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Snag longevity and surface fuel accumulation following post-fire logging in a ponderosa pine dominated forest

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A B S T R A C T

In a study of post-fire logging effects over an 8 year period at Blacks Mountain Experimental Forest, salvage logging was conducted at varying levels of intensity after a 2002 wildfire event. In a designed experiment, harvest prescriptions with snag retention levels ranging from 0% to 100% in 15 experimental units were installed. Observations of standing snags and surface fuels were made 2, 4, 6, and 8 years after the fire. Fire-killed snags fell rapidly over time, leading to elevated surface fuel levels in areas where no salvage logging was done. The 1000 h and larger surface fuels were strongly related with basal area retention level, with values ranging from 0–60 Mg ha^{-1} by year eight. However, when expressed as a percent of standing retained biomass, surface fuel accumulation was not related to treatment. In year 8, surface fuel was 81% of retained bole biomass. The retention of snags after this wildfire event provided snags for wildlife foraging and nesting habitat, however most of these snags were lost within 8 years after the fire. White fir snags were more stable than pine and appeared to be used with greater frequency than pine for cavity excavation.

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1. Introduction

Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) forests of interior North America, where fire has been excluded for decades, are now prone to high-severity crown fires. Fires in these areas once burned at primarily low to moderate severities under the historic regime of frequent fire (Arno, 2000; Wright and Agee, 2004; Skinner and Taylor, 2006). Tree mortality from fire was often most pronounced in the small size classes of trees and mortality of overstory trees was patchy, restricted to areas with localized build-up of surface fuel. Fire suppression-caused declines in fire activity have reversed in some parts of the western United States, with both the extent of burning (Westerling et al., 2006) as well as the proportion of acres burning at high severity increasing in recent decades (Miller et al., 2009).

High severity crown fires result in high levels of tree mortality, consuming leaves and small branches but leaving the boles largely intact. In the aftermath of such fires, managers often propose the salvage of wildfire-killed trees. Prompt removal of recently killed trees provides financial return and thus facilitates subsequent tree planting and release treatments. Salvage harvesting also has the potential to influence other site resources of interest to forest managers. This activity has the potential to disturb soils (e.g. Brais and Camire, 1998), remove potential wildlife habitat (Blake, 1982; Caton, 1996; Hitchcox, 1996; Morissette et al., 2002), impact natural tree regeneration (Greene et al., 2006), increase loading of fine surface fuels (Donato et al., 2006; McIver and Ottmar, 2007), and modify understory species composition (Purdon et al., 2004). Increasingly, salvage harvesting has been the subject of study to develop a fuller understanding of the consequences of this activity.

1.1. Snag retention and dynamics

The direct effect of salvage harvest is in reducing density of snags on the landscape. In ponderosa pine forests, snags contribute to wildlife habitat (Laudenslayer, 2002a; Farris et al., 2002), and retention of standing dead material may provide important forage and nesting opportunities for numerous species (Scott, 1979). However as these snags fall, they also contribute to elevated surface fuels (McIver and Ottmar, 2007). Managers therefore must find a balance between preserving the habitat value provided by snags while also mitigating the threat posed by excess surface fuels to future fire severity.

The rate at which snags decay and fall is important where decisions are made to retain snags after fire. Yet little is known of snag dynamics in a post fire environment. Some studies have shown that fire-killed snags remain standing for a relatively short period of time (e.g. Raphael and Morrison, 1987; Harrington, 1996). Laudenslayer (2002b) found that fire-killed snags deteriorate at

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approximately twice the rate of trees killed by means other than fire.

Standing snags may retain a substantial amount of biomass that will contribute to surface fuels over time as snags fall. Although large wood is not included in surface fire spread models, it can contribute to fire behavior and fire spread by acting as a source of embers, both directly by lofting from burning snags (van Wagtendonk, 2006), and indirectly through torching of trees preheated by burning of heavy fuels on the forest floor. Presence of coarse woody debris also presents a hindrance to fire suppression (Brown et al., 2003; USDA, 1976). Decomposing snags and logs provide a receptive surface for ignition of spot fires from embers (Stephens, 2004). In addition, fire effects are often related to the amount of fuel consumed (Knapp et al., 2005) and a substantial portion of the fuels consumed by fire may be contained within large logs, especially in areas that have experienced high tree mortality in the recent past. Large fuels increase burnout time, and prolonged heat exposure affects soil porosity and structure (McNabb and Swanson, 1990; Brown et al., 2003).

Concerns about the potential for negative impacts of salvage logging have led to a number of studies of fire salvage effects (McIver and Starr, 2001; Peterson et al., 2009). Unfortunately many of these studies have been unreplicated and/or observational in nature (McIver and Starr, 2001). In addition, salvage logging has in the past traditionally been viewed in black and white terms – either all merchantable material is removed or the stand is not entered at all, leaving few opportunities to study how a gradient in snag densities might influence fuel accumulation and wildlife attributes over time.

In addition to the direct impacts of snag removal on standing biomass, it is also possible that retained snag stability is influenced by salvage logging. Russell et al. (2006) reported a shorter half-life for snags in salvaged areas than those in unsalvaged areas.

1.2. Objectives

In this study we characterized the transition from fire-killed snags to surface fuel, over time, for a range of post-fire salvage intensities in a pine-dominated forest. This gradient in snag densities was produced with a post-fire thinning from below, producing plots with standing basal area ranging from zero (complete salvage) to 100% (unsalvaged), with intermediate levels in between. Thinning from below meant that plots with the lowest snag density also generally had the largest average snag size. While salvage, for economic reasons, often focuses on removing the largest most valuable trees, these same snags also are believed to provide the best wildlife habitat both in terms of use by cavity nesting birds and snag longevity. Thus, intermediate removal treatments maintaining some large snags might be envisioned as a compromise treatment for landscapes being managed to provide multiple resource benefits.

Our objective in this study was to (1) quantify the dynamics of standing snags and large surface fuel accumulation over time in relation to varying levels of post-fire salvage in a ponderosa pine-dominated forest, (2) quantify the dynamics of fine fuels post-fire salvage, and (3) evaluate cavity excavation among retained trees.

2. Methods

2.1. Study site

The study was established in a burned area at Blacks Mountain Experimental Forest (BMEF) in the southern Cascade Range of northeastern California (40.72°N latitude, 121.17°W longitude). Elevations range from 1700 to 2100 m. The climate is montane Mediterranean characterized by warm, dry summers and cold, wet winters. Annual precipitation ranges from 231–743 mm and falls primarily as snow from November to May.

