RESTORING NORTHERN SIERRA NEVADA MIXED CONIFER FOREST COMPOSITION AND STRUCTURE WITH PRESCRIBED FIRES OF VARYING INTENSITIES

Lars Schmidt[1], **Marco G. Hille**[2] and **Scott L. Stephens**[3]*

[1]Institute of Forest Management and Yield Science, Büsgenweg 5,
University of Göttingen, 37077 Göttingen, Germany

[2]Centre for Ecosystem Studies, Forest Ecology and Forest Management Group, Wageningen University and Research Centre. P.O. Box 47, 6700 AA Wageningen, The Netherlands

[3]Division of Ecosystem Science, Department of Environmental Science, Policy, and Management, 137 Mulford Hall. University of California, Berkeley, CA, 94720-3114, USA
*Corresponding author: 510-642-7304; fax 510-643-5438; stephens@nature.berkeley.edu

ABSTRACT

The effectiveness of low and high intensity prescribed fires in restoring the composition and spatial structure in a mixed conifer forest in the Northern Sierra Nevada is examined. The overstocked pre-fire stand had 480 trees ha^{-1}, a basal area of 39.5 m^2 ha^{-1}, and an inverse J-shaped diameter distribution with an average dbh of 23 cm. Prescribed fires produced tree mortality in the lower and intermediate dbh-classes and affected trees up to 40 cm dbh. In the low intensity prescribed fire, total tree density was reduced by 33% and basal area by 3% three years after fire. In the high intensity prescribed fire, total tree density and basal area was reduced by 73% and 20%, respectively, two years after the fire. The high intensity prescribed fire changed the dbh distribution from inverse-J to bell-shaped. The spatial structure of the stand burned under low intensity, assessed with the Winkelmass-method, was not altered. In the area burned with high intensity prescribed fire, post-fire tree mortality created gaps in the overstory and led to a higher degree of spatial clumping, attributes that are similar to some old-growth stands. The low-intensity prescribed fire was not intense enough to change forest structure significantly. Prescribed fires of at least moderate intensity may be needed to begin to restore current mixed conifer stands to pre-settlement conditions. Burning the accumulated surface fuels created from fire suppression and past harvesting with a low intensity fire may be useful in reducing fire hazards but this may not produce other restoration goals of lower tree densities and canopy gaps.

Keywords: Forest restoration, forest structure, fireline intensity, fire severity, fuel, canopy gaps

Citation: Schmidt, L.; M.G. Hille and S.L. Stephens. 2006. Restoring northern Sierra Nevada mixed conifer forest composition and structure with prescribed fire. *Fire Ecology:* 2(2): 20-33.

INTRODUCTION

Before Euro-American settlement, frequent fires influenced the composition, structure, and dynamics of mixed-conifer forests in the Sierra Nevada, California. The prehistoric fire regime consisted of mostly low to moderate intensity fires occurring every 6 to 12 years, typically occurring in late summer and fall (Skinner and Chang 1996, Stephens and Collins 2004, Moody et al. 2006). Due to the frequency of fire occurrence and subsequent fire-caused mortality, primarily in the smallest tree cohort, most areas of the Sierra Nevada mixed conifer forest type (approximately 5900 km², Davis and Stoms 1996) probably had low densities of understory trees and shrubs.

Under the pre-settlement fire regime, fires most often burned under low-moderate intensity with patches of high intensity. In these patches, direct fire-induced mortality and subsequent bark beetle (*Dendroctonous* spp.) attack on the damaged trees lead to scattered openings within a matrix of surviving trees (Stephenson et al. 1991, Stephens et al. 1999). Early reports on the composition and structure of mixed conifer stands describe them as relatively open with large trees distributed in clusters (Stephens and Elliott-Fisk 1998, Stephens 2000), and gaps of 0.1 to 0.25 ha in between (Sudworth 1900). Studies that have reconstructed stand composition and structure of these stands report much lower stem densities than today, larger trees, and a strong clumping of overstory trees (Harrod et al. 1999) (Figure 1).

Human activities since the mid 1800's have strongly changed most mixed conifer forest stands and simplified forest structures (SNEP 1996, Husari et al. 2006, Stephens and Sugihara 2006). Many stands were clear-cut and dense natural regeneration followed this disturbance (McKelvey and Johnston 1992, Husari and McKelvey 1996, Skinner and Chang, 1996, Elliott-Fisk et al. 1996, Stephens and Collins 2004). With strong fire suppression policies and infrastructure (Stephens and Ruth 2005), fire was excluded from stand development. As a result, dense overstocked and even-aged stands grew on top of a quickly accumulating surface fuels (Weatherspoon and Skinner 1995, Tappeiner and McDonald 1996).

As a consequence of the high stand densities and low light levels below the canopy, tree species composition shifted towards shade tolerant species that are able to regenerate in partial or full shade (e.g. incense-cedar (*Calocedrus decurrens* Torr.) and white fir (*Abies concolor* Gord. and Glend.)) (Parsons and DeBendeetti 1979). Changes in forest structure have increased the probability of high intensity, stand-removal

Figure 1. Schematic cross section of a typical pre-settlement mixed conifer forest in the Western Sierra Nevada. From the Sierra Nevada Ecosystem Project (SNEP 1996, drawing by Robert Van Pelt).

low-intensity surface fires of the past. A major forest management issue in the Sierra Nevada is currently focused on fire hazard reduction by silvicultural means and increasing the resilience against fire (SNEP 1996).

The main goal of these silvicultural methods is to reduce tree densities within the stand, especially in the low- and medium-diameter classes, and to shift species composition to include more shade intolerant species (Oliver et al. 1996). The common methods used to reach this goal are mechanical treatments (thinning from below with or without timber utilization), prescribed fire, or a combination of these methods (Reinhardt and Ryan 1998, Stephens 1998, Agee and Skinner 2005).

Mechanical treatments can be successful in reaching desired stand densities, species composition, and structure. In contrast, they are seldom cost-effective unless there is a large tree component removed, may cause soil compaction, and can create additional activity fuels if no fuel treatment is applied after the thinning. Mechanical treatments that modify the overstory without treating natural and activity fuels can result in potential fire behavior that is more severe than the untreated forest (Stephens 1998).

