Thinning and Prescribed Fire Effects on Snag Abundance and Spatial Pattern in an Eastern Cascade Range Dry Forest, Washington, USA

Paul F. Hessburg, Nicholas A. Povak, and R. Brion Salter

Abstract: Mechanical thinning and prescribed burning practices are commonly used to address tree stocking, spacing, composition, and canopy and surface fuel conditions in western US mixed conifer forests. We examined the effects of these fuel treatments alone and combined on snag abundance and spatial pattern across 12 10-ha treatment units in central Washington State. A snag census was conducted before and immediately after treatments on each unit where all snags were measured and classified as either "new" (<1 year as a snag) or "old" (>1 year as a snag) mortality, and bark beetle species were censused on the bottom 3-m of the bole. Before treatment, snags were found in all units and more than two-thirds of the snags were ponderosa pine. Burning (burn-only and thin + burn combined) treatments led to increases in total snag abundance in all but the largest diameter class. Snag abundance in the large snag class (>60 cm dbh) decreased in most treatment units indicating that units with high abundance before treatment had the potential to lose more snags with treatment or time. Treatments also affected the spatial distribution of snags. The thin-only treatment reduced clumpiness, leading to a more random snag distribution, whereas the burn-only and thin + burn treatments generally retained or enhanced a clumped snag distribution. Bark beetles attacked >75% of snags across all units before and after treatments, and red turpentine beetle (*Dendroctonus valens* LeConte) occurrence tended to increase after prescribed burning. Managers can use this information to tune silvicultural prescriptions to meet stocking, spacing, and fuel reduction objectives while retaining or recruiting snags, thereby increasing the utility of conditions for certain wildlife species. FOR. SCI. 56(1):74–87.

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SNAGS ARE THE KEY structural element of standing dead vegetation in most western US forest ecosystems, including the dry mixed conifer forests of eastern Oregon and Washington (Bull et al. 1997, Bull 2002). In addition to providing structural complexity, snags supply nesting, roosting, and hiding cover for a wide variety of vertebrate species (Rose et al. 2001) and forage habitat for woodpeckers and associated bird species by providing bark, ambrosia, and wood boring beetle larvae (Saab and Dudley 1998, Saab and Powell 2005). Snags also play integral roles in forest nutrient cycling dynamics by continuously adding organic detritus and coarse woody debris to the forest floor. This has important implications for fuel continuity and fire spread, soil organic matter development and fertility, and site productivity.

In the eastern Washington Cascade Range, the dry mixed conifer forests (hereafter, dry forests) occupy the warmest and driest environs of the Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl) zones (*sensu* Franklin and Dyrness 1988). There is now broad agreement that 20th century settlement and management activities have resulted in present-day dry forests with lengthened fire-free intervals (Hessburg et al. 1999, 2005; Everett et al. 2000, Hessburg and Agee 2003, Wright and Agee 2004) and altered live and dead forest structure and tree species composition (Harrod et al. 1999, Hessburg et al. 1999). Over a century of fire exclusion, fire suppression, selective harvesting, and domestic livestock grazing, among other factors, have led to substantive increases in forest density, compositional change toward shade tolerance and fire intolerance, loss of structural diversity, increased wildfire potential, increased susceptibility to bark beetle (Coleoptera: Curculionidae, Scolytinae) attack, and other important changes. Repeated selective harvest entries have reduced the occurrence of large-diameter trees (>60 cm dbh [1.37 m]), which in turn has reduced the abundance of large snags favored by some wildlife species (Saab and Dudley 1999, Lehmkuhl et al. 2003, Bagne et al. 2007).

Fuel reduction treatments are used in the western US with increased regularity to reduce the potential for stand-replacing wildfires, restore the native fire ecology, control insect- and disease-related tree mortality, and shift forest structural and compositional attributes to fall within more natural ranges (Landres et al. 1999, Gaines et al. 2007). The main objective of such treatments is to reduce intertree competition through the removal of small- to medium-diameter trees in the lower crown classes using mechanical

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thinning and prescribed burning treatments, alone or combined (Dodson et al. 2008). Treatments may directly affect the abundance, density, size and decay class distributions, species composition, and spatial arrangement of snags, by creating new snags and/or removing snags that were present before treatment (Saab et al. 2006, Bagne et al. 2007).

