Post Quema de Mortalidad de Arboles en un Bosque de Coníferas en Crater Lake, Oregon, USA.

**RESUMEN**: La mortalidad de árboles después de una quema programada fue monitoreada cuatro veces en 13 años en un bosque mixto de coníferas en Crater Lake, Oregon, USA. La mortalidad inmediata post quema estuvo concentrada en las clases de tamaño menores para todas las especies. La mortandad de árboles de mayor tamaño continuó, con un pico para *Pinus ponderosa* Dougl. y *Pinus lambertiana* Dougl. en el período de 3–7 años después de la quema, y un pico para *Abies concolor* (Gord. & Glend.) Lindl. para el período de 8–13 años. El monitoreo de la mortandad en largos períodos de tiempo mostró que los objetivos de la quema fueron logrados inmediatamente después del fuego, pero estuvieron comprometidos por la subsecuente mortandad de los árboles más grandes y de mayor tamaño. Esta mortandad retardada probablemente estuvo relacionada a la sequía extrema que también mató árboles grandes en áreas adyacentes que no fueron quemadas. Más aun, la quema podría reducir la densidad de árboles a los niveles históricos a menos que el fuego se mantenga en parches. Las estructuras fusionadas y las intenciones de los procesos serán esenciales para lograr los objetivos de los recursos de manejo en bosques secos con valor natural manejados.

*Index terms*: *Abies concolor*, long-term monitoring, *Pinus ponderosa*, *Pinus lambertiana*, prescribed fire

## INTRODUCTION

Fire has long been recognized as an important natural process in western U.S. forests. In national parks, this recognition was formalized after publication of the Leopold Report (Leopold et al. 1963) and institutionalized as U.S. Department of the Interior policy in 1968 (Kilgore 1973). Use of prescribed fire expanded in national parks (Botti and Nichols 1995), with general goals of restoring and maintaining natural ecosystems. Fire has also become an important component of ecological sustainability on multiple-use lands (Dale et al. 1999). In most dry forests of the West, tree density and shade-tolerant tree species have increased since fire exclusion began early in the twentieth century (Agee 1993, Covington and Moore 1994). Objectives of programs to restore and maintain the natural role of fire have included reducing tree density and shifting species composition to more shade-intolerant species, usually ponderosa pine (*Pinus ponderosa* Dougl).

At Crater Lake National Park, Oregon (Figure 1), managers began applying prescribed fire in 1976 to the drier forests that had ponderosa pine as a major structural element. These forests were assumed to have changed from low-density, single canopy old-growth forests of ponderosa pine, sugar pine (*Pinus lambertiana* Dougl.), and white fir (*Abies concolor* [Gord. & Glend.] Lindl) to multi-layered forests dominated by white fir (McNeil and Zobel 1980). The prescribed fire program had three primary objectives: (1) kill the postfire exclusion cohort of white fir, (2) favor pines in all size classes, and (3) maintain older structural elements of pines and fir. In 1981, a research study was begun in the southeastern portion of the park to evaluate the effect of prescribed fire on fuel dynamics and vegetation (Thomas and Agee 1986). In this local area, tree density

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*Natural Areas Journal 23:114–120*

before fire exclusion became effective was higher than elsewhere due to a single fire-free interval (1790–1820) that allowed a cohort of white fir to establish and grow large enough to survive subsequent fires of the nineteenth century.

In some western U.S. mixed-conifer forests, postfire mortality has continued long past the time when immediate, first-order fire effects should have been complete. Second-order effects from insects have usually been associated with this prolonged mortality period. These effects have been variously ascribed to extended smoldering from deep duff levels, season of burn, excessive scorch of foliage, or simply unknown reasons. At Lake Tahoe, California, pine bark beetles (*Dendroctonus ponderosae* Hopkins, *D. valens* LeConte and *Ips* spp.) attacked 31% of the pines within three years of autumn prescribed burning (Ganz et al. 2001). In southwest Colorado, Harrington (1993) found spring and summer burns to have higher mortality (28% and 30%, respectively) than autumn burns (12%). Little mortality occurred after postfire year 4. In Arizona, Sackett and Haase (1998) found 40% of old-growth pines died in the 18 y after application of low-intensity autumn prescribed fires at various frequencies, compared to about 15% on unburned plots. In California, Haase and Sackett (1998) found 67% of the old-growth sugar pine dead after long-smoldering summer and autumn prescribed fires, although giant sequoias (*Sequoiadendron giganteum* [Lindl.] Buchh.) showed no mortality. Stephens and Finney (2002), working in the same region, found forest floor consumption to be a significant predictor of mortality, along with crown scorch and tree diameter (a surrogate for bark thickness). At Crater Lake, Oregon, Swezy and Agee (1991) evaluated a 10-y sequence of prescribed burns and found spring burns to inflict higher mortality on old-growth ponderosa pine (about 30%) than autumn burns or unburned plots (about 10%). Thomas and Agee (1986), working in the same area, found mortality to continue for at least 4 y for large pines. This paper includes the results of two more periods of monitoring of tree mortality on the plots measured by Thomas and Agee (1986).