The area sampled was dominated by ponderosa pine (60–80% by basal area) with a mix of white fir (*Abies concolor* (Gord. & Glend.) Lindl. Ex Hildebr.) incense-cedar (*Calocedrus decurrens* (Torr.) Florin) and, infrequently, Jeffrey pine (*Pinus Jeffreyi* Balf.).

2.2. The Cone Fire

The Cone Fire burned 565 ha on BMEF in late September 2002. Fuel moisture during this late-season burn was low. A weather station 6 miles northwest of the ignition point recorded 2% for 10- and 100-h fuels and 5% for 1000-h fuels during the fire. Relative humidity was recorded at 6% with winds gusting to 51 km h^{-1}.

In the area of the burn with no prior fuel treatment, the stem density at the time of the burn averaged 1700 ha^{-1}, with a quadratic mean diameter of approximately 16 cm (Table 1). The elevated stem densities observed are consistent with the effects of an extended period of fire exclusion in interior pine stands of northern California (Skinner and Taylor, 2006). Indeed, fire history data for Blacks Mountain clearly show that fire has been almost non-existent on the landscape over the last 100 years (Data on file, PSW Research Station).

Approximately 5 years prior to the burn, some areas of the Experimental Forest were treated with a combination of thinning and prescribed fire (Oliver, 2000) and these areas were subject to low severity fire with very limited spread (Ritchie et al., 2007). However, the areas with no recent fuel-reduction treatments were subject to a high-severity crown fire, with few surviving trees. This portion of the Cone Fire without prior experimental fuel reduction treatments was subject to a post-fire salvage harvest to remove both merchantable and un-merchantable snags. The application of a post-fire salvage harvest afforded the opportunity to evaluate treatment effects.

2.3. Post-fire treatments

The salvage prescription in the Cone Fire called for complete removal of all trees with no green foliage remaining. The post-fire salvage operations began 12 months after the fire, the delay was due to the requirements of the National Environmental Policy Act (NEPA) in effect for National Forest lands. NEPA requires the development and review of a detailed planning document prior to any treatment implementation. Salvage operations for the experiment were concluded by November 2003.

The salvage area of 442 ha, including the study units, was combined with a unburned thin from below of 300 ha elsewhere on the forest for a combined removal of 33 Mg ha^{-1} (green weight) in sawtimber and 27.13 Mg ha^{-1} in non-sawtimber (chips). The timber sale was awarded at a bid price of $352,437 in September of 2003. The salvage area outside of the study plots was subjected to a complete removal of all snags. Because our experimental treatments are part of a larger sale, it is not possible to draw conclusions about the economic viability of any of our intermediate salvage treatments.

Table 1
Stand mean densities (with s.e.) by tree size in the experimental area prior to the Cone Fire.

	Diameter class (cm)			
	2–15	15–30	30–45	45+
Trees ha^{-1}	1192 (86)	438 (30)	54 (7)	20 (4)
Basal area m^2 ha^{-1}	8.4 (0.56)	15.1 (1.08)	5.3 (0.67)	5.2 (1.26)

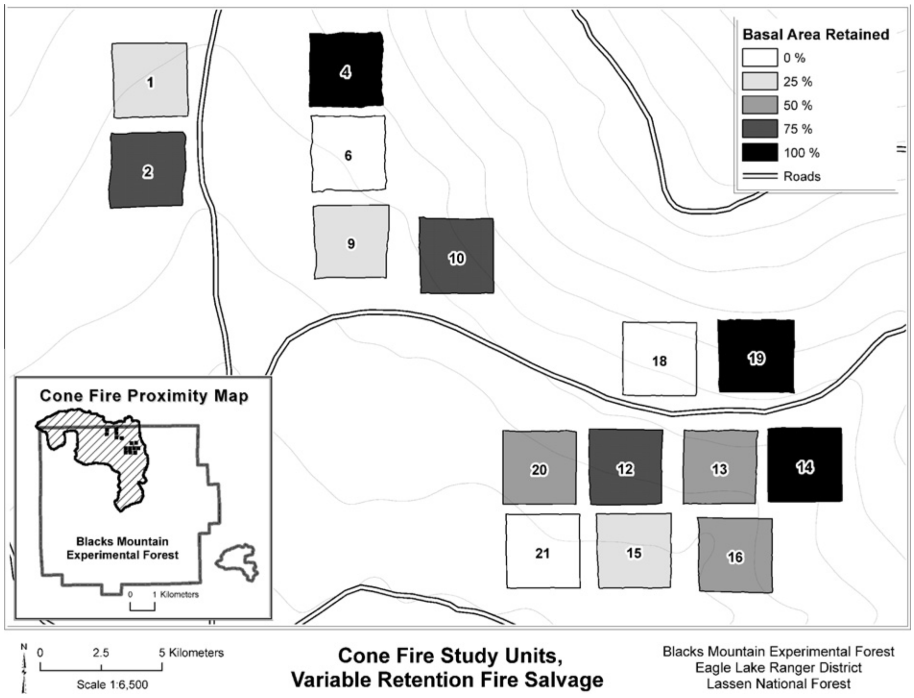

Fig. 1. Blacks Mountain Experimental Forest with the extent of the cone fir and location of variable retention salvage units.

Within the salvage project area, we implemented a study with modified salvage intensity wherein varying basal area levels of standing snags were retained. Fifteen 2 ha units were established and randomly assigned a target snag basal area retention level. Retention levels ranged from 0 to full retention with three each at the extremes and approximate intermediate levels of 4.6, 9.2, 13.8 m^2 ha^{-1}. The treatment units were established and random treatment assignment was completed prior to the initiation of any salvage activity (Fig. 1).

In three full snag retention units, no snags were removed and all equipment was kept out of the treatment unit. In the three retention-level-0 units, the generic salvage prescription was followed and all dead stems were removed from the site, regardless of tree size. In recognition of the importance of larger retained stems for wildlife habitat (Bunnell et al., 2002), the partial salvage harvests were executed from below to the targeted basal area, retaining the largest snags.

