

Stability of the large tree component in treated and untreated late-seral interior ponderosa pine stands¹

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Abstract: Ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) stands with late-seral features are found infrequently, owing to past management activities throughout western North America. Thus, management objectives often focus on maintaining existing late-seral stands. Observations over a 65 year period of stands with no past history of harvest showed substantial ingrowth in the smaller diameter classes and elevated rates of mortality among the largest mature trees in the stand. Adjacent stands, with combinations of thinning and prescribed fire, had far fewer high-risk mature trees and generally lower rates of mortality after treatment. Forecasts using individual-tree diameter growth and mortality models suggest that observed declines in these stands with remaining old trees and a dense understory will continue in the absence of any treatment. Increased vigor in thinned stands appeared to be offset by an increase in mortality of large trees when thinning was followed by prescribed fire.

Résumé : Partout dans l'ouest de l'Amérique du Nord, il est peu fréquent de rencontrer des peuplements de pin ponderosa (*Pinus ponderosa* Dougl. ex P. & C. Laws.) aux derniers stades de succession écologique à cause du type d'aménagement pratiqué dans le passé. Par conséquent, les objectifs d'aménagement sont souvent axés sur le maintien des peuplements aux derniers stades de succession écologique qui existent encore. Des observations s'étalant sur une période de plus de 65 ans dans des peuplements qui n'ont pas été récoltés dans le passé montrent que le recrutement est élevé dans les classes inférieures de diamètre et que le taux de mortalité est élevé parmi les plus gros arbres matures. Il y a beaucoup moins d'arbres matures à haut risque et le taux de mortalité est généralement plus faible dans les peuplements adjacents après qu'ils aient été soumis à diverses combinaisons d'éclaircie et de brûlage dirigé. Des prévisions basées sur la croissance en diamètre des arbres et des modèles de mortalité indiquent que le déclin va se poursuivre en l'absence de traitements dans les peuplements où de vieux arbres persistent et dont le sous-étage est dense. Dans les peuplements éclaircis, l'augmentation de la vigueur semble contrebalancée par un accroissement de la mortalité chez les gros arbres lorsque l'éclaircie est suivie d'un brûlage dirigé.

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Introduction

Ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) is widely distributed throughout western North America. The species is important in interior forests both commercially and for its contribution to forest structure and habitat. Throughout its range, stand structures have changed substantially during the last century, primarily owing to two factors: past harvesting practices and fire exclusion (Skinner and Chang 1996; Taylor 2000; Fitzgerald 2005).

The exclusion of fire in forests dominated by western pine has led to increases in density among small trees (Lauden-slayer et al. 1989; Dolph et al. 1995). The occurrence of this phenomenon is ubiquitous; thus, the open park-like

stands thought to be common before European settlement are now rarely encountered. Furthermore, widespread harvesting of interior pine stands has removed much of the large-tree component, replacing large, widely spaced yellow-bark pine trees with smaller, uniformly spaced pine trees (Agee 1993, p. 337). Because growth rates in these interior pine stands are generally slow, recovery of this stand component takes many years.

Maintenance and restoration of late-seral forest conditions and structures have become a focus of federal land management. Recent large-scale planning efforts in the western United States (e.g., USDA 2001) have identified this as a priority. Management guidelines dictate target conditions to meet specified objectives for late-seral stand structures.

Large trees, which often reach ages of 200–500 years, are an important component of late-seral stands dominated by interior pine. Yet, maintenance of extant large trees appears to be hindered by the presence of dense understory vegetation (Oliver 1997). Dense canopies place stands at greater risk of severe fire and expose the mature trees to levels of competition they are unaccustomed to (Agee 1990, 1993). Trees that have survived hundreds of years in relatively open stands are weakened by this increased competition for limited resources, increasing their susceptibility to insect attack and subsequent mortality. Exclusion of fire appears to

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be a key factor in the current dynamic of interior pine stands (Bork 1984; Agee 1993).

Given this current dynamic, what strategies are effective for the maintenance and restoration of these late-seral stands? Is a passive management approach the best method to maintain old-growth stand conditions, or can treatments such as thinning or prescribed burning effectively enhance stand structure in old-growth pine stands? Kolb et al. (2007) suggest that growth of old ponderosa pine trees can be accelerated with careful thinning, but prescribed fire may expose older trees to a risk of delayed mortality.