Bark beetles can cause further tree mortality after fuel reduction treatments by attacking weakened or damaged residual trees (e.g., Sullivan et al. 2003, Wallin et al. 2003, Parker et al. 2006, Fettig et al. 2007). Furthermore, accumulations of downed woody debris immediately after mechanical thinning operations may release chemical attractants, thereby supplying bark beetles with breeding and over-wintering habitats (Hindmarch and Reid 2001). Subsequent bark beetle-caused tree mortality may lead to undesired levels of standing fuels, reductions to forest density, or altered species composition, and may require future management (Fettig et al. 2007). Managers need tools to predict and evaluate the effects of various fuel reduction treatments on snag abundance to tailor prescriptions to meet management objectives.

Whereas premanagement era live-tree densities have been studied in some dry forests via stand-level reconstructions (e.g., Covington and Moore 1994, Fulé et al. 1997, 2002; Harrod et al. 1999), snag abundance and spatial pattern are less understood because of their transience (Harrod et al. 1999). In this study, combinations of thinning and burning treatments were applied to dry mixed conifer forests of eastern Washington State, where density management, fuels reduction, and reduction of stand susceptibility to bark beetle attack (>18–20 m^2/ha basal area) were the primary treatment objectives. The objectives of this study were to quantify pre- and posttreatment snag abundance, size, type, and spatial distribution in treatment units, determine the effects of thinning and burning treatments on snag abundance and spatial point patterns, and quantify the assemblage of tree-killing bark beetles present before and after treatments.

Methods

Study Area

The study was conducted in the eastern Cascade Range of Washington State within the confines of the Okanogan-Wenatchee National Forest (Figure 1). The study site, known as Northeastern Cascades (47°25′42″N, 120°32′42″W; elevation range: 620–1,228 m), was one of 12 in the Fire and Fire Surrogate (FFS) project (Fire Research and Management Exchange System 2008); a long-term study to assess the ecological impacts and effectiveness (for reducing stand density, fuels, and susceptibility to bark beetles) of surrogate treatments such as thinning, which are used instead of or in combination with fire (see McIver and Weatherspoon 2009 for detailed information on the FFS study network).

Dry forests of the study area are dominated by ponderosa pine (*Pinus ponderosa* Dougl. *ex* Laws) and Douglas-fir in the overstory, with understory layers comprised of a mixture of Douglas-fir, ponderosa pine, and occasionally grand fir. Plant associations are those on the dry end of the Douglas-fir and grand fir series (Lillybridge et al. 1995, Dodson et al. 2008). Climate of the area is continental but with rain shadow effects produced by the Cascade Range. Average annual precipitation is about 56 cm, mostly occurring as snow during the winter months. Soils of the study area are stony, sandy loams and stand slope averages vary from 30 to 50% (Zabowski et al. 2009).

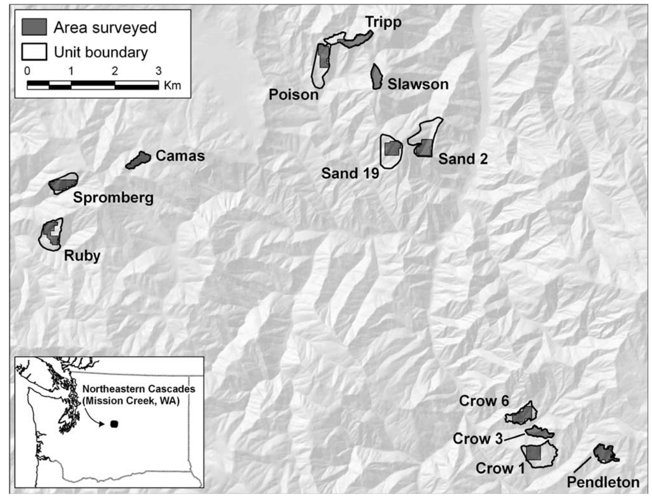

Figure 1. Vicinity map of the Northeastern Cascades site of the FFS project in central Washington State showing treatment unit boundaries and surveyed areas.