Application of prescribed fires can reduce fuel loads significantly (van Wagtendonk 1996) and do not require large-scale mechanized equipment, but are harder to control and their effects are more difficult to predict. The effects of the fire on stand structure and stand composition can be highly variable; the intensity, fuel consumption, and season of the applied fire determines the ecological outcome and its consistency with restoration goals (Covington et al. 2001, van Mantgem et al. 2003, Fulé et al. 2004). Fire intensity, pre-fire fuel loads and consumption, and stand structure are the major factors that are linked to fire effects, such as tree mortality (Stephens and Finney 2002, Kobziar et al. 2006).

The restoration of mixed-conifer forests is complicated by fuel accumulation and profound changes in stand structure. Therefore, the question arises, whether natural stand structures can be restored with prescribed fire alone? Some studies suggest that only a combination of cutting and prescribed fire can produce the desired open stand structures (Fiedler et al. 1998). The objective of this study was to assess how prescribed fires of low and moderate intensities can be used to restore pre-historical forest structures. The reduction of stand density and change in spatial structure is quantified and compared to historic stand data to evaluate the success of this restoration approach.

METHODS

Study Area

The experimental area is compartment 292 at the University of California Blodgett Forest Research Station located in the western Sierra Nevada, California, U.S.A. (N 38°54'30; W 120°40'25; elevation 1400 m a.s.l.). This stand is managed as a reserve area with no harvesting occurring in the last 25 years. A detailed description of the history and present conditions at Blodgett Forest Research Station can be found in Olson and Helms (1996).

The stand sampled represents a typical mixed-conifer forest with five conifer species (ponderosa pine [*Pinus ponderosa* Laws.], sugar pine [*Pinus lambertiana* Dougl.], Douglas-fir [*Pseudotsuga menziesii* Mirb. Franco], white fir, and incense-cedar, and two broadleaved tree species (California black oak [*Quercus kelloggii* Newb.], and tanoak [*Lithocarpus densiflorus* Hook. and Arn.].

Two prescribed fires with different intensities were applied in this stand. A low-intensity fire with flame lengths of 0.5 to 1 m burned the southern portion of compartment 292 in October, 2001. This prescribed fire was set three days after the first significant fall rainfall (25 mm) that preceded three months of no precipitation. At the time of the burn, the air temperature was 16°C, relative humidity was 62%, and duff moisture varied from 30-65% (Hille and Stephens 2005). The area burned by this prescribed fire was approximately 3 ha.

The second prescribed fire was conducted in October 2002 under much drier conditions (average duff moisture at 12%, temperature of 22°C and relative humidity of 38%), resulting in higher fire intensity with flame lengths between 1 and 2.5 m. Both fires were ignited with strip-head fires with uphill runs of 3-5 m between strips. The second prescribed fire burned an area of approximately 20 ha.

Sampling Procedures

Forest stand inventories were conducted using 24 circular plots with a 11.3 m radius (area = 0.04 ha) in July 2003 and 2004. The plot centers were systematically located on a 35 x 35 m grid over the two burned areas; the starting point of each grid was randomly placed. Within each plot, all trees at or above 2.5 cm dbh were sampled. Variables measured included species, dbh, height, and pre- and post-prescribed fire crown base height. Chi-square tests were applied to test for differences in the pre- and post-fire dbh-distribution for both areas (low and high intensity prescribed fires) of the stand.

Additionally, the Winkelmass method (Gadow and Fuldner 1992, Fuldner 1995, Gadow et al. 1998, Gadow and Hui 2002, Aguirre et al. 2003) was used to assess spatial patterns, which describes the degree of regularity or irregularity of the spatial distribution of the four nearest neighbors of a reference point (hereafter referred to as the *structural group of four*). The concept is based on the classification of the angles α_j (j = 1,2,3,4) between the immediate neighbors of the 4 trees with reference to the plot centers. An immediate neighbor is the next tree following a given clockwise direction. As a reference quantity, the standard angle α_0 is used (with four neighboring trees α_0 equals 360/4 = 90 degrees). By comparing the angles (α_j) between the four trees with α_0 we can derive a binary random variable v_j, which is “0” for angles ≤ 90 degrees and “1” for angles > 90 degrees. The Winkelmass W_i is defined as the fraction of the angles α_j which are smaller than 90 degrees (Equation 1).

$W_i = 0$ indicates that the trees in the vicinity of the reference tree are positioned in a regular pattern, whereas $W_i = 1$ displays an irregular or clumped distribution. $W_i = 0.5$ approximates a random distribution of the four neighboring trees. All possible values of W_i and examples for corresponding tree distributions are shown in Figure 2.

On a stand level, the average *Winkelmass* $\overline{W}$ (Equation 2) of several plots and its frequency distribution is used to analyze spatial structure. To determine spatial patterns, the average Winkelmass is compared to simulated Winkelmass calculations from regular, random and clumped stand structures (Table 1).

Equation 1.

$$W_i = \frac{1}{4}\sum_{j=1}^{4} v_j \quad \text{with} \quad v_j = \begin{cases} 1, & \alpha_j < \alpha_0 \\ 0, & \text{otherwise} \end{cases} \quad \text{and} \quad 0 \le W_i \le 1 \qquad (1)$$