In this paper, changes in stand structure observed over a period of approximately 65 years are quantified for interior ponderosa pine stands in northeastern California. Response to treatments, expressed as tree survival and vigor for adjacent treated stands over a 5 year period, are then compared with the untreated, natural stands. Forecast changes in the large-tree component are then presented, based on observed diameter increment and mortality.

Materials and methods

Blacks Mountain experimental forest is located in northeastern California at 40°40'N, 121°10'W. Elevations range from 1700 to 2100 m a.s.l. Primary species throughout the forest are ponderosa pine and Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.), with white fir (*Abies concolor* (Gord. & Glend.) Lindl.) and incense-cedar (*Calocedrus decurrens* (Torr.) Florin) observed at higher elevations in the forest. Mean precipitation at Blacks Mountain is 457 mm, with most falling during the winter months as snow. The forest is 4200 ha, with most (3715 ha) classified as interior ponderosa pine type (Eyre 1980).

Data for this analysis come from two sources: (i) a 1933–1934 census of all compartments in the forest (hereinafter referred to as the 1934 census) and (ii) a sample of treated stands and untreated research natural areas (RNA) from the Blacks Mountain ecological research project (BMERP; initiated in 1996) conducted post-treatment and again after 5 years.

1934 census

Upon establishment of the Blacks Mountain experimental forest, a complete census was conducted (Hasel 1938). At the time of the 1934 census, the forest was essentially unmanaged, with most of the area having no prior history of timber harvest. The census included all trees >7.6 cm diameter at breast height. All live trees were recorded by 5 cm (2 inch) diameter classes, by species, and by Dunning tree class (Dunning 1928) for each stand in the forest. In this survey, Jeffrey pine and ponderosa pine were combined and referred to as yellow pine.

Untreated RNA

Five of the compartments at Blacks Mountain experimental forest have been designated as RNA (Cheng 2004). Four of these units are forested and are included in this analysis. A fifth unit, largely made up of open meadow, is not considered here. The RNA have never been harvested. Two of the units were burned without any pre-treatment (Skinner 2005). Using the sampling protocol of the BMERP (Oliver 2000),

Table 1. Sampling in research natural areas (RNA) A–D at Blacks Mountain experimental forest with year initially sampled.

RNA	Year		Area (ha)	Elevation (m a.s.l.)	No. of sample points
	Sampled	Burned			
A	1999	—	35.43	1770–1820	16
B	1998	1999	39.28	1830–1950	19
C	1997	1997 ^a	57.46	1720–1760	24
D	1999	—	28.36	1840–1920	12

^aBurn took place several months after sample plots were established.

plots were established in the RNA prior to the application of prescribed fire (1997 and 1998), and then remeasured after fire introduction. Sampling intensity was approximately one plot per 2 ha, with a plot size of 0.08 ha for large trees (>29.2 cm diameter at breast height) and 0.02 ha for small trees (≤29.2 cm diameter at breast height). The measurement protocol is described by Zhang et al. (2008). Mean size of RNA units is 40 ha, with a range of 28–57 ha (Table 1).

High structural diversity treatments

In the late 1990s, a large-scale interdisciplinary study was established at Blacks Mountain experimental forest to investigate the effects of stand structure, grazing, and prescribed fire on vegetation, small mammals, and other forest processes (Oliver and Powers 1998; Oliver 2000). One observation that influenced the experimental design was the apparent accelerated mortality rates of the mature trees in these stands.

The first stage of treatment implementation was the creation of contrasting stand structures. A strong contrast was created by thinning stands to one of two prescriptions. A low structural diversity treatment called for removal of all large overstory trees, creating a stand with even spacing and a single canopy layer of saplings or small saw-timber sized trees. The contrasting high structural diversity prescription called for thinning from below around all the largest overstory trees, leaving only one smaller-diameter tree for future stand development within the drip-line of these dominants (Oliver 2000). After thinning, prescribed fire was applied to one half of each of the treated units. This prescription effectively retained all trees >~50 cm diameter at breast height. With full treatment implementation, there are six high and six low structural diversity units. Each unit is approximately 80–100 ha, with a split for application of prescribed fire to half (Oliver 2000).

Treated units were sampled post-treatment using a nested fixed-area plot design (Oliver 2000; Zhang et al. 2008). The trees and snags on these plots were then remeasured 5 years later. Snag condition codes (Thomas et al. 1979) were recorded and a risk rating was established for each tree >60 cm diameter at breast height (Salman and Bongberg 1942). Trees were given a risk rating code from 1 to 4, with 1 being the lowest risk and 4 the highest. Because there were relatively few class 4 trees, classes 3 and 4 were combined to define a single high-risk classification. Class 3 is defined as:

- having ragged or thin crowns and some thin and bunched foliage.