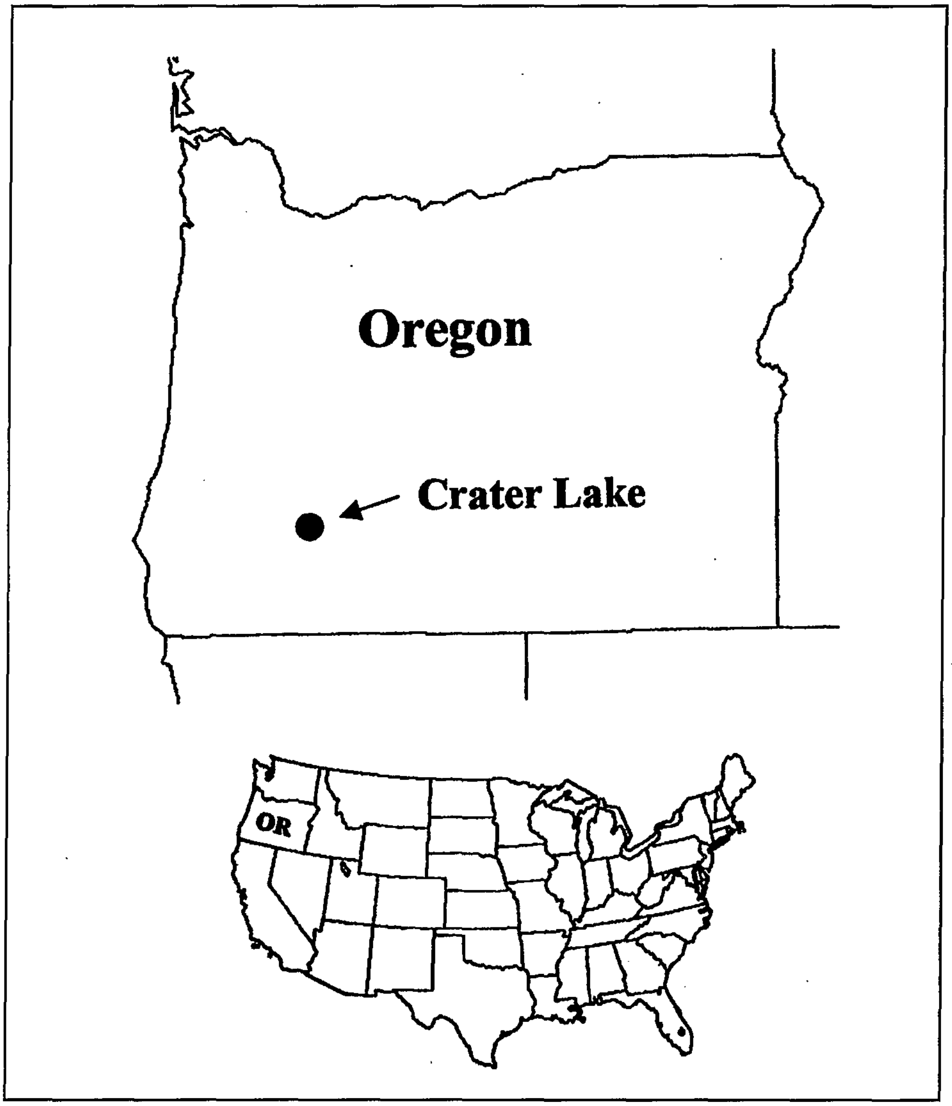

**Figure 1. Location of Crater Lake National Park in southern Oregon, USA.**

## METHODS

Four 0.25-ha plots were established in a mixed-conifer forest historically co-dominated by ponderosa pine, sugar pine, and white fir at Crater Lake (Thomas and Agee 1986). Plots were established in two mixed-conifer variants, one with ponderosa pine and white fir and a second with these species plus sugar pine. One plot in each mixed-conifer variant was established where pines had been selectively removed in the 1930s before this area was added to the park. Species, diameter at breast height (dbh), and age were determined for every tree exceeding 5.5 cm dbh. Age was established by increment coring each tree.