Treatments

Twelve treatment units, 10 ha in size, were chosen for the study (Figure 1). The treatments were: (1) commercial thinning only, (2) prescribed fire only, (3) commercial thinning followed by prescribed fire, and (4) untreated control. Treatment assignment was random, producing three replicates of each treatment, with the exception that two units were not considered for prescribed fire because of road access limitations and another because of the presence of the northern spotted owl (*Strix occidentalis* caurina). Treatment units were relatively homogeneous stands occurring mostly on southerly aspects. Objectives common to all treatment methods were to restore low-density dry forest stand structure, reduce ladder and surface fuels, and reduce the risks of bark beetle attack and high-severity fire. The overarching objective of the national FFS study was to yield posttreatment stands with an 80% codominant and dominant tree survival rate under an 80th percentile fire weather scenario (McIver and Weatherspoon 2009).

Thinning treatments were designed to reduce stand density and favor drought and fire-tolerant species (i.e., the largest ponderosa pine and Douglas-fir). Residual densities were targeted to fall within the estimated historical density and spatial distribution for the area (approximately 10–14 m^2/ha at irregular spacing based on Harrod et al. 1999). Stands were generally thinned from below, leaving the largest and most vigorous trees. The thinning prescription called for leaving 1.5–2.6 snags >25 cm dbh/ha as follows: 0.7–1.2 snags/ha in the 25–37 cm snag diameter class, 0.4–0.8 snags/ha in the 38–50 cm snag diameter class, and 0.4–0.6 snags/ha in the >50 cm snag diameter class. Snag leave densities were adapted from Harrod et al. (1999). Thinning was accomplished with chainsaw felling during the winter of 2002–2003. Merchantable logs were limbed after felling such that tops and branches remained on site, and merchantable logs were helicopter-yarded to landings external to the study area. Nonmerchantable trees were also felled and left on site. Snag removal due to occupational safety and health concerns during the thinning operations was required, which may have precluded meeting snag stocking requirements in portions of some units.

Prescribed fire treatments were conducted on only four of six burn units in the spring of 2004 because of unsuitable burn conditions (rapid spring green-up), which left two units unburned in 2004. The final two units scheduled for prescribed burning were later burned in 2006 to balance the study design for future measurements, but data were not collected after those burns because of a lack of funding. Thus, analyses for the current study were based on an unbalanced design (control, $n = 4$; burn-only [BO], $n = 2$; thin-only [TO], $n = 4$; and thin + burn [T+B], $n = 2$). Ignition was by hand and helicopter lighting. In 2004, flame lengths ranged from 0.2 to 1.0 m, and burns were patchy (23–51% area blackened) with the spring burn conditions (Agee and Lolley 2006). After treatments, Agee and Lolley (2006) estimated total forest floor mass to be 44.7, 48.7, 26.1, and 27.3 Mg/ha on control, TO, BO, and T+B treatment units, respectively.

Snag Survey

Pretreatment (2000) and posttreatment (2004) surveys were conducted as a complete census of all snags ≥20 cm dbh in a contiguous 10-ha area within each treatment unit during the late spring to early autumn. Smaller snags are generally considered less important for roosting and nesting habitat and therefore were ignored in our assessments (Saab and Powell 2005). Field crews were supplied with 0.25-m resolution color digital orthophotos of each treatment unit (1:900 photo scale) where unit boundaries, a 40 × 40 m grid, and 10-m elevation isoclines were superimposed to aid in navigation. All snags ≥20 cm dbh were located and surveyed (see below), and their locations were plotted on the orthophotos in the field. These data were then digitized with ArcGIS (Environmental Systems Research Institute, Inc. 2006) for further analyses.