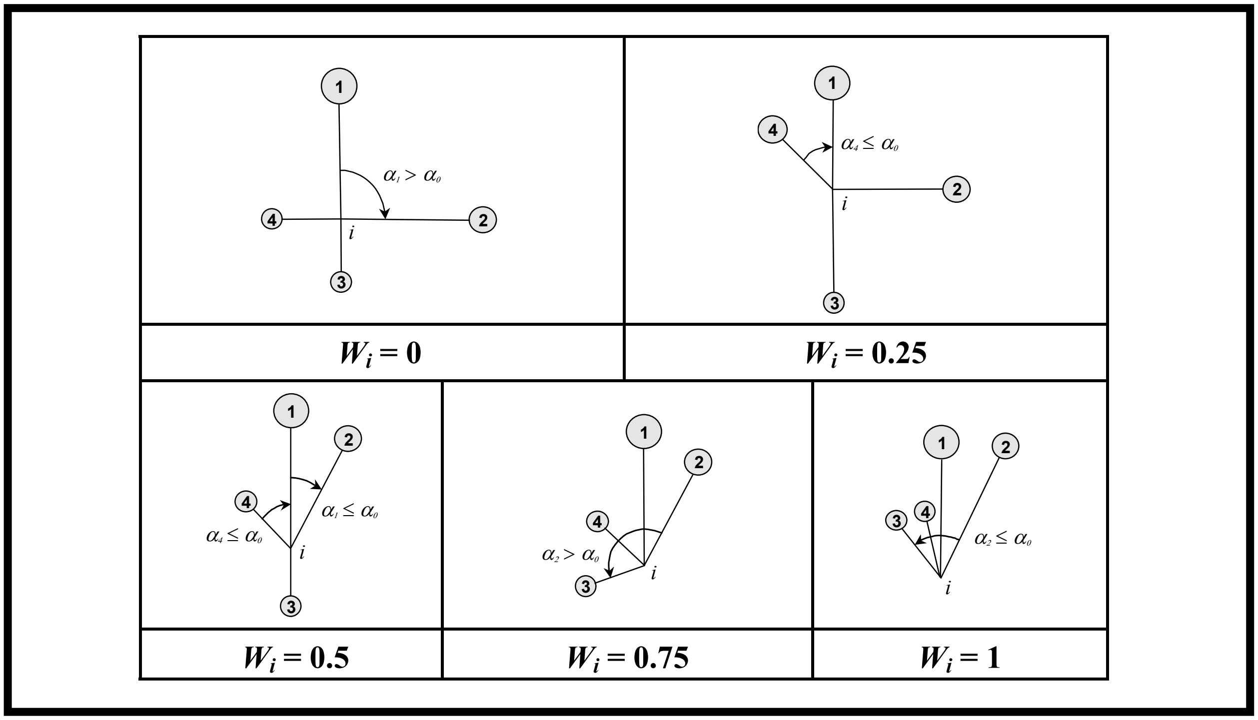

Figure 2. Possible values of W_i at a sample point. There are always two angles between two neighboring trees, either clockwise or counter-clockwise. For calculation of W_i, the smaller of the two angels is used (Gadow et al. 1998, Gadow and Hui 2002).

Equation 2.

$$\overline{W} = \frac{1}{N}\sum_{i=1}^{N} W_i \qquad (2)$$

with W_i = *Winkelmass* of the *i*-th reference tree
N = number of reference trees

Table 1. Mean Winkelmass value thresholds on a stand level and their corresponding spatial descriptions (following Gadow and Hui, 2002).

$\overline{W}$	Description
0	regular
0.25	
0.5	random
0.75	
1	clumped

RESULTS

Stand Composition

Pre-fire, five conifer and two broad-leafed species were found in the two areas of compartment 292, with similar densities and sizes (Tables 2 and 3). A dense understory (mainly white fir and incense-cedar) was found in both stands. The overstory in compartment 292 consists mainly of ponderosa pine and sugar pine, with some Douglas-fir and white fir reaching the upper canopy layer. The overstory trees reached dbh of more than 70 cm and heights up to 45 m. A second stratum consists of intermediate white fir, Douglas-fir, and incense-cedar. Below, a third stratum of suppressed trees (mainly incense-cedar) and advanced regeneration of incense-cedar and white fir was found. On a compartment level, the total stand density was 495 ha^{-1} (trees above 2.5cm dbh), with a basal area of 40m^2 ha^{-1} (Tables 2 and 3).

Fire induced tree mortality reduced stem density by 33% (from 479 ha^{-1} to 323 ha^{-1}) in the low-intensity prescribed fire two years after the fire, and by 73% (from 516 ha^{-1} to 138 ha^{-1}) in the area of the high-intensity prescribed fire in the first year after the fire. In the following year, tree mortality was much lower and reduced total stem density by an additional 2% of the trees in the low intensity burn; second-year mortality in the high intensity burn was 13% of the trees that were still alive after the first post-fire year. Large numbers of incense-cedar and white fir were killed, especially by the high intensity prescribed fire, whereas the number of sugar pine, ponderosa pine, and Douglas-fir trees remained almost unchanged (Tables 2 and 3).

The change in total basal area was relatively small, with a reduction due to fire-induced mortality of 3% in the low intensity burn (Table 2) and 20% in the high intensity burn (Table 3). Similar to the change in tree

Table 2. Stand variables (mean ± standard deviation) for the area burned by a low intensity prescribed fire of compartment 292 at Blodgett Forest Research Station before, and three years after the burn, calculated from inventory data from 12 circular plots.

	Pre-fire			Post-fire		
Tree species	Stand density	dbh	Basal area	Stand density	dbh	Basal area
	N (ha^{-1})	(cm)	(m²ha^{-1})	N (ha^{-1})	(cm)	(m²ha^{-1})
Black oak	13.4(1.4)	41.6(9.1)	1.9(0.2)	13.4(1.4)	41.6(9.1)	1.9(0.2)
Douglas-fir	48.5(3.5)	29.2(21.2)	5.4(0.5)	37.1(3.0)	35.5(20.7)	5.3(0.5)
Incense-cedar	243.5(14.1)	18.8(3.4)	9.1(0.4)	158.9(9.6)	23.9(4.5)	8.4(0.4)
Ponderosa pine	3.1(0.6)	75.3(25.2)	1.5(0.1)	3.1(0.6)	75.3(25.2)	1.5(0.1)
Sugar pine	12.4(1.71)	80.4(24.4)	6.9(0.9)	12.4(1.4)	80.4(24.4)	6.9(0.9)
Tan oak	11.3(3.2)	34.4(-)	1.1(-)	10.3(3.0)	35.5(-)	1.1(-)
White fir	146.5(6.5)	28.1(11.9)	17.1(0.6)	102.1(5.2)	36.7(-)	16.5(0.6)
Total	478.3(12.0)	25.7(6.0)	43.0(0.8)	337.3(7.9)	32.6(7.0)	41.6(0.7)

Table 3. Stand variables (mean ± standard deviation) for the area burned by a high intensity prescribed fire of compartment 292 at Blodgett Forest Research Station before, and two years after the burn, calculated from inventory data from 12 circular plots.