We reconstructed stand structures from before fire suppression ("historical": ca. 1900) by selecting all trees on unlogged plots that were alive in 1900 and sorting them by tree species and 1980 diameter. Diameters in 1900 were reconstructed by subtracting growth between 1900 and 1980 on 30 trees stratified by species and diameter and applying these corrections to all trees. The reconstruction of stand structure is a rough estimate because of the small sample of actual reconstruction and the lack of inclusion of any trees that were alive in 1900 but died before 1980 (e.g., Stephenson 1999). We calculated basal area

Table 1. Reconstructed stand structure of the two mixed-conifer variants, Crater Lake, Oregon. Density represents 1900 density of trees that were alive in 1980. Age is average age in 1900 of trees alive in 1980. Diameter and basal area are reconstructed 1900 values of trees that were still alive in 1980. Standard deviation of age and diameter are shown in parentheses.

| Mixed-conifer Forest Variant and Species | Density (trees $ha^{-1}$) | Average Age (y) | Average Diameter (cm) | Basal Area ($m^2$ $ha^{-1}$) |
|---|---|---|---|---|
| **Ponderosa pine variant** | | | | |
| *Pinus ponderosa* | 40 | 211 (122) | 74 (9.5) | 20 |
| *Pinus lambertiana* | 12 | 179 (202) | 78 (20) | 5 |
| *Abies concolor* | 296 | 60 (52) | 15 (23) | 13 |
| **Sugar pine variant** | | | | |
| *Pinus ponderosa* | 16 | 125 (17) | 76 (29) | 7 |
| *Pinus lambertiana* | 44 | 121 (17) | 59 (51) | 16 |
| *Abies concolor* | 120 | 57 (38) | 39 (17) | 21 |

from the estimated diameters and density based on all trees that were alive in 1900.

The prescribed fires had low fireline intensity and fire spread was patchy. Average scorch height was 0.3–9.1 m across the plots, and area burned ranged from 55% to 80% of each plot. After the fires, mortality was measured the first summer (year 1), the summer of the second postfire year (year 2), and the summers of years 4, 8, and 13 after the fires. Results to year 4 were published in Thomas and Agee (1986). At the end of the 13-y period, proportional mortality was similar across plots ($c^2_{n=3}$= 0.62, *P*=0.68) so results for the 13-y analysis were pooled across plots (total area = 1 ha). Chi-square analysis (2 by 2 contingency tables, critical value = 3.84 at *a*= 0.05 with df = 1) were used to evaluate whether the frequency of mortality for ponderosa pine, sugar pine, and white fir differed between burned and unburned areas. *P*-values less than 0.05 were considered significant.

We evaluated effects of a possible second prescribed fire using FOFEM (Reinhardt et al. 1997). FOFEM evaluates the probability of "first-order" or direct mortality from fires of different flame lengths (e.g., fireline intensities) based on inputs of tree species and diameter. The model predicts mortality as a function of volume of crown scorch and bark thickness. We created tree lists for the unlogged plots and the plots where the pines had been selectively removed in the 1930s, and evaluated first-order mortality from several possible flame lengths.

## RESULTS

### Stand Reconstruction

Basal area of *Abies concolor*, *Pinus lambertiana*, and *Pinus ponderosa* was reduced 89%–94% for trees below 40 cm diameter, 28%–98% for trees 40–60 cm diameter, and 19%–50% for trees exceeding 60 cm diameter, to reconstruct values back to 1900 A.D. Density and basal area estimates indicated that these stands had substantial basal area and many large trees before fire suppression became effective (Table 1). They probably had a two-tiered canopy structure composed of the pre-1800 trees and a smaller but substantial 80- to 100-y-old cohort at that time. A fire-free interval of about 30 y (1790–1820), apparent in adjacent stands (McNeil and Zobel 1980), allowed a cohort of white fir to establish and develop fire tolerance by the time the next fire occurred. This cohort (many of the 296 trees $ha^{-1}$ that averaged 15 cm dbh and 60 y of age in 1900) accounted for 18% of the 1900 basal area and 14% of the 1900 density. Density increases in the twentieth century (trees > 5.5 cm only) showed a substantial increase (153%) over pre-1900 density, but basal area increase since 1900 (5.4% of total 1980 basal area) was not proportional because growing space was limited and trees that established remained small.