In the field, each snag was categorized by tree species and mortality class: either "new" (<1 year as a snag) or "old" (>1 year as a snag) (Table 1), and dbh and total tree height were recorded. Mortality classes were based on several factors including (1) the degree of needle chlorosis/necrosis, (2) the degree of fine-branch retention, (3) condition of the cambium (proportion live or dead), (4) bark condition (loose or solid), (5) signs and symptoms of bark beetle attacks, and (6) signs of wood-boring insects (Table 1). Mortality classes were used to identify significant pulses in mortality that may have occurred immediately before treatment in 2000 and to differentiate treatment-related from other mortality in the field after the burn treatment implemented in spring of 2004.

Table 1. Categories of dead and dying trees surveyed at the Northeastern Cascades site of the Fire and Fire Surrogate project in central Washington State

Main and Subcategories	Characteristics
New snags[a]	
Killed—current year	In mid to late summer, the cambium is necrotic, all foliage is red but fully retained, fine branches are retained, bark is solid and attached, bark beetle activity is evident throughout the length of the bole by pitch tubes, reddish brown boring frass and entrance holes to egg galleries, sapwood decay and basidiomes are absent
Attacked—current year	In spring to early summer, the cambium is alive or mostly so, all foliage is retained but onset of chlorosis is evident, bark is solid, bark beetle activity is evident throughout the length of the bole by pitch tubes, reddish brown boring frass and entrance holes to egg galleries, sapwood decay, and basidiomes are absent
Old snags	
Dead (1–2 years)	Cambium is dead, most needles are cast, most fine branches are retained, bark is solid but may be removed easily and may have evidence of recent wood borer or older bark beetle activity
Dead (>2 years)	Sapwood has decay, some bark is sloughed, evidence of significant old wood borer galleries is present, fine branches have been lost, top may be broken out, evidence of bark beetles is old, signs of woodpecker activity may be seen

Statistical analyses were run separately for the main categories of new, old, and total (new + old) snag classes.
[a] The terms "new" and "old" are used relative to the two sampling periods (pre- and posttreatment). For example, a snag classified as "new" is <1 year as a snag at the time of survey, whereas one classified as "old" is >1 year as a snag at the time of survey.

Bark Beetle and Wood Borer Survey

An additional survey of the bark beetle species attacking the lower 3 m of the tree bole was incorporated with the snag census, in which the signs and symptoms of bark beetle attack were directly assessed on each tallied snag. This survey could not account for the presences of *Ips* species inhabiting the upper portions of tree boles and therefore conservatively estimated occurrence of this beetle. Bark beetle species were identified by the characteristic egg and larval gallery patterns, the presence of pitch tubes, the presence and color of boring frass, and the presence and number of egg gallery ventilation holes, by examination of living and dead pioneering females and callow adults that had been killed by parasites and predators in galleries, by the tree species attacked, and by the location of the attack on the bole (Goheen and Willhite 2006). Evidence of wood boring insects (Coleoptera: Buprestidae and Cerambycidae) was also recorded using methods similar to those for the bark beetle survey, but only the presence or absence of wood borers was identified using their characteristic gallery patterns.

Statistical Analysis

Two-way analysis of variance (ANOVA) was used to test for initial differences in snag abundance before treatment. Two-way ANOVA was chosen because of the low replications for BO and T+B treatments, which were insufficient to draw inferences on individual treatment effects. Treatments were grouped into main treatments (i.e., thinned/unthinned and burned/unburned), which increased sample size, reduced error variance, and allowed us to look at both main treatment effects and interactions. Response variables were total snag densities and basal area, density of small (20–39.9 cm), medium (40–59.9 cm), and large (>60 cm) dbh snags, density of snags attacked by bark beetles, and snag quadratic mean diameter (QMD). QMD is defined as the diameter of the tree of average basal area in the stand, a standard metric used in many forest biometry applications (Curtis and Marshall 2000). All analyses were run separately for new and old snags and total tree mortality.