Table 2. Research natural area (RNA) diameter distribution and species composition in 1934 and 1999.

RNA	1934						~ 1999					
	No. of trees·ha ⁻¹			Species mix (%) ^a			No. of trees·ha ^{-1b}			Species mix (%) ^a		
	9–30	30–60	>60	YP	WF	IC	9–30	30–60	>60	YP	WF	IC
A	198	49	46	87	4	9	735 (135)	63 (11)	19 (3)	75	8	17
B	86	43	51	80	4	16	1195 (153)	36 (6)	22 (4)	54	14	32
C	192	29	34	96	2	2	797 (108)	68 (9)	19 (3)	92	7	1
D	107	46	66	75	17	8	1047 (162)	46 (8)	23 (8)	56	31	13

^aPercent basal area for ponderosa and Jeffrey pine (yellow pine (YP)), white fir (WF), and incense-cedar (IC). Actual years of measurement for RNA B and RNA C before prescribed fire were 1998 and 1997, respectively.

^bValues in parentheses are SEs.

- having needles of fair to poor color and appearing shorter than average.
- having some branches and twigs fading or dead.

Class 4 is similar, but with the presence of dead branches in the crown and evidence of recent bark beetle activity.

For this analysis, the stand density, estimated mortality rates, and net change in trees·ha⁻¹ from each of the six high structural diversity units in both the burned and unburned splits, were calculated for the large-tree (>60 cm diameter at breast height) cohort of the stand. We observed the number of trees alive at the beginning of the growth period and the number of trees that died during the 5 year period. Low diversity treatment units were excluded from the analysis, as all large trees were removed.

Using the observed mortality in each high diversity split plot, a mortality model was fit to the data:

$$[1] \quad l(\pi_{ijk}) = \mu + \text{Block}_i + \tau_j + \varepsilon_{ijk}$$

where $l(\pi_{ijk})$ is the logit transformation for probability (π) of mortality for block i , burn treatment j , and unit k ($k = 1, 2$): $\log[\pi_{ijk}/(1 - \pi_{ijk})]$, and τ is the burning effect. The Block term is assumed random, with variance σ_B . This was fit using a generalized linear model, assuming the unit-level error term is $\varepsilon_{ijk} \sim N(0, \sigma)$. The model was fit for all species grouped and for pine only. Parameter estimates were very similar for both analyses; results for combined species are reported because overdispersion was considerably lower for this fit. We compared these results for treated stands with the observed mortality rates from the RNA.

The distribution of risk ratings 5 years after treatment was compiled. For burned versus unburned, we compared the numbers of trees classified as high or very high risk in the high diversity treatment units. The general model was the same as eq. 1, with π defined as the proportion of trees at high risk or very high risk. As with mortality, risk was fit for all species combined.

To consider longer term implications of this analysis, future growth and mortality were simulated using growth and mortality models developed from the observed stands. The process employed a bootstrap analysis of the data using sampling with replacement of grid points (sample units) within each unit. This process was repeated 1000 times to generate the bootstrap dataset. Then, for each of the 1000 samples, growth and mortality models were fit and applied to the bootstrap samples, forecasting to a point 15 years after first observation. Because remeasurement of the RNA took place at an 8 year interval, forecasts were made from

year 8 to year 15. In treated units this forecast was from year 5 to year 15.

The general form of the diameter growth model was:

$$\Delta \text{dbh} = \exp(\beta_{0s} + \beta_{1s} \log(\text{dbh}) + \beta_{2s} \text{dbh}^2 + \beta_{3s} I_{\text{burn}})$$

where parameter (β_{ps}) estimates for species s vary from 1 to 3 (ponderosa pine, white fir, and incense-cedar) and I_{burn} is an indicator variable for burned units. Probability of periodic mortality was calculated by species and burn treatment. In forecasting growth and mortality of treated and untreated units, the burn effect was assumed to be limited to the observed growth period. Changes in trees·ha⁻¹ > 60 cm diameter at breast height were quantified by unit and variability was expressed by the interquartile range.