### Tree Mortality

Tree mortality was greatest in the first postfire year, accounting for 56% of the total mortality. The other 44% of trees died over the remainder of the 13-y period (Table 2, Figure 2). Immediate mortality was concentrated in trees of small diameter and young age, with larger and older trees beginning to die in the year 2–year 4 period (Thomas and Agee 1986). In the subsequent mortality noted in postfire years 8 and 13, average diameter and age of trees that died in those periods continued to increase (Figures 3 and 4). Ponderosa pine and sugar pine had similar patterns of the largest, oldest trees dying in the period year 4–year 8, while fewer larger, old white firs were killed in postfire years 8–13. As time-since-fire increases, it is more diffi-

Table 2. Density of trees (trees $ha^{-1}$) dying across 1 ha in postfire monitoring years, Crater Lake, Oregon. Mortality is defined as the number of trees dying from one interval to the next.

| Species | Postfire Year 1 | 2 | 4 | 8 | 13 | Total |
|---|---|---|---|---|---|---|
| *Pinus ponderosa* | 2 | 2 | 3 | 2 | 2 | 11 |
| *Pinus lambertiana* | 9 | 14 | 8 | 2 | 3 | 36 |
| *Abies concolor* | 180 | 43 | 42 | 12 | 17 | 294 |
| **Total** | 191 | 59 | 53 | 16 | 22 | 341 |

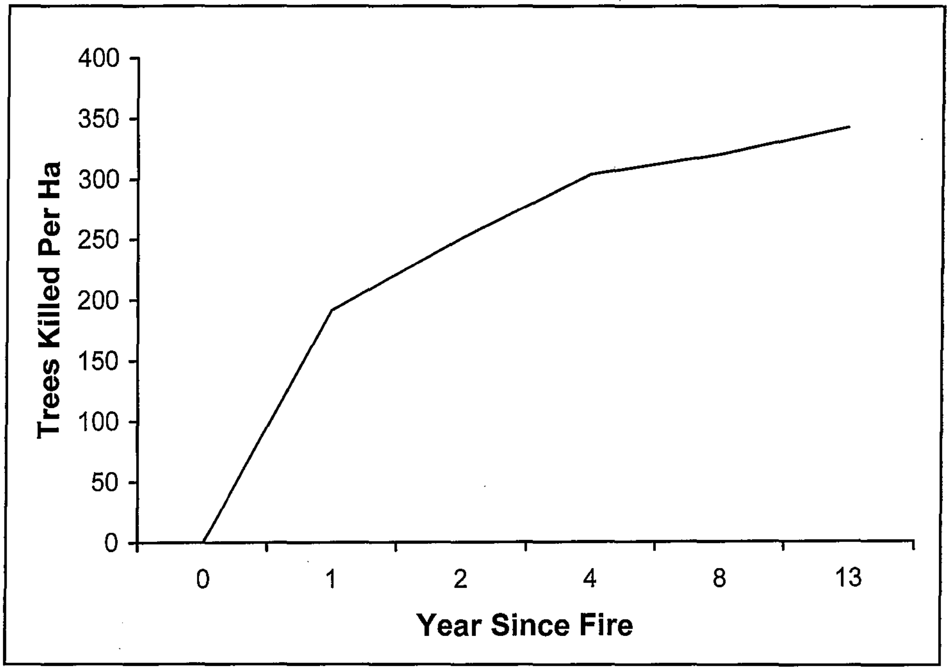


**Figure 2. Cumulative tree mortality over the 13-y postfire period in mixed-conifer study site at Crater Lake National Park. Note that the time axis is not linear.**