Initial post-treatment observations were obtained in the spring of 2004 (year 2). A 5 $\times$ 5 grid of points at 25 m spacing, were permanently monumented within each of the treatment units. Measurement plots with a radius of 8 m were centered at each permanent grid point. Within the sample plots, retained snags were tagged and species, breast height diameter (dbh) and height were recorded. Plots were remeasured every 2 years concluding in 2010. If snags snapped or uprooted over time, this condition was recorded by the measurement crew, along with the height of the breakage. A total of 3002 trees were sampled in the 15 treatment units. Among the sampled snags, 2060 were ponderosa or, infrequently, Jeffrey pine. Since ponderosa and Jeffrey pine are virtually indistinguishable after fire and Jeffrey pine is a minor component of these stands (Oliver, 2000), these two species were combined in the analysis. Of the remaining snags, there was a roughly equal split between fir and incense-cedar. Maximum observed snag diameters were 93 cm for white fir, 75 cm for incense-cedar and 76 cm for pine, but snags greater than 60 cm were scarce throughout the study area (2.8 snags ha^{-1}). Reflecting the severity of this fire, surviving stems were very rare and found on only one treatment unit (study area survival rate ~0.05%).

Four 100 m planar-intercept fuels transects were established in each treatment unit for estimates of 1000 h material (7.6–20.3 cm in diameter). These were remeasured every 2 years. Sixteen shorter transects were established for 1, 10 and 100 h fuels with lengths of 1, 2 and 4 m respectively.

Total standing snag volume was calculated, as well as the amount transitioned to surface fuel at each measurement period, as a function of breast height diameter and height at each periodic measurement, by employing taper equations (Wensel and Olson, 1995). Standing bole volume was estimated from the height of the snag, with volume above the point of breakage partitioned as surface fuel. Biomass estimates were derived using specific gravity values of 0.32 for white fir, 0.41 for incense-cedar, and 0.40 for ponderosa pine (van Wagtendonk et al., 1996). These specific gravity values were assumed fixed for the 8 years of the study.

For 10,000 h surface fuels, the estimate from snag decay measurements (20.3 cm breakage) was added to the fuels transects estimate for material between 7.6 and 20.3 cm. The total biomass was thus partitioned into standing and surface fuels for two size classes: 1000+ h (7.6 cm and larger) and 10,000 h (20.3 cm and larger) fuels, plus 1–100 h surface fuels.

The total retained standing biomass of material 7.6 cm and larger ranged from 0 Mg ha^{-1} on plots with complete salvage removal of all standing snags, to 63 Mg ha^{-1} in control plots with no post-fire salvage.

In order to evaluate the suitability for cavity nesters, during the 2008 remeasurement, we located and recorded the height of all cavities excavated by woodpeckers in each standing snag. We included only those excavations that appeared to be complete as judged by the size and shape of the cavity.

3. Analysis

3.1. Direct effects of treatments

Breast height basal area of standing snags was obtained for each treatment unit after salvage was completed by taking the mean value for the 25 sample plots in each unit. This basal area retention level was used to quantify salvage intensity because it is a widely-used guide, or target, for marking crews, thus it has a direct linkage to management prescriptions. Standing fuels >7.6 cm in the summer following salvage treatments were evaluated by correlating the bole biomass of observed standing snags on the permanent plot grid to the basal area retained in each treatment unit.

3.2. Snag decay

Snag decay process for individual trees was evaluated graphically for each species across a range of four snag diameter classes (2–15 cm, 15–30 cm, 30–45 cm and 45 cm+). Average height of standing snags (those with a height > 0) was calculated for each period and percent of snags with at least some portion still standing was calculated for each species and diameter class.

We tabulated observed cavity excavation as a proportion of trees with at least one excavated cavity by species and size class.

3.3. Percent area of large wood

The relationship between the percentage of ground covered by coarse woody debris and basal area of snag retention was evaluated at each measurement period from 2 years post-fire to 8 years post-fire. Ground area for material between 7.6 and 20.3 cm was calculated directly from the fuel transects. Area for wood >20.3 cm was calculated from individual tree taper equations using the point of breakage for each observed snapped snag. Area was expressed as a percent of total acreage of the unit. The relationship with basal area retention appeared approximately linear. The data were plotted and ordinary least squares regression was fit for each observation period:

$$A_{ij} + d_{0j} + d_{1j}baret + \varepsilon_{Aij},$$

where A_{ij} = ground surface area percent covered by wood >7.6 cm in diameter at year j = 2, 4, 6 and 8, *baret* = snag basal area retained ($m^2\ ha^{-1}$), d_{0j} and d_{1j} are estimated parameters, and ε_{Aij} = random error with $V(\varepsilon_{Aj}) = \sigma^2_{Aj}$.

3.4. Surface fuel accumulation, 1000 h and larger

Models were fit for accumulated surface biomass (*SB*) as a function of basal area of snags retained for two different size classes of material. The first size class was the 1000 h and larger class including pieces >7.6 cm in diameter. The second size class is a subset of the first, and includes all material >20.3 cm in diameter. This second size class is often referred to as 10,000 h fuels. For 1000 h fuels, plots of the initial post-harvest observations, appeared to take the form of a negative exponential. In this relationship, higher levels of surface fuel biomass appeared to be associated with higher levels of salvage intensity:

$$SB_{i2} = e^{(b_1 + b_2 baret_i)} + \varepsilon_{SBi2}, \quad (2a)$$

where SB_{i2} = surface biomass >7.6 cm in diameter for plot i ($Mg\ ha^{-1}$) in year 2, and *baret* = basal area in retained snags ($m^2\ ha^{-1}$), ε_{SBi2} = random error. However, in the subsequent years, plots of the data indicated a marked change in the relationship. A power function:

$$SB_{ij} = c_{1j} baret_i^{c_{2j}} + \varepsilon_{SBij}, \quad (2b)$$

where c_{1j} and c_{2j} are unknown parameters, appeared appropriate for j = 4, 6, and 8 years post-fire. Models (2a) and (2b) were fit using SAS Proc NLIN. Although there is some evidence of increasing variance among residuals, this appeared to be weak and various weighting schemes resulted in instability in model behavior. Given that the true form of the error structure is unknown and difficult to estimate with small samples, we employed an unweighted analysis where $V(\varepsilon_{SBj}) = \sigma^2_{SBj}$. An R^2 value was obtained for each fit using corrected total sums of squares. We obtained an asymptotic 95% confidence interval for surface biomass associated with each fit (with nonlinear estimation confidence intervals are asymptotic because we rely on large sample properties).We also evaluated surface fuel biomass as a ratio (percent) of standing bole biomass retained, and fit a linear model using ordinary least squares with basal area retention as a predictor.