Treatment effects on snag basal area, abundance, and diameter and occurrence of bark beetle species were analyzed separately for each snag mortality class (i.e., new, old, and total). Two-way analysis of covariance (ANCOVA) was used to analyze change in new, old, and total snag mortality as a function of treatment. The response variable for these models was the change in condition from pre- to posttreatment, and the pretreatment value was used as the covariate. If the covariate was not significant ($P \leq 0.10$), it was removed from the model, resulting in an ANOVA. New snags were analyzed using ANOVA with the posttreatment value as the response. A covariate was not included in these models because this analysis was used to directly test the effect of treatments on the creation of new snags.

For all analyses, response variables initially violated ANOVA normality assumptions based on Q-Q normal plots, histograms, and Shapiro-Wilk's test of normality and were natural log-transformed. We used Levene's test for equality of variances to verify the equality of individual treatment variances. Scatter plots of the standardized residuals versus standardized predicted values were used to evaluate error distribution. When normality assumptions were violated, response variables were transformed using natural log transformations. The GLM procedure in SAS (version 9.1.2; SAS Institute Inc. 2004) was used for all ANOVA/ANCOVA, and the univariate procedure was used for all diagnostic analyses). For ANCOVA models, we determined, on the basis of the scatter plots of response variables versus pretreatment levels, that there were no differences in slopes among treatment combinations, and a common slope model was assumed for all analyses.

We accepted $P \leq 0.10$ as the observed probability level for type I error in hypothesis tests. Although less conservative than $P \leq 0.05$, we considered $\alpha = 0.10$ to be an acceptable chance of type I error for large-scale field studies with low replication and well within the bounds of convention (Zar 1999). A significant difference is implied when a difference among means is reported, but we report exact P values in the text to allow readers to assess the probability of error relative to their standard of significance (Zar 1999). Similar studies have used a less conservative $\alpha = 0.10$, citing reasons such as inherently low statistical power because of small sample sizes (Fulé et al. 2007) and an inflated type II error rate because of several multiple comparisons on various response variables (Youngblood et al. 2006), both of which are germane to the current study.

We used indicator species analysis (ISA) to identify whether any bark beetle species was associated with any main treatment (thinned versus unthinned or burned versus unburned) (Dufrene and Legendre 1997). ISA combines information on relative abundance and constancy of species to estimate the indicator value of a species. The maximum indicator value for a species within the treatment types was tested for statistical significance against random expectation calculated by 4,999 Monte Carlo permutations. The response variable for ISA was the density of new snags attacked by each recorded beetle species. The change in the number of snags attacked by bark beetles was analyzed using ANCOVA for each species of bark beetle separately. ISA analysis was run in PC-ORD (version 5.0; McCune and Mefford 1999).

The spatial point pattern of snags before and after treatments was assessed using a univariate Ripley's K analysis, which tests the hypothesis that the spatial arrangement of snags does not deviate from complete spatial randomness (CSR) (Ripley 1988, Haase 1995). The function is defined such that the density of points within an area (λ) multiplied by Ripley's K statistic, $K(d)$, is equal to the expected number of points within radius d. In this application, point patterns of snags were analyzed at 1-m intervals to a distance of 100–150 m, depending on the shape of the treatment unit. The "*K*est" and "envelope" functions in the *SpatStat* package in R (version 2.5.1) were used for this analysis (Baddeley and Turner 2005). Ripley's isotropic correction was used to reduce bias due to edge effects (Ripley 1988). A linear transformation, $L(d)$, was used following the method of Besag (1977), with $L(d) = \sqrt{(K(d)/\pi)} - d$, where the expected value for CSR at distance d is zero. Values of $L(d) > 0$ indicate a clumped pattern, values <0 indicate a uniform pattern, and values ~ 0 indicate a random pattern. A 95% critical envelope was calculated for each unit using the default point-wise option in *SpatStat*, which computes critical values using 99 Monte Carlo simulations at each distance d.