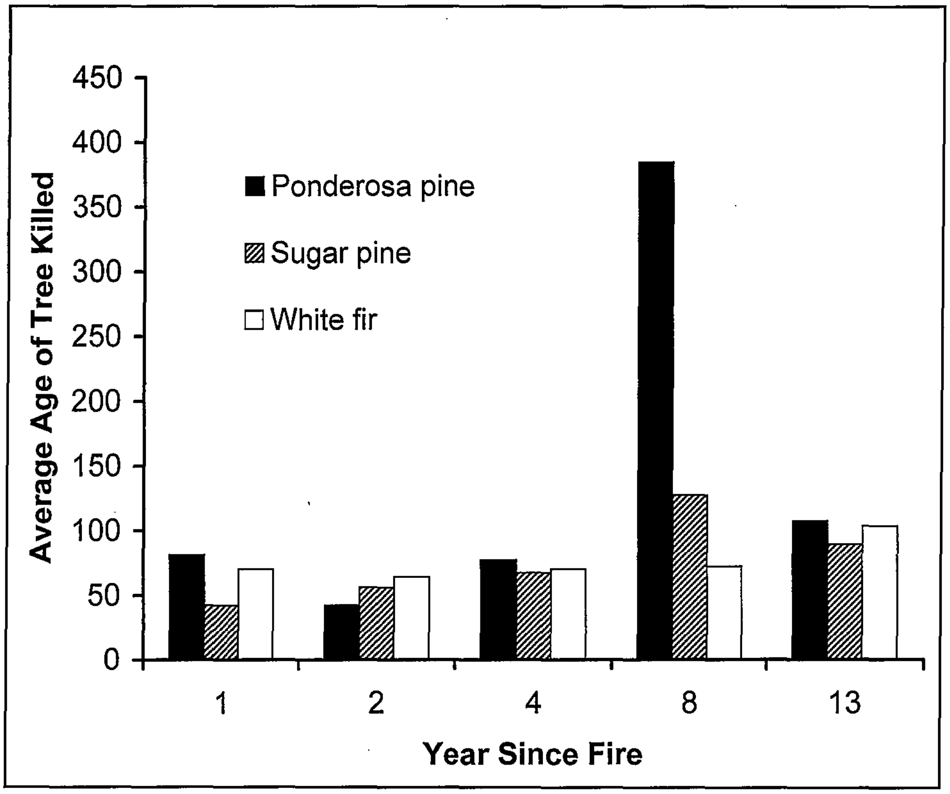


**Figure 3. Average age (y) of trees that died in each postfire monitoring period in mixed-conifer study site at Crater Lake National Park.**

cult to attribute tree mortality directly to the fire or to fire-stressed trees being attacked by bark beetles. Up to postfire year 4, bark beetles (*Dendroctonus* spp.) were actively killing both of the pine species, and fir engraver (*Scolytus ventralis* LeConte) was responsible for white fir mortality (Thomas and Agee 1986). These agents continued to be active in subsequent years, but another synergistic disturbance, drought, was also present (Figure 5). Every year but one from year 4 to year 13 had below-normal precipitation. It is not possible to separate out the stress caused by fire from that caused by drought in sustaining bark beetle activity in the postfire period. Regionally, over 75% of the fir engraver mortality to white fir between 1979 and 1994 occurred between 1988 and 1993, while over 40% of the mountain pine beetle mortality to pines over the same period occurred in 1985–86 (Oregon Department of Forestry, Salem, unpubl. data).

Sugar pine was most sensitive of the three tree species to the prescribed fires, with 59% of the total pre-fire density removed after 13 y. White fir was second at 52%, and ponderosa pine was least sensitive at 28% mortality of the pre-fire density. When only trees greater than 20 cm dbh were included, the order of mortality remained the same: sugar pine at 36%, white fir at 25%, and ponderosa pine at 17%. This compares to mortality on unburned areas of 10%, 4%, and 14%, respectively, for trees of the three species greater than 20 cm dbh. Chi-square analysis indicated that the frequency of mortality in burned areas differed from that in unburned areas for white fir ($\chi^2 = 53.6$, $P < 0.0001$) and for sugar pine ($\chi^2 = 3.87$, $P < 0.05$), but not for ponderosa pine ($\chi^2 = 0.12$, $P = 0.73$).