	Pre-fire			Post-fire		
Tree species	Stand density	dbh	Basal area	Stand density	dbh	Basal area
	N (ha^{-1})	(cm)	(m²ha^{-1})	N (ha^{-1})	(cm)	(m²ha^{-1})
Black oak	1.9(0.4)	50.8(49.2)	0.57(0.4)	-	-	-
Douglas-fir	14.3(1.0)	26.9(24.5)	1.74(0.3)	4.8(0.7)	59.3(22.8)	1.6(0.4)
Incense-cedar	260.9(12.0)	19.4(4.8)	10.6(0.3)	76.2(3.4)	31.7(4.8)	6.7(0.3)
Ponderosa pine	9.5(0.7)	73.6(12.0)	4.3(0.2)	8.6(0.7)	74.3(12.0)	3.9(0.2)
Sugar pine	9.5(1.2)	75.3(18.7)	4.6(0.4)	8.6(1.2)	77.7(15.2)	4.4(0.4)
Tan oak	4.8(1.4)	9.9(-)	0.1(-)	-	-	-
White fir	215.2(11.2)	17.4(13.5)	13.8(0.6)	49.5(2.6)	50.4(18.0)	11.7(0.6)
Total	516.1(18.4)	20.8(8.7)	35.7(0.9)	147.7(6.1)	44.1(10.1)	28.3(1.0)

density, basal area of incense-cedar and white fir were reduced the most (8% and 3% in the low, and 37% and 15% in the high intensity fires, respectively).

Diameter Distribution

The diameter distribution for the pre- and post-fire stands indicates that most of the mortality occurred in the lower diameter classes. In the area burned by the low intensity prescribed fire, 68% of trees smaller than 10 cm dbh, and 38% of trees between 10 and 20 cm dbh, were killed in the first two years after the fire (Figure 3). In the larger diameter classes, almost no mortality occurred. In the third year after the fire, almost no additional mortality was observed. Pre- and post-fire (third year) diameter distributions in the low intensity prescribe fire were significantly different (χ^2=227, df=11, p<0.001).

In the area burned by a high intensity prescribed fire, almost no trees in the lower dbh-classes (< 20 cm) survived the fire. Even in the larger diameter classes of up to 40 cm dbh, high mortality occurred (Figure 3). Almost all mortality was observed in the first year after the burn, in the second year, a few additional small trees died. Pre- and post-fire diameter distributions two years after fire were significantly different (χ^2=0.25E+5, df=11, p<0.001).

Winkelmass Tree Positions

Overall, the structural groups of four had an average *Winkelmass* value of 0.61 (low intensity), and 0.63 (high intensity), before prescribed burning. Using the classification system of Hui and Gadow (2002), the pre-fire stand structure was slightly clumped. In the post-fire stand, the average *Winkelmass* value for all structural groups of four remained the same in the low intensity burn, while in the high intensity, the average *Winkelmass* value increased to 0.67, indicating a higher degree of clumping. Pre- and post-fire frequency distributions of *Winkelmass* values were not significantly different in low intensity burn (Chi-square test with df=3; χ^2 =0.6, p=0.896), but were in the high intensity burn (χ^2 =12.7, p=0.005).

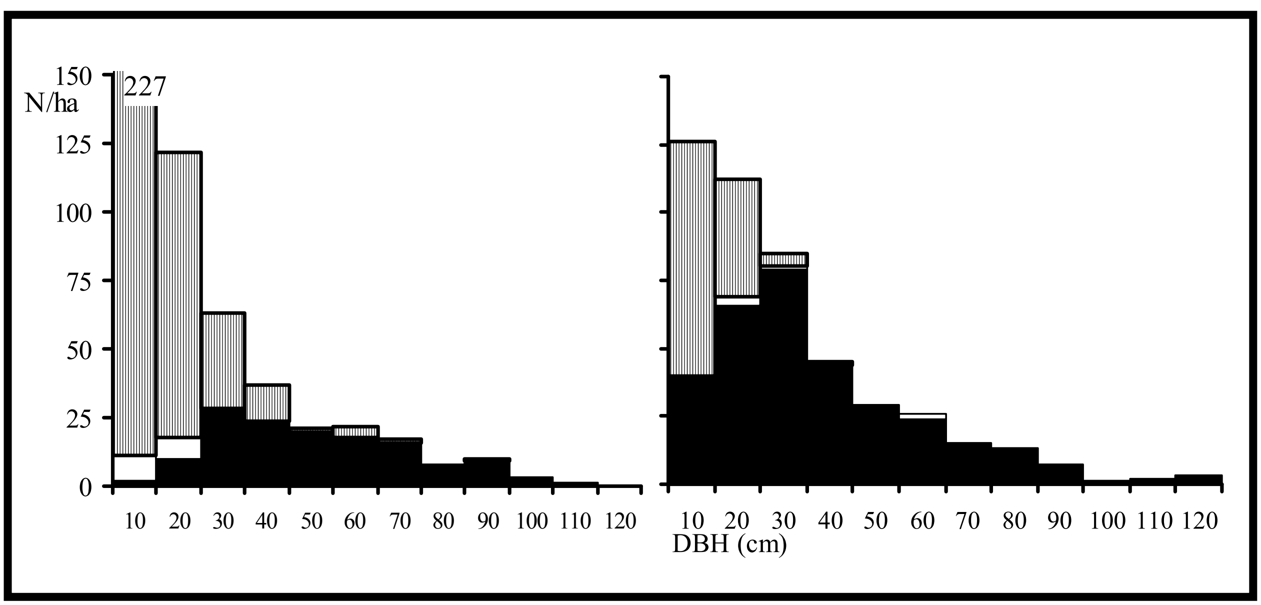

Figure 3. DBH- frequency distribution pre-fire (entire bars), one year (black bars + empty bars), and two years (black bars) after fire, in the high intensity burn (left figure), and the low intensity burn (right figure) in compartment 292 at Blodgett Forest Research Station.