Results

Change in stand structure

Stand structure has changed substantially since the initial observations in 1934. Considering only the stands with no treatment history, density in small trees (<30 cm diameter at breast height) was very low in 1934 relative to the pre-burn samples in 1998 and 1999 (Table 2). Numbers of large trees (>60 cm diameter at breast height) decreased, while numbers of medium sized trees (30–60 cm diameter at breast height) showed no consistent trend. A signed rank test showed differences in density for both large and small trees were statistically significant (Table 3). The numbers of living large trees have been reduced by about half in all units. Furthermore, there was an apparent shift in species distribution in three stands (Table 2). There was a decrease in pine contribution to basal area by 12%–20% for three of the four units between 1934 and 1999, with an attendant increase in white fir and incense-cedar. The remaining RNA had very little change in species composition.

Change in large-tree density post-treatment

Post-treatment samples from the high diversity treatment units revealed a relatively stable large-tree component for the thinned-only split. A net change of 4.5% (0.8 trees·ha⁻¹) was observed, although the 90% confidence interval ranges from –17% to 24.2%, so these units are essentially unchanged in terms of large-tree density. Stands with prescribed fire after thinning had a mean net decrease of 15% (–1.1 trees·ha⁻¹), with a 90% confidence interval of $\pm 20\%$.

The fitted mortality model (eq. 1) for large trees in high diversity treatment units revealed a lower 5 year mortality rate for unburned than burned units (Table 4), with a mean

Table 3. Signed rank test *p* values for comparing density in 1934 with sampled density ~1999 by tree diameter class in four untreated research natural areas (RNA).

RNA	<i>p</i> value		
	9–30 cm	30–60 cm	>60 cm
A	0.0034	0.2655	0.0004
B	0.0001	0.4797	0.0002
C	<0.0001	0.0007	0.0002
D	0.0025	0.9686	0.0039

Table 4. Percentage of large trees by risk rating estimated from high diversity treatment (thinned) units and the research natural areas (RNA; unthinned).

	Risk rating		
	Low	Medium	High
High diversity			
Unburned	47	38	15
Burned	47	36	17
RNA			
A, unburned	3	43	54
D, unburned	3	36	61
B, burned	3	29	68
C, burned	5	25	70

difference of 7.2% ($p = 0.025$); 5 year periodic mortality rate in unburned treated units was 1.2%. Comparable periodic large-tree mortality rates in the untreated RNA ranged from 6% to 19%.

Risk rating

The proportions of trees by risk category are shown in Table 4. Because the results were fairly consistent across treated units, mean values are given for burned and unburned units. This shows a substantial difference between unthinned RNA and the high diversity treatment units.

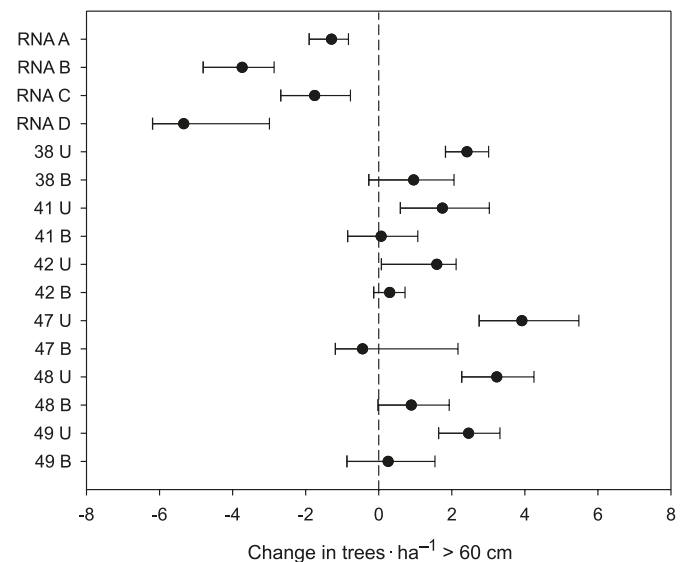
The 90% confidence interval for percentage of trees with high-risk ratings in thinned and burned units was from 10% to 24% and 9% to 19% for units with thinning only. However, the observed proportions of high-risk ratings for the unthinned (RNA) units were much higher, ranging from 54% to 70%, and well outside the previously mentioned confidence interval. Likewise, there appears to be a dramatic difference in the proportions of trees with low risk ratings. While the RNA units range from 3% to 5% trees with low-risk ratings, the 90% confidence interval for thinned and burned units ranges from 34% to 52% and 41% to 57% for units with thinning only.