Accumulations of large fuel (>20.3 cm) were essentially nil in the first observation (year 2) and highly variable in years 4 and 6 due to the infrequency with which large pieces of material broke and fell early in the study. By year 8, enough larger material had accumulated to show trends in this fuel size across the levels of salvage intensity. Accordingly, we fit only one model (year 8), for 10,000 h fuels, employing the same power function as (2b).

3.5. Surface fuel accumulation, 1–100 h

Accumulations of smaller material were modeled separately for 1–10 h fuels and 100 h fuels. A repeated measures analysis was conducted for 1–10 h surface fuels over time as with a linear model and assumed first order autocorrelation to determine if there was any time or treatment effect on fine fuels.

Similarly, a quadratic model for year was fit for 100 h fuels:

$$SB_{100,i,j} = d_0 + d_1\sqrt{baret} + d_2 t + d_2 t^2 + \varepsilon_{100,i,j}$$

where t is years since fire.

4. Results

4.1. Initial impact on standing and surface biomass

Salvage treatments created a range of snag breast-height basal areas from 0 (for three units with salvage of all snags) to 38.72 $m^2\ ha^{-1}$ retained (Fig. 2). Post-treatment standing bole biomass (1000 h fuels) ranged from 0 $Mg\ ha^{-1}$, in stands where all material was removed, to a maximum of 62.5 $Mg\ ha^{-1}$ in one of the control units. Retained basal area and standing bole biomass for material >7.6 cm were highly correlated (ρ = 0.82, p < 0.001) in the year following treatment implementation. The standing

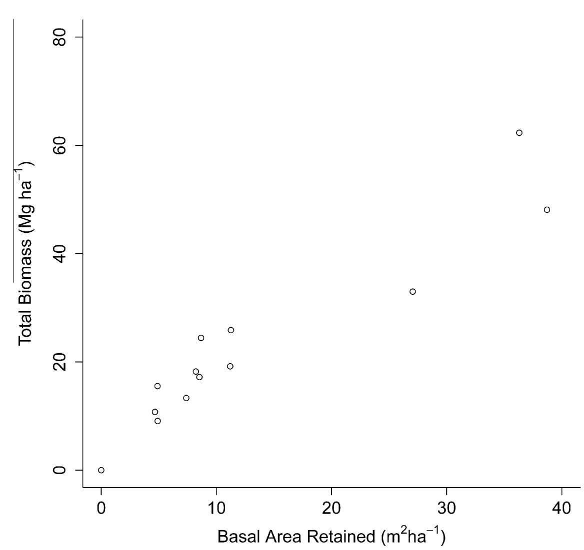

Fig. 2. Standing bole biomass (1000 h and 10,000 h fuel, 7.6 cm and larger), excluding branches, plotted over basal area retained in the salvage of fire-killed trees (note there are three data points at the origin).

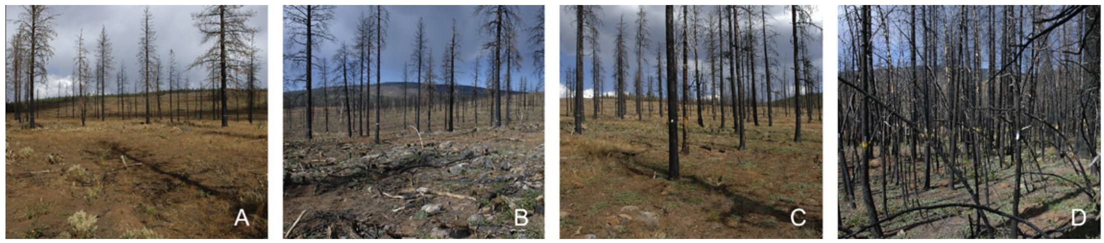

Fig. 3. Four of the variable retention units photographed in 2004, shortly after treatment with retention levels of (A) 4.7 $m^2\ ha^{-1}$, (B) 8.7 $m^2\ ha^{-1}$, (C) 11.3 $m^2\ ha^{-1}$, and (D) 36.3 $m^2\ ha^{-1}$ (unit D is an untreated control).

10,000 h biomass ranged from 0, in complete salvage units, to a maximum of 43.6 Mg ha^{-1} in unsalvaged units.

At initial post-treatment observation, surface fuels were uniformly low across the range of treatments (Figs. 3 and 4a). Total surface fuel biomass of material >7.6 cm had a mean of 3.1 and range of 0.46–3.37 Mg ha^{-1} (s.d. = 1.0). Initially, percent cover of woody fuels was also low, with material >7.6 cm ranging from 0.29% to 1.27% with a mean of 0.78 (s.d. = 0.30).

4.2. Snag decay

Retained snags typically fell in pulses during high wind events in the fall and winter months. Smaller snags most often came down entirely, by uprooting or breaking near the ground line (below 1.5 m), while larger snags more frequently snapped at some point up the stem, leaving some piece of vertical material. In this decay process, fire-killed snags became shorter, on average, over time. This process varied with both tree size and species. The mean height of the largest ponderosa pine snags (>45 cm diameter) remaining standing (height >1.5 m) decreased from about 24 m to 13 m, with 41% still standing by year 8 (Fig. 5). In contrast the smallest ponderosa pine snags (<15 cm) very rarely broke off but only 11% remained standing. Only 16% of pine snags between 30 and 45 cm were still standing; this is significantly less than that observed for large pine snags (Fisher's exact p-value = 0.0002).

Similar trends were observed for white fir (Fig. 5). Although for fir, snag stability appeared uniformly higher than those observed for pine. If we consider snag longevity on an individual-tree basis, assuming independence we can make comparisons using Fisher's exact test. For example among large snags (>45 cm) we observed 92% remaining at year 8 vs. 41% for large pine (Fisher's exact test p-value = 0.0006). The comparison of percent standing at year 8 for 30–45 cm pine vs. fir is also highly significant (Fisher's exact test p-value < 0.0001).