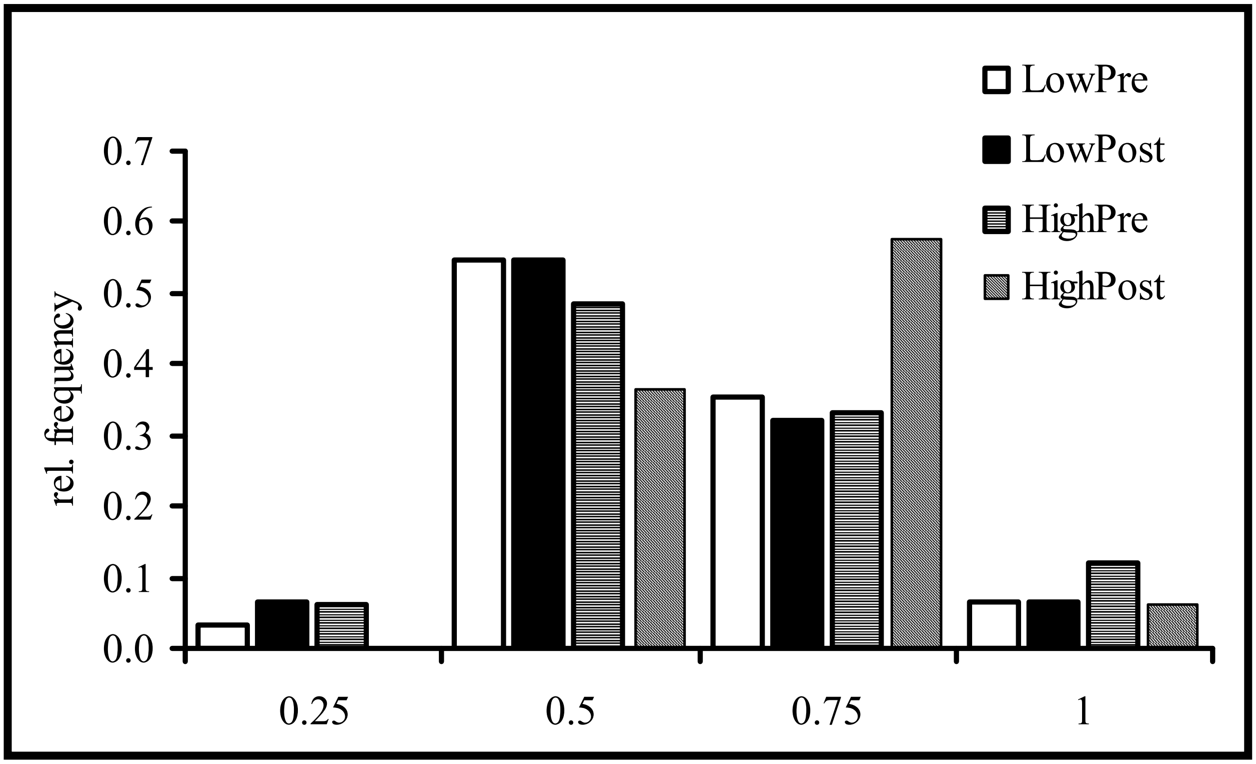

Figure 4. Relative frequency distributions of Winkelmass values in the pre- and post-fire stands for the high and low intensity prescribed fires. Number of sampled structural groups is 33 for each of the two burns.

stands before and after burning (Figure 4). In the low intensity burn, the frequency distribution of Winkelmass values was not significantly different from the pre-fire situation and most values center on 0.5 (random distribution). In the high intensity burn, a reduction of structural groups with a *Winkelmass* of 0.5 and a higher percentage of groups with a value of 0.75 was observed (Figure 4). Additionally, no structural groups with *Winkelmass* values of 0.25 were detected after the high intensity prescribed fire.

DISCUSSION

Tree density decreased 33% in the low intensity prescribed fire and by 73% in the high intensity prescribed fire. Tree density in the low intensity burn three years after the fire is still above estimated pre-settlement densities of approximately 220 trees ha^{-1} in some old-growth mixed conifer stands in the northern and central Sierra Nevada (Stephens 2000). In the high intensity burn, tree density two years after the fire is below this reference value.

Most trees died directly after the prescribed fires. In the low intensity burn, the mortality level was 29% the second year after fire, and dropped to 2% in the third year after the fire. In the high intensity burn, the mortality level was highest the first year after the fire (73%), but decreased sharply in the second year (13%). We expect that over 95% of prescribed fire induced tree mortality had occurred for all species in this study (Stephens and Finney 2002)

Fire-induced mortality mostly affected trees in lower diameter classes, as shown in this and previous studies (van Wagtendonk 1983, Ryan and Reinhardt 1988, Stephens and Finney 2002). The strong correlation evident when comparing the post-fire dbh frequency distributions for the two prescribed fires (Figure 3). High mortality occurred in the understory of both prescribed fires. The understories of both fire units before prescribed burning was applied were dominated by white fir and incense-cedar, after fire the densities of these shade tolerant species were strongly reduced (Tables 2 and 3).

Sugar pine and ponderosa pine, which were present mainly in the overstory, experienced very little mortality. Compared to forest stand data collected by George Sudworth in 1900 (Stephens 2000), who sampled several uncut mixed conifer stands in the Sierra Nevada (including one stand within present day Blodgett Forest, Bob Heald personal communication 2005), species composition of the overstory after both fires still has higher proportions of white fir and incense-cedar. The high intensity prescribed fire produced species compositions closer to that recorded in 1900, primarily because of a relatively large reduction in white fir and incense-cedar trees (Tables 2 and 3). Total basal area was only slightly reduced by the low intensity prescribed fire and this stand is still dominated by shade tolerant species (Table 2).

The higher mortality in the lower diameter classes strongly altered the shape of the post-fire diameter frequency distribution (Figure 3). Both pre-fire stands had an inverse J-shaped diameter frequency distribution and this changed to a bell-shaped distribution after fire, particularly with high intensity prescribed fire (Figure 3). Compared to Sudworth's data (1900), our post-fire stands still have fewer large trees and have more trees in the dbh-classes below 70 cm, especially in the area that experienced the low-intensity fire. However, high intensity prescribed burning did produce a post-fire dbh distribution that is more similar to that recorded by Sudworth in 1900. The lack of large trees in the overstory was primarily created by past ‘sanitation harvests’ that removed the largest trees to open growing space for younger trees (Olson and Helms 1996, Tappeiner and McDonald 1996).