This single prescribed fire event reduced tree density in the unlogged forest to close to the historic (1900 A.D.) level (Table 3). The residual pines were somewhat underrepresented compared to the 1900 level, due to the postfire bark beetle mortality, but white fir was slightly above the 1900 level. In the logged forest, where pines had been selectively removed, postlogging regeneration survived the fire and both sugar pine and ponderosa pine density

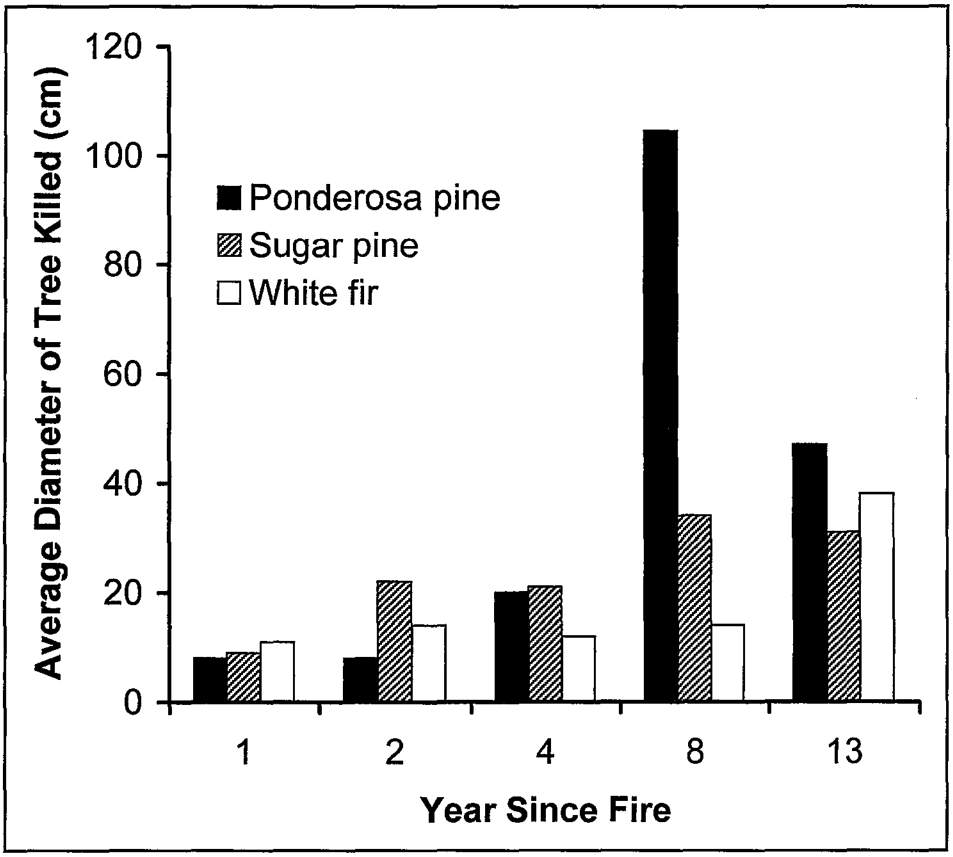


**Figure 4. Average diameter (dbh in cm) of trees that died in each postfire monitoring period in mixed-conifer study site at Crater Lake National Park.**