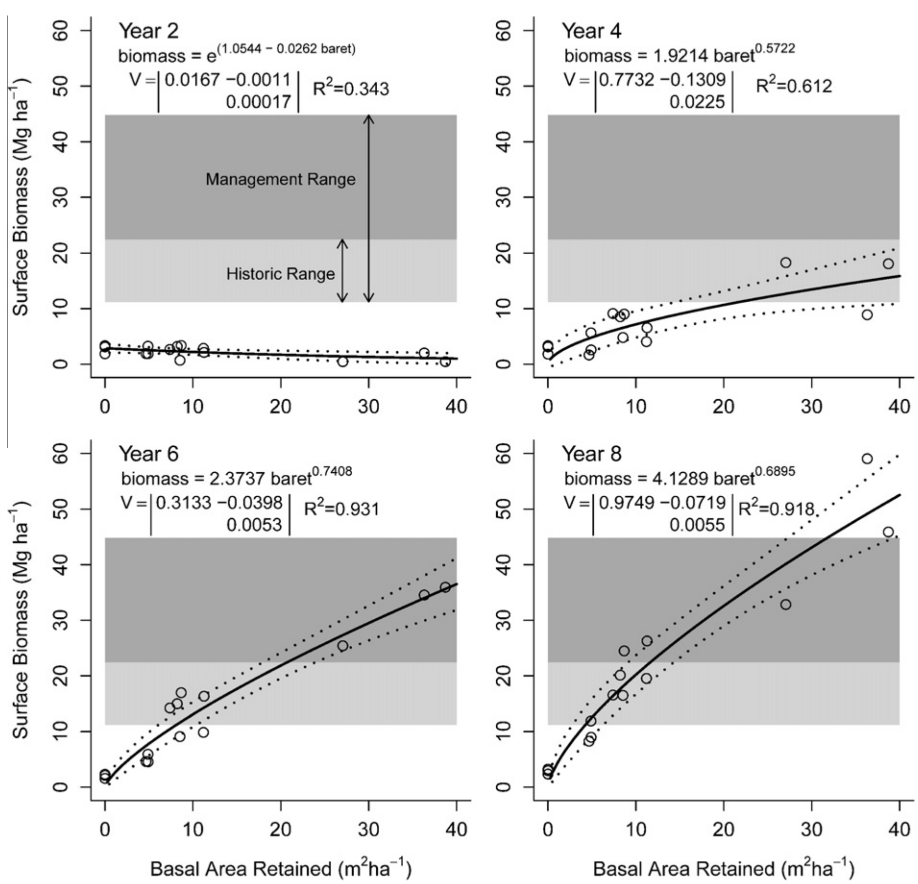

Fig. 4. Surface fuel accumulation, observed (circles) and modeled (solid line) with 95% confidence intervals (dotted lines) and parameter estimate covariance matrix (V), for material >7.6 cm in diameter, over basal area retained (*baret* $m^2\ ha^{-1}$); historic and management ranges (Brown et al., 2003) are shaded.

Incense-cedar snags were very stable for the life of the study across the range of observed diameters; snag retention was high for all size classes, ranging from 85% to 100%. Although the sample size for incense-cedars >30 cm was fairly small ($n = 22$), all of these snags were still standing in year 8. Heights of incense-cedar snags also appeared constant between years 2 and 8 (Fig. 5).

Combined density (snags ha^{-1}), using a threshold of 30 cm minimum breast height diameter and 1.5 m minimum height, decreased over time. All snags were intact at age 2. Expressed as a proportion of the year 2 snag density, the mean proportion remaining was 0.848 (s.d. = 0.115) at year 4, 0.614 (s.d. = 0.141) at year 6, and 0.404 (s.d. = 0.169) at year 8. In year 8, the proportion still standing ranged from 0.05 to 0.60.

Occurrence of cavity excavation among sampled trees appeared to increase with tree diameter and was more common in fir than pine at year 6 (Table 2). We saw little evidence of excavation

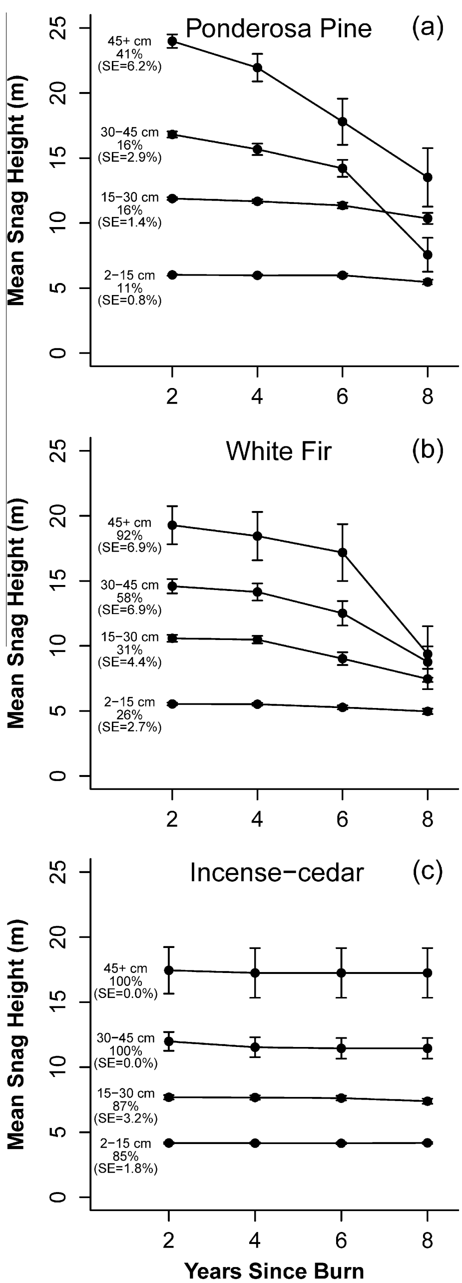

Fig. 5. Mean snag height (±1 s.e.) over time, by four diameter classes and percent of snags fallen by year 8 for ponderosa pine (a), white fir (b) and incense-cedar (c).

Table 2
Percentages of retained snags in the study area with at least 1 observed cavity by diameter class.

Species	5–30 cm	30–40 cm	40+ cm
Fir	1	23	56
Pine	.4	9	16

among incense-cedar (one observed cavity). Approximately 62% of all observed cavities in year 6 were in fir trees, although only 23% of retained leave trees >30 cm in diameter were fir at the start of the experiment. At the time of the cavity observation, this proportion had increased to 32% because of the higher rates of snagfall among retained pine.