It has been hypnotized that old-growth mixed conifer forests contained regeneration patches, were local high fire intensities created gaps, and stimulated tree recruitment (Stephenson et al. 1991, SNEP 1996, Stephens et al. 1999). The high intensity prescribed fire did create some gaps as shown by the 150 m randomly placed inventory transect (Figure 5). We believe that the high intensity prescribed fire applied in this study was an appropriate treatment to begin to recreate a more natural mixed conifer forest structure. We realize that primary tree mortality is a function of fireline intensity and fuel consumption (Stephens and Finney 2002). This study focused on the former process but consumption of ground fuels can also kill trees.

The spatial arrangement of trees (assessed with the *Winkelmass* value) was not changed by the low intensity prescribed fire, but was affected by the high intensity prescribed fire where post-fire stand structure is more clumped (Figure 4). In the high intensity prescribed fire, mortality was not spatially homogenous. Groups of small and intermediate sized trees were killed by the fire and this produced the clumped *Winkelmass* values (Gadow and Fuldner 1992, Fuldner 1995, Gadow et al. 1998, Gadow and Hui 2002; Aguirre et al. 2003). In the grid points within these patches of dead trees, the four closest living trees outside this 'mortality patch' are much more likely to be in the same direction, and therefore, the *Winkelmass*-value results in a higher degree of clumping.

This study suggests that prescribed fires of at least moderate intensity are needed to begin to restore mixed conifer stands to pre-settlement conditions. Fires of this type kill the majority of understory trees and can open

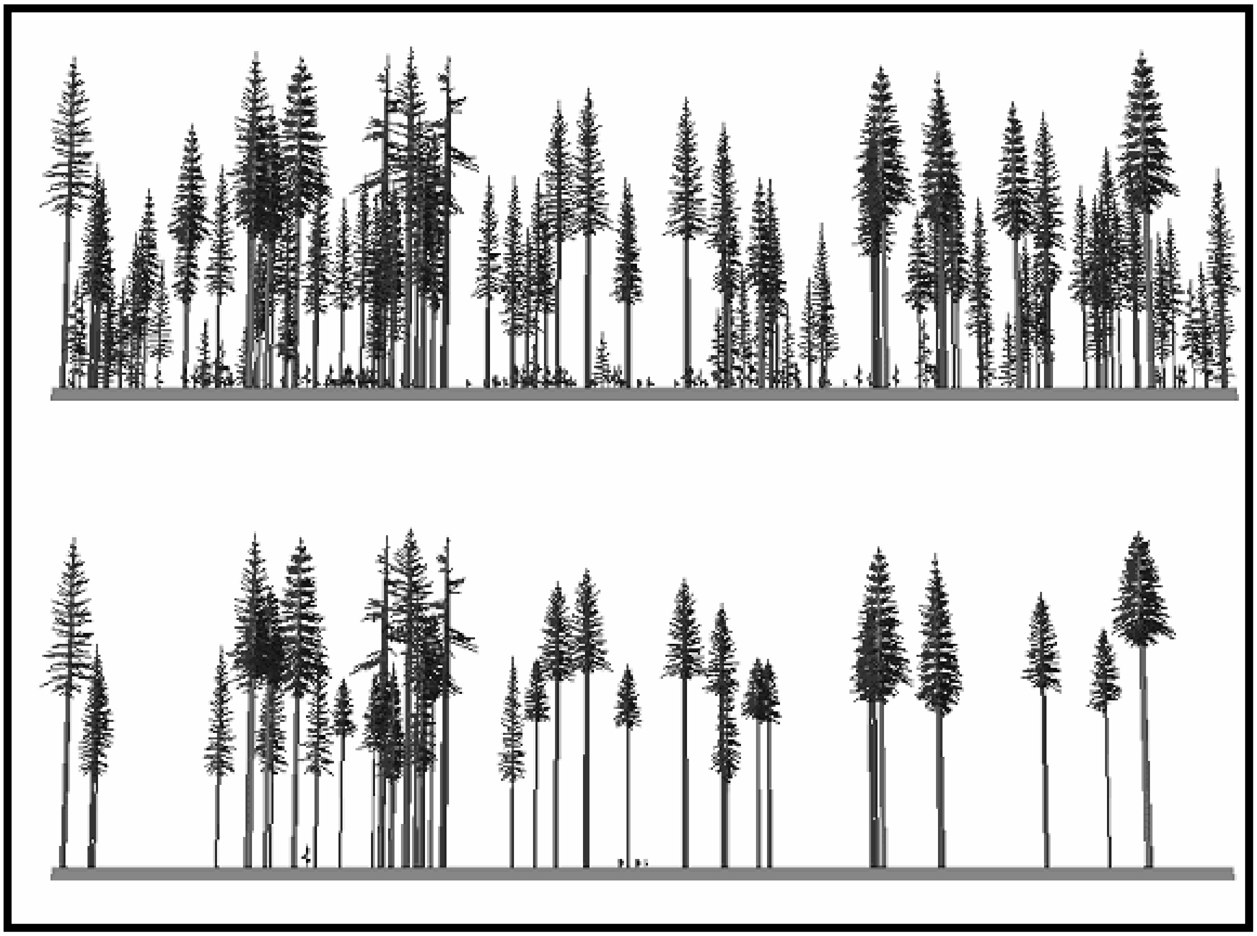

Figure 5. Forest structure of the random cross section (150 x 10 m) through the pre- (upper figure) and post-fire (lower figure) stand that was burned with a high intensity prescribed fire. Note the creation of gaps, the elevated crown base heights due to crown scorching, and the almost entire removal of understory trees in the post-fire stand. Remaining dominant trees are mainly white fir, incense-cedar and sugar/ponderosa pine. Drawn with the SVS software (McGaughey 1997).

canopy gaps, attributes common in old-growth structures. Low intensity prescribed fires can be very effective in reducing surface fuel loads (van Wagtendonk 1996, Stephens 1998, Stephens and Moghaddas 2005) but may not achieve other common restoration goals of reduced forest density and creation of canopy gaps.

Burning accumulated surface fuels with a low intensity fire may also preclude the ability of significantly changing stand structure with prescribed fire. The surface fuels that have accumulated in the last century because of fire suppression and past harvesting can be useful if the objective is to restore pre-settlement forests structure with prescribed fire alone. Certainly there are diverse conditions in Sierra Nevada mixed conifer forests but those stands that have high fuel loads, moderate intensity prescribed fire can be used to begin forest restoration. As also shown by Fulé et al. (2004), a high intensity restoration fire can have a strong impact on stand structure. Our results demonstrate that mechanical treatments are not always necessary to achieve the goal of restoring pre-settlement stand conditions.