The forecast to 15 years was consistent with the short-term changes observed (Fig. 1). Changes in large-tree density were positive for thinned units without prescribed fire; median values ranged from 2 to 4 trees·ha⁻¹. Large trees in the thinned and burned unit appear to be essentially stable. Changes range from -1 to approximately -5 trees·ha⁻¹ in the unthinned RNA.

Discussion

The mortality among the largest trees (>60 cm diameter at

Fig. 1. Forecast change in trees·ha⁻¹ >60 cm diameter at breast height 15 years after study installation (first quartile, median, and third quartile from bootstrap analysis) for thinned (U), thinned and burned (B), and unthinned research natural areas (RNA) A–D at Blacks Mountain experimental forest.



breast height) in these stands over the last 60–70 years has been substantial. There has been a net loss of more than half of the largest trees in the stand. This accelerated mortality and instability in the overstory is likely a result of increased competition from the dense understory that developed during a period of fire exclusion. In untreated stands, the mortality is continuing at a pace that will produce stands in which large, old trees are scarce at best, and given the numbers of trees with high-risk ratings, there appears to be a threat of elevated future mortality rates where trees with high-risk ratings comprise >50% of the remaining overstory.

Trees in the unharvested units generally have medium- or high-risk ratings. Less than 6% of the trees >60 cm diameter at breast height in the RNA have a low-risk rating. This suggests that advanced rates of mortality can be expected in the overstory trees in unthinned stands.

Thinned stands had much lower mortality rates and showed a slight increase in overstory structure as ingrowth surpassed mortality. Mortality in thinned and burned plots is still elevated, but this is likely a one-time phenomenon. The mortality observed in these thinned and burned units is secondary mortality that may have been avoided by delaying the burn some years after thinning to give residual trees time to recover. The application of prescribed fire in the RNA appears to have accelerated mortality rates. However, this remains unclear, as one unburned RNA also has high rates of mortality.

Forecasts of stand dynamics to a point 15 years after study installation suggest that observed changes in stand structure in untreated areas will continue. The numbers of large trees in treated areas generally increased in this analysis. The mean prescribed fire effect was a reduction of approximately 2 large trees·ha⁻¹. Because growth rates at Blacks Mountain experimental forest are relatively low, it is likely that any recovery to previous density levels will take decades. Because the burn-only treatment will likely take

several entries to reduce surface fuel levels (Skinner 2005), we may be underestimating the losses to large trees from future prescribed fires in the long term.

Conclusions

Stand structures in these interior pine stands have changed substantially over the last 70 years. Unmanaged stands have a much denser understory and far fewer living large (>60 cm diameter at breast height) trees than were observed in the past. The pine component has declined and incense-cedar and white fir have increased. The decline in the large-tree component is continuing in stands that are left unmanaged. Prescribed burning appears to increase rates of mortality of mature trees in the short term.

At this point in the experiment, there is evidence that ingrowth into the large tree (>60 cm diameter at breast height) class is actually exceeding mortality, appearing to reverse a 65 year decline in this important tree cohort of late-seral ponderosa pine stands. Because the lowest mortality rates are associated with the thinned-only treatment, this holds the best prospect for a relatively rapid short-term recovery from decades of accelerated large-tree mortality. For the thinned and burned units, in the longer term, immediate postfire mortality may be offset by lower surface fuels and increased resiliency to wildfire. If current mortality rates continue in the untreated RNA, there will likely be very few remaining mature trees >60 cm diameter at breast height in the coming decades. Without some form of management, high mortality rates in the overstory component will likely continue, given the high proportion of trees with a high at-risk rating. Density levels and risk of fire or bark beetle attack will remain high and growth rates will be low, producing few ingrowth trees into the larger diameter classes. Continued monitoring of these stands will allow us to establish whether this trend will continue in the long term.