Results from the unit-level Ripley's K analysis were pooled to the treatment level to help identify treatment effects on the spatial pattern of snags. We followed the functional data analysis (FDA) methods described by Youngblood et al. (2004). As described by Youngblood et al. (2004), the spatial point patterns of individual plots cannot be directly pooled together because the Ripley's K function is sensitive to the number of points, the plot area, and the plot shape. A reasonable way to avoid this problem is to use FDA, a nonparametric technique used when the data are curves or functions rather than discrete points (Ramsay and Silverman 1997). To accomplish FDA, we applied a general B-spline with 10 basis functions (no internal knots) to convert discrete $L(d)$ estimates for each unit at each time period to functional data curves and then calculated the average of these curves. The flexibility (i.e., the number of base functions) used in smoothing the data is arbitrary, and we chose a level that maximized smoothing while expressing the within-treatment variability observed in the spatial patterns. To determine significance of the pooled estimates of $L(d)$, we again followed the methods of Youngblood et al. (2004). The outcomes of the 99 Monte Carlo simulations for each unit at each survey period (pre- and posttreatment) were used to estimate the variance, $V(d)$, in CSR at each distance (d). These estimates were averaged for each treatment using the same FDA techniques outlined above for the $L(d)$ function. Standard errors were calculated as $SE = \sqrt{V(d)/n}$, with n equal to the number of pooled treatment units. Confidence envelopes (±2 SE) were constructed to determine significant departures from CSR. A maximum search distance of 60 m was used in the FDA, as this was the maximum distance common to all units.

Results

Pretreatment Snag Census

Initial snag density and basal area across all treatment units averaged 54.8 ± 44.1 (SD) snags/10 ha and 7.8 ± 4.5 m^2/10 ha, respectively. Snag density and basal area were higher on thinned (TO and T+B) units compared with unthinned (control and BO) units (ANOVA; $P < 0.09$). Snag diameters followed a negative exponential distribution, with the majority of stems in the 20–39.9 cm dbh class and fewer larger stems (Figure 2). Within diameter classes, there were more medium-sized snags (40–59.9 cm dbh) on