CONCLUSIONS

Our low intensity prescribed fire mostly killed trees smaller than 10 cm dbh and failed to reduce total stem density to levels found in old-growth stands. Stand composition and the spatial structure were not moved towards an old growth structure that should include tree clumping and gaps in the overstory. The high intensity prescribed fire produced high mortality in the low and intermediate dbh-classes but did not kill many large trees. Fire-induced mortality occurred with spatial variation and created gaps in the overstory, attributes common in old-growth stands. (Stephens and Fulé 2005)

Mortality after burning was almost completed within two years of the fire, after this time mortality dropped substantially. The application of prescribed fire with a flame height of 1 to 2.5 m (classified as 'high intensity' in this study) may be an appropriate method to begin restoring forest structure in similar mixed conifer forests. Approximately 5,900 km^2 of mixed-conifer forests in the Sierra Nevada are in similar conditions (Davis and Stoms 1996) as the pre-fire stands described in this study. In this study the trees in the two burned areas experienced little bark beetle attack (*Dendroctonous* spp.) post-fire; in some prescribed fires bark beetles can be an important secondary mortality agent. Most trees in this study were relatively young because of past seed-tree harvests in the early 1900's, forests with a substantial component of old trees may respond differently.

Restoration of natural stand structures with prescribed fire is possible, but fire intensities have to be high enough in some areas of the stand to kill intermediate sized trees and create stand openings. Restoration of these forest ecosystems will require a multi-step process including follow-up fires to reduce dead and downed fuels from standing dead trees. Once desired conditions are achieved, prescribed or managed lightning fires must be continued to maintain these forests into the future.

ACKNOWLEDGMENTS

This paper is dedicated to Marco Hille. Marco was tragically killed by a tree-fall accident in Germany in 2005. He was a fantastic person and a very productive young scientist, he also had many friends in Europe and the USA and we all miss him. We thank the University of California Center for Forestry for assisting with this project. This study was made possible with support of the Robert-Bosch-Foundation, Germany, to the C.T. de Wit Research School in Production Ecology and Resource Conservation, Wageningen University; University of California Agricultural Experiment Station funds were also used to support this research. We especially like to thank Jason Moghaddas for his valuable help in this study.

LITERATURE CITED

Agee, J.K., and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211: 83-96.

Aguirre, O., G. Hui, K.V. Gadow, and J. Jimenez. 2003. An analysis of spatial forest structure using neighborhood -based variables. Forest Ecology and Management 183:137-145.

Covington, W.W., P.Z. Fulé, S.C. Hart, and R.P. Weaver. 2001. Modeling ecological restoration effects on ponderosa pine structure. Restoration Ecology 9:421-431.

Davis, F.W., and D.M. Stoms. 1996. Sierran vegetation: a gap analysis. Chapter 23 in: Sierra Nevada Ecosystem Project: Final report to Congress, vol. II. Davis: University of California, Centers for Water and Wildland Resources.

Elliott-Fisk D.L., T.C. Cahill, O.K. Davis, L. Duan, C.R. Goldman, G.E. Gruell, R. Harris, R. Kattelmann, R. Lacey, D. Leisz, S. Lindstrom, D. Machida, R.A. Rowntree, P. Rucks, D.A. Sharkey, S.L. Stephens, and D.S. Ziegler. 1997. Lake Tahoe case study. Sierra Nevada Ecosystem Project. Addendum (Davis: University of California, Centers for Water and Wildland Resources). pp. 217-276.

Fiedler, C.E., S.F. Arno, and M.G. Harrington. 1998. Reintroducing fire in ponderosa pine-fir forests after a century of fire exclusion. Pages 245-249 in T.L. Pruden and L.A. Brennan (eds). Fire in ecosystem management: shifting the paradigm from suppression to prescription. Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tall Timbers Research Station, Tallahassee, FL.

Füldner, K. 1995. Zur Strukturbeschreibung in Mischbeständen. Forstarchiv 66:235-40.

Fulé, P.Z., A.E. Cocke, T.A. Heinlein, and W.W. Covington. 2004. Effects of an intense prescribed forest fire: is it ecological restoration? Restoration Ecology 12:220-230.

Gadow, K.V., and K. Füldner. 1992. Bestandesbeschreibung in der Forsteinrichtung. Tagungsbericht der Arbeitsgruppe Forsteinrichtung. Klieken bei Dessau, Germany.

Gadow, K.V., and G.Y. Hui. 2002. Characterizing forest spatial structure and diversity. Proceedings of the SUFOR International workshop on Sustainable Forestry in Temperate Regions in Lund, Sweden.

Gadow, K.V., G.Y. Hui, and M. Albert. 1998. Das Winkelmass - ein Strukturparameter zur Beschreibung der Individualverteilung in Waldbeständen. Centralblatt für das gesamte Forstwesen 115:1-9.

Harrod, R.J., B.H. McRae, and W.E. Hartl. 1999. Historical stand reconstruction in ponderosa pine forests to guide silvicultural prescriptions. Forest Ecology and Management 114: 433-446.

Hille, M.G., and S.L. Stephens. 2005. Mixed conifer forest duff consumption during prescribed fires: Tree crown impacts. Forest Science 51: 417-424.

Husari, S.J., and K.S. McKelvey. 1996. Fire management policies and programs. Chapter 40 in: Sierra Nevada Ecosystem Project: Final report to Congress, vol. II. Davis: University of California, Centers for Water and Wildland Resources.

Husari, S., T. Nichols, N.G. Sugihara, and S.L. Stephens. 2006. Fuel management. In: Fire in California Ecosystems, N.G. Sugihara, J.W. van Wagtendonk, J. Fites-Kaufman, K.E. Shaffer, and A.E. Thode (eds.). University of California Press. Berkeley, CA. (pp. 444-465.)

Kobziar, L.N., J. Moghaddas, and S.L. Stephens. 2006. Tree mortality patterns following prescribed fires in a mixed conifer forest. Canadian Journal of Forest Research 36: 3222-3238.