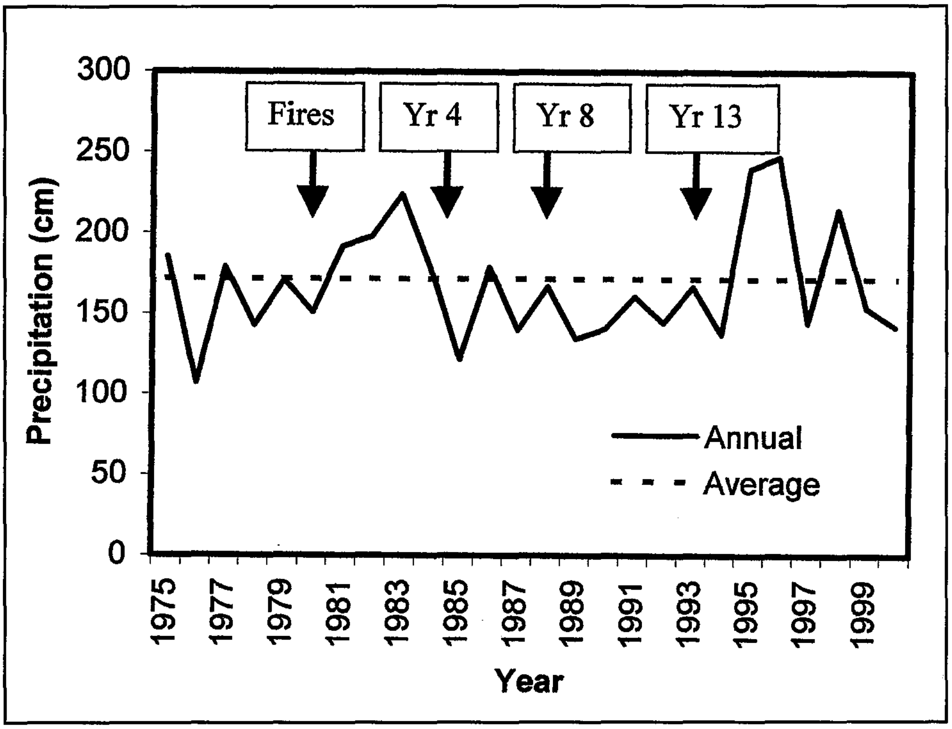


**Figure 5. Deviations from average precipitation during the postfire monitoring period. Weather station is at Crater Lake headquarters, about 600 m higher in elevation.**

exceeded the 1900 stocking level in the adjacent stands. White fir had stocking about 50% higher than the 1900 stocking level in the adjacent stand.

The projected effects of a second prescribed fire were estimated through the use of FOFEM (Reinhardt et al. 1997). A second prescribed fire with a flame length of 0.6 m would reduce stocking below the historic levels in both logged and unlogged stands (Table 3), and would kill 68% of the post-1900 cohort that remained after the first fire. Flame lengths of 1.2 and 1.8 m would kill 86% and 96% of this cohort, but are at the margin of usual safe control, and would possibly affect the vigor of or kill larger and older trees, as did the first fire. FOFEM assumes that the fire uniformly affects the entire area of the stand, and where fires are patchy and miss some areas, FOFEM will overpredict mortality.

## DISCUSSION

Although data for repeated fires is sparse, mortality of larger and older trees from fires with low flame lengths is largely unexplained. In the Southwest, mortality of large ponderosa pines after multiple fires has been substantial (Sackett and Haase 1998). Excessive crown scorch from fires of high intensity is one possible cause of mortality. Smoldering combustion from excessive fuel buildup has been targeted as a possible cause where crown scorch is not high (Swezy and Agee 1991, Haase and Sackett 1998, Stephens and Finney 2002). This smoldering can kill fine roots and girdle the cambium at the tree base. The extended smoldering combustion from duff should be less during a second prescribed fire applied within a decade or two of the first, but smoldering from coarse woody debris may be about the same as, or perhaps more than, during the first fire. In the first prescribed fire of this study, substantial coarse woody debris was consumed (~30 Mg $ha^{-1}$ of 67 Mg $ha^{-1}$) but at year 4 near-future totals were estimated to exceed pre-fire levels based on mortality up to year 4 (Thomas and Agee 1986). Additional coarse woody debris due to mortality was added in the postfire year 5–year 13 period, so that at year 20, fuel loading of < 100-h timelag fuels is 98% of the pre-

Table 3. Comparison of historic (1900 A.D.) tree density (trees $ha^{-1}$) in unlogged areas to that in burned areas (logged and unlogged) after 13 y and after a simulated second prescribed fire (using a 0.6-m flame length and assuming 100% coverage by the fire).

| Species | Historic Forest | Burned Forest (Year 13) | | After 2nd Prescribed Fire | |
|---|---|---|---|---|---|
| | | Unlogged | Logged | Unlogged | Logged |
| *Pinus ponderosa* | 28 | 22 | 34 | 21 | 18 |
| *Pinus lambertiana* | 28 | 20 | 30 | 16 | 7 |
| *Abies concolor* | 208 | 222 | 328 | 131 | 139 |
| **Total** | 264 | 264 | 392 | 167 | 164 |

fire load, and for > 100-h timelag fuels is 81% of the pre-fire load, with substantial snag material still standing and yet to be added to the downed wood fuel load.