4.3. Large wood surface area

Ground surface area covered by coarse woody debris >7.6 in diameter increased over time during this study (Fig. 6). The highest levels, about 10% at the end of the study, were associated with unsalvaged areas. There was little change in values for areas with complete removal of snags.

4.4. Surface fuel accumulation

The models (2a and 2b) for 1000-h surface fuel biomass over time show an evolving relationship between surface fuel accumulation and retained snag basal area. Initially, at year 2, the relationship is relatively weak ($R^2 = 0.34$), with the highest levels of surface fuels associated with the completely salvaged plots and decreasing as salvage intensity decreases. The parameter estimate associated with basal area retention at year 2 (Fig. 4a) is marginally significant (asymptotic p-value = 0.062). However, as with surface area, from year 4 on the relationship is stronger (R^2 from 0.61 to 0.93), and higher levels of surface fuels are associated with lower levels of salvage intensity. From years 4 to 8, the highest surface fuel accumulations are associated with the unsalvaged plots (Fig. 4b–d). The estimated root mean squared error generally increased over time, and ranged from 0.75 to 4.80 Mg ha^{-1} for 1000+ h surface fuels.

The surface biomass for fuels >7.6 cm exceeded a historic threshold (Brown et al., 2003) of 22 Mg ha^{-1} by year 8 for basal area retained above about 10 m^2 ha^{-1}. Two of the three untreated controls exceed maximum management threshold of 44 Mg ha^{-1} (Brown et al., 2003) by year 8 (Fig. 4).

When surface fuel biomass (>7.6 cm) was expressed as a percent of retained biomass, we found no linear relationship with basal area retention at any period of the study (Fig. 7). In year 4 the intercept was 18% (p-value = 0.011) and the slope term had a p-value of 0.814. In year 6, the intercept was 42% (p-value < 0.001) and the slope term had a p-value of 0.648. In year 8, the intercept was 81% (p-value < 0.001) and the slope term had a p-value of 0.757.

Although 10,000 h fuels do not influence fire spread, fuels in this size do influence resident time locally and may influence resistance to fire suppression. It took longer for 10,000 h fuels to begin to accumulate on the forest floor. Early in the study these values were very low and it was not until year 8 that we began to see a well-defined relationship with treatment. While the total biomass is naturally lower, the general shape of the relationship with basal area retention for material >20.3 cm is similar at year 8 (Fig. 8).

4.5. Surface fuel accumulation, 1–100 h fuel

We found no evidence of a treatment effect on either 1–10 h fuel ($p = 0.5536$), or 100 h fuel ($p = 0.7769$). However for both

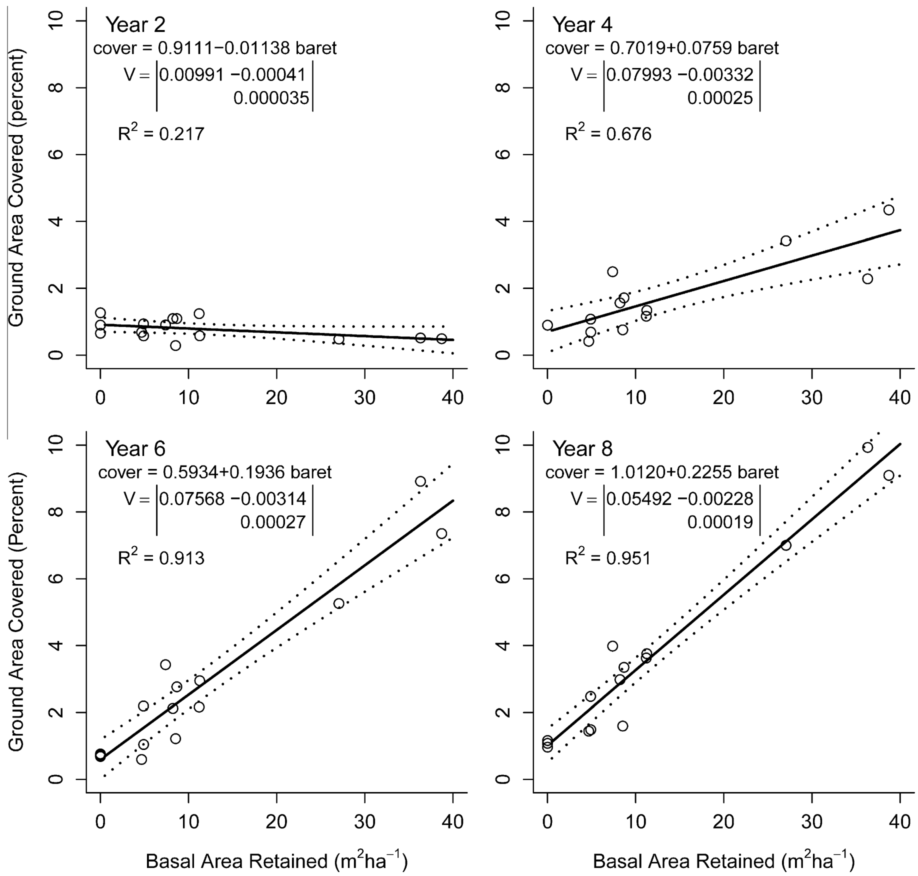

Fig. 6. Percent ground area covered by fuels >7.6 cm, observed (circles) and modeled (solid line), with 95% confidence intervals (dotted lines) and parameter estimate covariance matrix (V), over snag basal area retained (*baret* m^2 ha^{-1}).

1–10 and 100 h size material, surface fuels did appear to change over time. The coefficient for year since fire in 1–10 h fuel was −0.1200 (s.e. = 0.0235, $p < 0.0001$), indicating a decrease in fine fuels (0–2.54 cm in size) over time (Table 3). In the 100 h fuel model, a statistically significant coefficient on both t (0.999, s.e. = 0.299, $p = 0.0015$) and t^2 (−0.0856, s.e. = 0.029, $p = 0.0083$) indicates the levels for 100 h fuels may have peaked (Table 3). The maximum level for observed 100 h fuels occurred in the 6th year after the fire when there was 3.07 mg ha^{-1} (s.e.=0.21). The maximum observed mean fuel load for 1–10 h fuels was in year 2 (1.39 mg ha^{-1}, s.e. = 0.15).