McGaughey, R.J. 1997. Visualizing forest stand dynamics using the stand visualization system. Pages 248-257 in: Proceedings of the 1997 ACSM/ASPRS Annual Convention and Exposition; April 7-10, 1997. Seattle, WA. Bethesda, MD: American Society for Photogrammetry and Remote Sensing. Vol. 4. Software available at http://forsys.cfr.washington.edu/svs.html

McKelvey, K.S., and J.D. Johnston. 1992. Historical perspectives on forests of the Sierra Nevada and the Transverse Range of Southern California: Forest conditions at the turn of the century. Pages 225-246 in: The California spotted owl: A technical coordination by J. Verner, K.S. McKelvey, B.R. Noon, R.J. Gutierrez, G.I. Goud Jr., and T.W. Beck. GTR PSW-133.

Moody, T.J., J. Fites-Kaufman, and S.L. Stephens. 2006. Fire history and climate influences from forests in the Northern Sierra Nevada, USA. Fire Ecology 2 :115-141.

Oliver, W.W., G.T. Ferrell, and J.C. Tappeiner. 1996. Density management of Sierra Nevada forests. P. 491-500. Chapter 11 in: Sierra Nevada Ecosystem Project: Final report to Congress, vol. III. Davis: University of California, Centers for Water and Wildland Resources.

Olson C.M., and J.A. Helms. 1996. Forest Growth and Stand Structure at Blodgett Forest Research Station 1933-95. Chapter 16 in: Sierra Nevada Ecosystem Project: Final report to Congress, vol. III. Davis: University of California, Centers for Water and Wildland Resources.

Parsons, D.J., and S.H. DeBendeetti. 1979. Impact of fire suppression on a mixed-conifer forest. Forest Ecology and Management 2: 21-33.

Reinhardt E.D. and K.C. Ryan. 1998. Analyzing effects of management actions including salvage, fuel treatment, and prescribed fire on fuel dynamics and fire potential. Pages 206-209 in T.L. Pruden and L.A. Brennan (eds). Fire in ecosystem management: shifting the paradigm from suppression to prescription. Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tall Timbers Research Station, Tallahassee, FL.

Ryan, K.C., and E.D. Reinhardt. 1988. Predicting post-fire mortality of seven western conifers. Canadian Journal of Forest Research 18:1291–1297.

Skinner, C.N., and C. Chang. 1996. Fire regimes, past and present. Chapter 40 in: Sierra Nevada Ecosystem Project: Final report to Congress, vol. III. Davis: University of California, Centers for Water and Wildland Resources.

Stephens, S.L., 1998. Effects of fuels and silvicultural treatments on potential fire behavior in mixed conifer forests of the Sierra Nevada, California. Forest Ecology and Management 105:21-34.

Stephens, S.L. 2000. Mixed conifer and upper montane forest structure and uses in 1899 from the central and northern Sierra Nevada, California. Madrono 47:43-52.

Stephens, S.L., and D.E. Elliott-Fisk. 1998. Sequoiadendron giganteum-mixed conifer forest structure in 1900-1901 from the southern Sierra Nevada, California. Madrono 45:221-230.

Stephens, S.L., D. Dulitz, and R.E. Martin. 1999. Giant sequoia regeneration in group selection openings of the southern Sierra Nevada. Forest Ecology and Management 120:89-95.

Stephens, S.L., and M.A. Finney. 2002. Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effects of crown damage and forest floor combustion. Forest Ecology and Management 162:261-271.

Stephens, S.L., and B.M. Collins. 2004. Fire regimes of mixed conifer forests in the north-central Sierra Nevada at multiple spatial scales. Northwest Science 78:12-23.

Stephens, S.L., and P.Z. Fulé. 2005. Western pine forests with continuing frequent fire regimes: possible reference sites for management. Journal of Forestry 103: 357-362.

Stephens, S.L., and J.J. Moghaddas. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a mixed conifer forest. Forest Ecology and Management 215:21-36.

Stephens, S.L. and L.W. Ruth. 2005. Federal forest fire policy in the United States. Ecological Applications 15:532-542.

Stephens, S.L., and N.G. Sugihara. 2006. Fire management and policy since European settlement. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J. and Thode, A.E. editors. Fire in California's ecosystems. University of California Press, Berkeley, CA pp. 431-443.

Stephenson, N.L., D.J. Parsons, and T.W. Swetnam. 1991. Restoring natural fire to the sequoia-mixed conifer forest: Should intense fire play a role? Tall Timbers Fire Ecology Conference 17:312-337.

Sudworth, G.B. 1900. Stanislaus and Lake Tahoe Forest Reserves, California and Adjacent Territory (Twenty-first annual report to the Secretary of the Interior Part V--Forest Reserves). Washington, D.C.: United States Geological Survey.

SNEP 1996. Sierra Nevada Ecosystem Project, Late successional old-growth forest conditions. Vol. I, Chap. 6. Centers for Water and Wildland Resources, University of California, Davis. Pp. 91-112.

Tappeiner J.C., and P.M. McDonald. 1996. Regeneration of Sierra Nevada forests. Chapter 12 in: Sierra Nevada Ecosystem Project: Final report to Congress, vol. III. Davis: University of California, Centers for Water and Wildland Resources.

van Mantgem, P.J., N.L. Stephenson, L.S. Mutch, V.G. Johnson, A.M. Esperanza, and D.J. Parsons. 2003. Growth rate predicts mortality of Abies concolor in both burned and unburned stands. Canadian Journal of Forest Research 33: 1029-1038.

van Wagtendonk, J.W. 1983. Prescribed fire effects on forest understory mortality. In: Proceedings of the Tall Timbers Fire Ecology Conference, Tallahassee, Florida, pp. 136–138.

van Wagtendonk, J.W. 1996. Use of a deterministic fire growth model to test fuel treatments. Pages 1155-1166 *in* Assessments and scientific basis for management options. Sierra Nevada Ecosystem Project, final report to congress, volume II. University of California, Centers for Water and Wildland Resources, Davis, California.

Weatherspoon, C.P., and C.N. Skinner. 1995. An assessment of factors associated with damage to tree crowns from the 1987 wildfires in northern California. Forest Science 41:430-451.