Selection of the year 1900 as the reference condition for this study was arbitrary. It represents but one point in time that may in fact be unique (Landres et al. 1999, Stephenson 1999). At this site, one unusually long fire return interval in 1790–1820 A.D. appears to be related to a pulse of successful white fir regeneration that survived subsequent fires. Had 1800 been the reference point, that regeneration would have been absent from the > 5.5 cm dbh class in the late twentieth century. Choosing a reference point that far back in time introduces the additional error due to trees that died in the interim and that may have largely decayed or were consumed by fires during 1800–1900. Although 1900 is an arbitrary point in time, it is within the historic range of variability and acts as a better reference condition than absence of any historic reference. The conditions of that time do, however, need to be interpreted as a point within a distribution and not necessarily as a mean, median, or absolute target.

Comparing mortality in burned areas must take into account other sources of mortality in unburned areas. Unburned areas have been "treated" with fire exclusion for a century and are under stress from the presence of abnormally high tree densities. In times of drought, trees in unburned areas should be under considerable stress, and unusually high levels of mortality should be expected. In this study, burned areas that had reduced density suffered similar or higher mortality of the large trees (> 20 cm dbh) than unburned areas, suggesting that trees in burned areas are significantly stressed from the effects of a first prescribed fire. White fir, because of its initial high density in small size classes, was reduced relative to unburned areas. The sugar pine sample size was small but also showed significant differences for large-tree mortality between burned and unburned areas. Sugar pine appears to be vulnerable to low-intensity but long-smoldering fires in other areas (Haase and Sackett 1998, Stephens and Finney 2002). Mortality of ponderosa pine appears to have been similar to that in unburned areas, probably because most of the trees were large and burned in the autumn. Swezy and Agee (1991) showed that spring fires at Crater Lake were associated with much more ponderosa pine mortality than autumn burns.

Prescribed fire should be considered a periodic treatment for ecosystem restoration in dry forest types where historic fires were frequent. However, there are trade-offs between objectives for fuel reduction and objectives for stand structure. A second fire in our study stands would be effective in reducing fuel, much of which was created by the first fire, but is predicted to bring tree density below targeted historic levels for forests at this location even if direct mortality only is considered. Normally, reducing tree density below 170 trees $ha^{-1}$ would be consistent with meeting ecological objectives in dry forests, but the historic tree density in this local forest was rather high compared to other mixed-conifer forests (McNeil and Zobel 1980, Harrod et al. 1998). Where the first fire so significantly reduces tree density, and mortality continues over time, fuel reduction objectives for a second fire may need to be compromised to retain residual trees. One technique to reduce mortality at a stand level is to ensure that the second fire is as patchy as the first (20%–45% unburned area). In most mixed-conifer forests, fire will leave unburned patches, and these can be preserved by avoiding second and third pass-throughs with drip torches in attempts to have complete coverage of the prescribed fire.

A broader conceptual framework to be considered in prescribed fire reintroduction is whether structure or process objectives should be paramount (Agee and Huff 1986). In the former, desired future conditions based on species, size, and density would be the target, while in the latter, desired future dynamics of fire (frequency, intensity, season, extent [in this case, patchiness], and their ranges) and other disturbances (particularly insects) would be the management target. Although these are usually considered mutually exclusive objectives, they can be complementary to one another (Stephenson 1999). Both the structural goals and the process goals are imperfect. Structural solutions can be criticized as suffering from the "snapshot in time" approach—an attempt to recreate a structure that may be unusual within the forest type's historic range. The process goal, if implemented without regard to structure, may yield structures well outside the historic range. A solution that considers both may result in more sustainable conditions.

The principles of adaptive management involve learning by doing, and resources management can be considered essentially an experiment (Walters 1986, Hilborn 1992). Long-term monitoring of prescribed fire, such as occurred in Arizona (Sackett and Haase 1998) and in this study, will enable learning that can be applied to future prescribed fire experiments.

## ACKNOWLEDGMENTS

Analysis was supported by USDA Forest

Service Joint Venture Agreement PNW 01-JV-11261900-033, funded through the Joint Fire Sciences Program. Original research was supported by National Park Service contract CX-9000-1-E002, Pacific Northwest Region, Seattle. I appreciate the use of data collected by T. Thomas, help in collecting subsequent year data from R. deGouvenain and D.M. Swezy, and reviews of the manuscript by M. Huff, R. Lolley, D. Perrakis, and M. Rasmussen. The Editorial Board of the *Natural Areas Journal* also provided valuable comments.

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