5. Discussion

Initially we observed a greater amount of surface fuels with salvage logging than without. Although this trend was consistent with other findings (Donato et al., 2006; McIver and Ottmar, 2007; McGinnis et al., 2010), it was of marginal statistical significance. More importantly, the trend was of no practical significance; surface fuel levels were uniformly low and well below the historic range for fuels in this forest type (Brown et al., 2003). We found no support for the contention that post-fire salvage logging necessitates subsequent fuel treatment for elevated fuels. The whole tree removal system used in this salvage project minimized the loss of tops and limbs during logging, as indicated by the low levels of fine fuels (1–100 h).

In this ponderosa-pine dominated system, snags retained after fire fell rapidly (Fig. 9) and, over time, a strong relationship developed between the basal area of snags retained and the surface fuels accumulated. McIver and Ottmar (2007) modeled elevated surface fuel levels for unsalvaged areas 25–50 years post fire, but we observed this in evidence within only 4 years after the Cone Fire and excessive levels of surface fuels by year 8 (Fig. 4). With successive observations from years 6 through 8, the relationship between basal area retention and 1000 h surface fuel was fit well with a power function, the slope of which increased over the course of the study.

Some have suggested that snags should be retained in clumps to increase snag longevity (Chambers and Mast, 2005; Russell et al., 2006). However, it is important to note that these trends are not in evidence when surface fuel loads are expressed as a percentage of standing bole biomass retained on each treatment unit and retention is expressed as snag basal area retained. Thus at years 4, 6, and 8 after fire, the percent of standing bole biomass in surface fuels was estimated at 18%, 41% and 81% respectively indicating a trend in heavy surface fuel accumulation over time, yet the slope term was essentially zero for basal area retained, indicating no effect of increasing levels of retention on the percent of material coming down.

The general trends with surface area were consistent with those observed for surface biomass, although nonlinearity was not in evidence. Initially, increased levels of fuel surface area were associated with higher levels of salvage intensity. However, 4, 6 and 8 years after the fire, this relationship reversed as material came down from standing snags and quickly overwhelmed the levels of any material observed early in the study. By year 8, unsalvaged ground area covered by 1000 h fuels approached 10%, while completely salvaged units had around 1% of the ground covered by surface fuels. For comparison, Research Natural Areas at Blacks Mountain with heavy surface fuel accumulations had intact surface fuel cover <2.5% (Oliver, 2000).

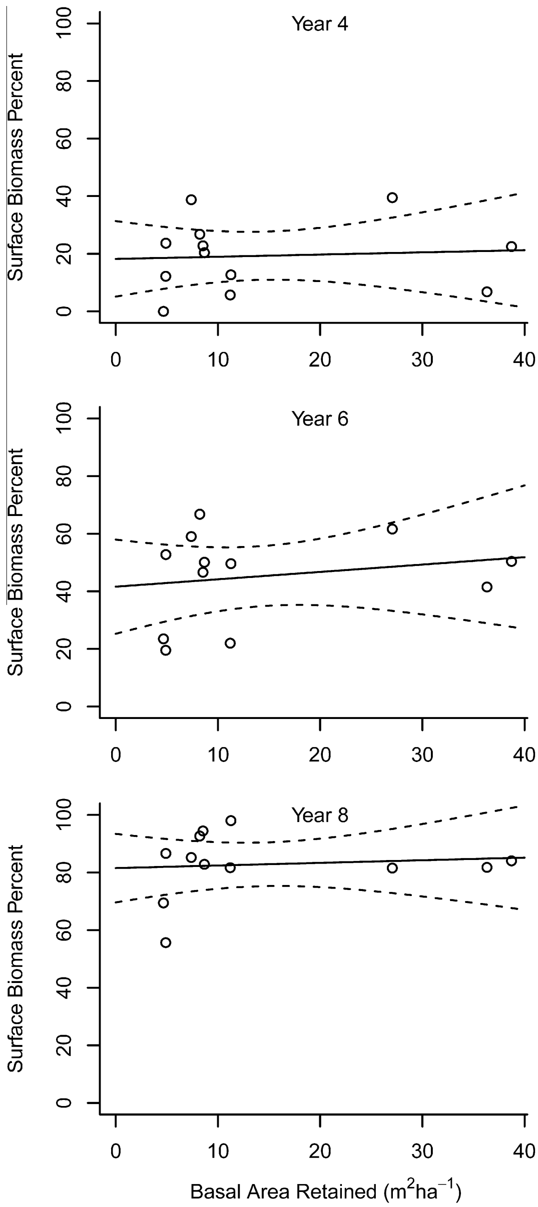

Fig. 7. 1000 h and larger surface fuel expressed as a percentage of standing biomass after treatment, with 95% confidence intervals.

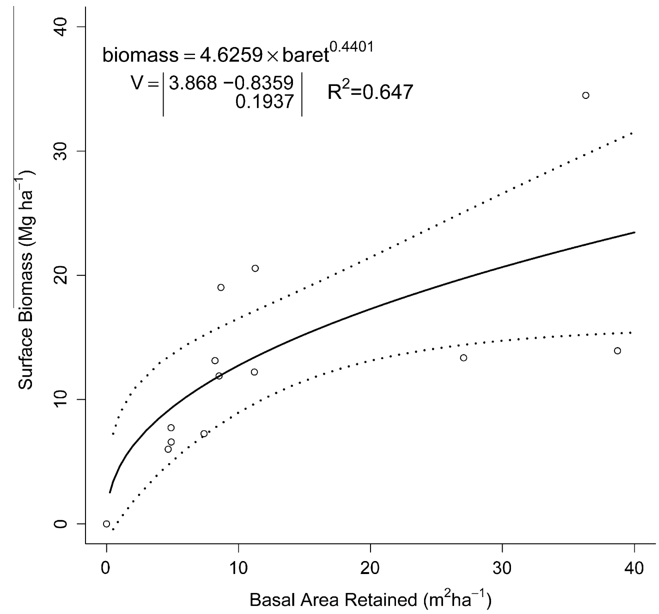

Fig. 8. Surface fuel accumulation, observed (circles) and modeled (solid line), with 95% confidence intervals (dotted lines) and parameter estimate covariance matrix (V) for material >20.3 cm in diameter (10,000 h) as a function of basal area retained (*baret* m^2 ha^{-1}).

Table 3
Observed mean (with s.e.) levels of surface fuels for 1–10 h size and 100 h size over time since fire.