References

- Agee, J.K. 1990. The historical role of fire in Pacific northwest forests. In *Natural and prescribed fire in Pacific northwest forests*. Edited by J.D. Walstad, S.R. Radosevich, and D.V. Sandberg. Oregon State University Press, Corvallis, Ore. pp. 25–38.
- Agee, J.K. 1993. *Fire ecology of Pacific Northwest forests*. Island Press, Washington, D.C.
- Bork, J.L. 1984. Fire history in three vegetation types on the eastern side of the Oregon Cascades. Ph.D. thesis. Oregon State University, Corvallis, Ore.
- Cheng, S. 2004. Forest service research natural areas in California. USDA For. Serv. Gen. Tech. Rep. PSW-GTR-188.
- Dolph, K.L., Mori, S.R., and Oliver, W.W. 1995. Long-term response of old-growth stands to varying levels of partial cutting in the eastside pine type. *West. J. Appl. For.* **10**: 101–108.
- Dunning, D. 1928. Tree classification for the selection forests of the Sierra Nevada. *J. Agric. Res.* **36**: 755–771.
- Eyre, F.H. (Editor). 1980. *Forest cover types of the United States and Canada*. Society of American Forestry, Washington, D.C.
- Fitzgerald, S.A. 2005. Fire ecology of ponderosa pine and the rebuilding of fire-resilient ponderosa pine ecosystems. In *Proceedings of the Symposium on Ponderosa Pine: Issues, Trends, and Management*, 18–21 October 2004, Klamath Falls, Oregon. *Technical co-ordinators* M.W. Ritchie, D.A. Maguire, and A. Youngblood. USDA For. Serv. Gen. Tech. Rep. PSW-GTR-198.
- Hasel, A.A. 1938. Sampling error in timber surveys. *J. Agric. Res.* **57**: 713–736.
- Kolb, T.E., Agee, J.K., Fule, P.Z., McDowell, N.G., Pearson, K., Sala, A., and Waring, R.H. 2007. Perpetuating old ponderosa pine. *For. Ecol. Manage.* **249**: 141–157. doi:10.1016/j.foreco.2007.06.002.
- Laudenslayer, W.F., Jr., Darr, H.H., and Smith, S. 1989. Historical effects of forest management practices on eastside pine communities in northeastern California. In *Multiresource management of ponderosa pine forests*. *Technical co-ordinators* A. Teale, W.W. Covington, and R.H. Hamre. USDA For. Serv. Gen. Tech. Rep. RM-185. pp. 26–34.
- Oliver, W.W. 1997. Can we sustain uneven-aged ponderosa pine stands? An interdisciplinary study in northeastern California. In *Proceedings of the IUFRO Interdisciplinary Uneven-aged Management Symposium*, 15–19 September 1997, Corvallis, Oregon. *Compiled by* W.H. Emmingham. Oregon State University, Corvallis, Ore. pp. 610–618.
- Oliver, W.W. 2000. Ecological research at the Blacks Mountain Experimental Forest in northeastern California. USDA For. Serv. Pacific Southwest Research Station. Gen. Tech. Rep. PSW-GTR-179.
- Oliver, W.W., and Powers, R.F. 1998. Interdisciplinary field research in ponderosa pine. *J. For.* **86**: 4–9.
- Salman, K.A., and Bongberg, J.W. 1942. Logging high risk trees to control insects in the pine stands of northeastern California. *J. For.* **40**: 533–539.
- Skinner, C.N. 2005. Reintroducing fire into the Blacks Mountain Research Natural Area: effects on fire hazard. In *Proceedings of the Symposium on Ponderosa Pine: Issues, Trends, and Management*, 18–21 October 2004, Klamath Falls, Oregon. *Technical co-ordinators* M.W. Ritchie, D.A. Maguire, and A. Youngblood. USDA For. Serv. Gen. Tech. Rep. PSW-GTR-198.
- Skinner, C.N., and Chang, C. 1996. Fire regimes past and present. In *Sierra Nevada ecosystem project, final report to Congress*. Vol. 2: Assessments and scientific basis for management options. Centers for Water and Wildland Resources, University of California Davis Water Resources Center Rep. 37. pp. 1041–1069.
- Taylor, A.H. 2000. Fire regimes and forest changes along a montane forest gradient, Lassen Volcanic National Park, southern Cascade Mountains, USA. *J. Biogeogr.* **27**: 87–104. doi:10.1046/j.1365-2699.2000.00353.x.
- Thomas, J.W., Anderson, R.G., Maser, C., and Bull, E.L. 1979. Snags. Chapter 5. In *Wildlife habitats in managed forests: the Blue Mountains of Oregon and Washington*. Edited by J.W. Thomas. USDA For. Serv. Agric. Handb. 553. pp. 60–77.
- USDA. 2001. Record of decision Sierra Nevada forest plan amendment environmental impact statement. USDA, Washington, D.C.
- Zhang, J., Ritchie, M.W., and Oliver, W.W. 2008. Vegetation responses to stand structure and prescribed fire in an interior ponderosa pine ecosystem. *Can. J. For. Res.* **38**. This issue.