Fuel size	Year			
	2	4	6	8
1–10 h	1.39 (0.15)	1.39 (0.093)	1.01 (0.074)	0.71 (0.056)
100 h	1.49 (0.21)	2.19 (0.23)	3.07 (0.21)	2.49 (0.27)

Smaller surface fuels were apparently unaffected by treatment and remained at very low levels throughout the duration of the study. Accumulations of 100 h fuels appears to have ceased by year 8 (Table 3), and this is consistent with the fact that so many of the retained snags had fallen or broken off by this time. Given the absence of large trees to contribute to litter fall, these fuel levels will remain low until the planted stand and shrub community has developed enough to begin contributing significant amounts of litter fall. The fine 1–10 h fuels actually decreased during the study. This could be due to decay of very small material over time.

The more important observation with regard to the levels of 1–100 h fuels is that they are so low as to provide for very poor rates of fire spread. The closest fuel models we could relate from Scott and Burgan (2005) would be TL1 and TU1, both of which have higher levels of fine fuels and are associated with low to very low rates of spread.

There is some evidence of a greater rate of accumulation of small fuels in the unsalvaged areas, however since this is based on only three control plots, it is not possible to draw any strong conclusions in this regard.

The historic range for surface fuels of 11.2–22.4 presented by Brown et al. (2003) was exceeded by year eight for stands with 10 m^2 ha^{-1}, in retained snags. The 44 Mg ha^{-1} upper limit of the recommended management range from Brown et al. (2003) was exceeded by year eight for two of the unsalvaged units in our study, with the maximum observed surface fuel load of 60 Mg ha^{-1} 8 years post fire. None of the salvaged units exceeded the recommended management range, although some do exceed the historic range from Brown et al. (2003).

It has been recommended that, rather than salvaging snags, it would be advisable to allow fire-killed trees to remain and fall periodically over a span of decades (Donato et al., 2006). This strategy does not appear viable at Blacks Mountain; since most retained biomass fell within the first 8 years, there will be little left to come down in subsequent decades (Fig. 7).

While similar stands dominated by poles and small to medium saw-timber are common in interior forests throughout the western United States, the scarcity of large trees (>60 cm) means that total post-fire surface fuel accumulations at Blacks Mountain are limited due to the absence of any large individuals that can contribute substantial amounts of biomass. It also means that the observed surface fuel accumulations likely occur at a greater rate than would be observed for an area featuring large old trees (those greater than 60 cm in diameter), as larger snags tend to be retained longer on the landscape.

Snags retained after fire can provide important habitat, particularly for foraging and reproduction of numerous species of birds.

Fig. 9. Plot 12, a treatment unit with 11.3 m^2 ha^{-1} in retained snags, photo-point 2 years after the fire (1000 and 10,000 h surface fuel = 2.12 Mg ha^{-1}, snags ha^{-1} = 60) and 8 years after the fire (1000 and 10,000 h surface fuel = 26.3 Mg ha^{-1}, snags ha^{-1} = 3), an illustration of dynamics of standing snags and fuel accumulation after fire.

Eight years after the Cone Fire, most of the ponderosa pine snags had fallen. Only 16% of pine snags between 30 and 45 cm and 41% greater than 45 cm were still at least partially intact, so the contribution to wildlife habitat in retained pine snags was brief relative to the time it will take to grow replacement trees of sufficient size to produce habitat in the future. In contrast, about 92% of fir trees >45 cm were still partially intact after 8 years with a mean height of just over 9 m. Even for fir snags between 30 and 45 cm, 58% were still partially intact 8 years post fire. Early in the life of the study, the breakage of fir snags, particularly the largest snags (>45 cm) lagged well behind the rate for pines, however this gap has closed somewhat with the most recent observations. Thus, the opportunities for cavity nesting birds appear to be greater for retained fir than pine, at least within the time frame of this study. The difference between large and small snag fall rates confirms findings of others (e.g. Dahms, 1949; Raphael and Morrison, 1987; Chambers and Mast, 2005). The greater longevity of white fir snags was also observed by Landram et al. (2002). Managers may want to consider favoring white fir snag retention over ponderosa pine.

Although incense-cedar was extremely stable over the life of the study and has contributed little to surface fuel loading, we observed little cavity excavation among these snags indicating no value for cavity nesting during the study.

When expressed as a density value, the number of snags ha^{-1} >30 cm in diameter and >1.5 m in height was reduced by decay and breakage to 40% at year 8 with a 95% confidence interval of 29–51%. Although variability of snag retention proportions increased over the life of the study, future values will begin to stabilize and show lower variability as some plots are already approaching a percentage of zero by year 8.

Overall, snag retention was fairly brief in relation to the amount of time it takes to grow a replacement tree in these dry interior forests. For example, with a site index of 23 m at age 100, stands at Blacks Mountain will take over 100 years of unmanaged stand development to achieve an average tree diameter of 30 cm (Meyer, 1938). Yet, the contribution to surface fuels and fire hazard of 1000 h fuels could present a long-term problem. With the poor retention rates of pine snags below 45 cm dbh in particular, managers need to weigh whether the contribution to habitat is worth the longer-term contribution to surface fuel levels and the loss of revenue associated with retaining merchantable snags of this size. The number and species of snags to be retained may be influenced by these considerations.

Favoring large trees for snag retention reduced harvest revenue. However, this type of partial salvage also promoted nesting and foraging habitat for some cavity nesting species. In stands with a cohort of large trees (>60 cm) this tension between habitat, biomass accumulation and economic viability may be increased. Even in the absence of large diameter trees, high levels of surface fuels, exceeding historic levels (Brown et al., 2003), may result within a relatively brief time period if salvage harvests are not completed. Elevated surface fuels can constitute a significant risk to the succeeding stand (Agee and Skinner, 2005) and present a challenge and safety risk to fire crews in any subsequent burn of these areas.

The uniformity and severity of burn may also have resulted in accelerated fall rates observed in this study. Harrington (1996) found accelerated rates of snag-fall among small ponderosa pine trees killed at the time of the fire in comparison to trees that succumbed to secondary mortality.

It is important to understand the tension between costs and benefits of fire salvage and the influence of species and tree size. Managers should be aware that after high-severity fire in a dry interior pine forest with few large snags (>45 cm diameter), the maintenance of standing dead material appeared to be brief in comparison to the anticipated growth and development of the subsequent stand. Retention of snags should be influenced by considerations of species and tree size, as well as the timing of tree mortality relative to the fire event.

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