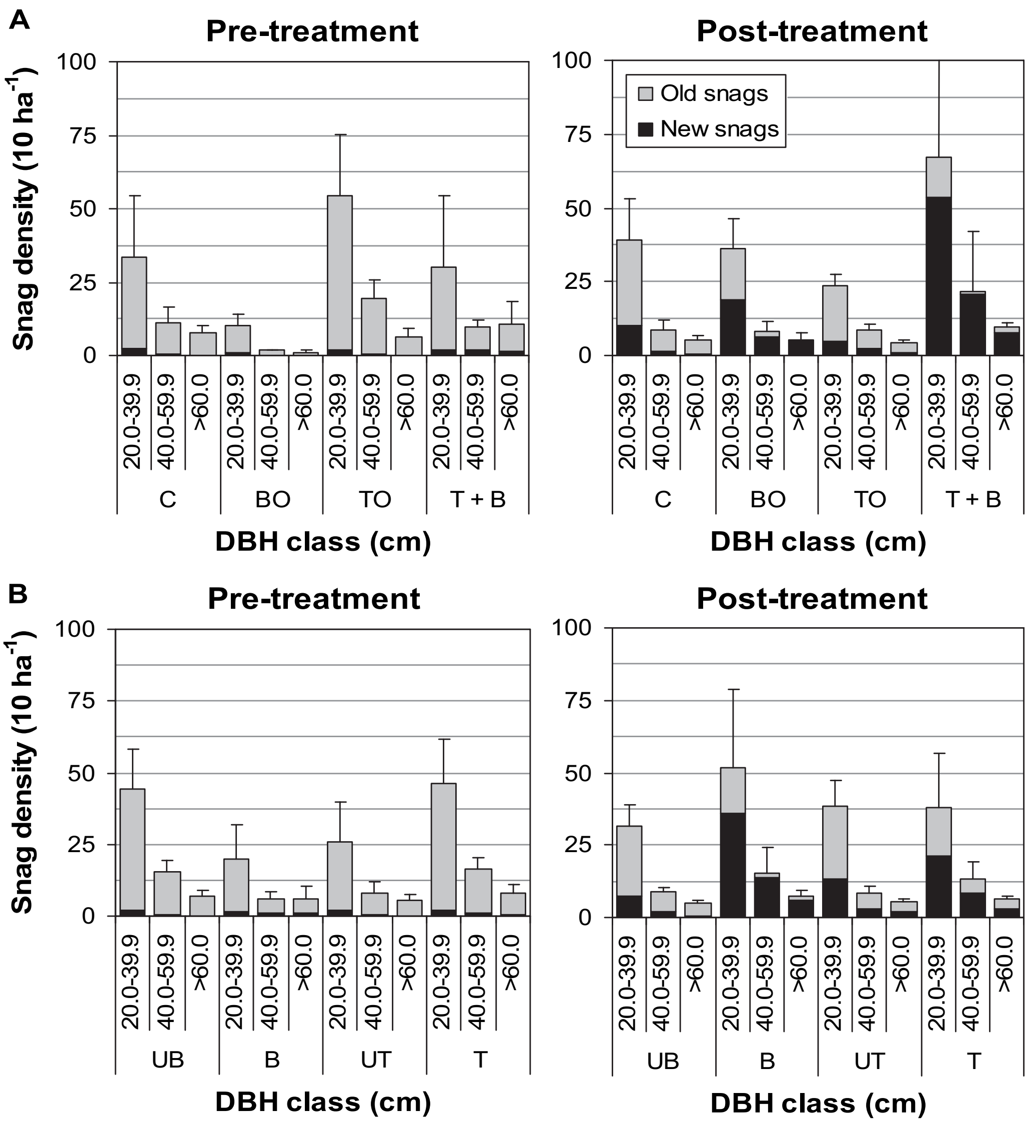

Figure 2. Diameter distribution of snags before and after treatments in the Northeastern Cascades site of the FFS project in central Washington State. Results are presented by (A) individual treatment effects and (B) main treatment effects. Old snags were trees that died >1 year before the survey and new (current year) snags died <1 year before the survey. Error bars represent mean ± SE for all snags combined (old + new). Treatments are as follows: (A) C, control; BO, burn-only; TO, thin-only; T+B, thin + burn; (B) UB, unburned (control and thin-only); B, burned (burn-only, thin + burn); UT, unthinned (control and burn-only); T, thinned (thin-only and thin + burn).

unburned versus burned units (ANOVA; $F = 3.78$, df = 1, 8; $P = 0.088$) and on thinned compared with unthinned units (ANOVA; $F = 5.17$, df = 1, 8; $P = 0.052$) (Figure 2). QMD averaged 46 cm for all snags across all treatment units.

Most snags (94%) were old (>1 year as a snag), suggesting that recent mortality from fire, insects, diseases, and other agents was modest before treatments. Consistent with the live tree stocking (Dodson et al. 2008, Hessburg et al. 2008), ponderosa pine comprised more than two-thirds of snags across all units, Douglas-fir comprised approximately one-quarter, and grand fir the remainder. Evidence of past and recent bark beetle activity was observed in all treatment units and >85% of the snags showed evidence of mass attacks by bark beetles. Incidence of active bark beetle attacks was low before treatments with approximately 3 new snags/10 ha showing signs of beetle activity in the year of the pretreatment survey. Evidence of a *Dendroctonus* spp. was most abundant on all snags (new + old), including the western pine beetle (*Dendroctonus brevicomis* LeConte), the mountain pine beetle (*Dendroctonus ponderosae* Hopkins), the Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins), and the red turpentine beetle (*Dendroctonus valens* LeConte), in order of declining abundance. Species of other genera, including *Ips* and *Scolytus*, were also present, but were much less common (Figure 3).

Treatment Effects on Snag Abundance—Burning

Burning caused a two-fold increase in total snag density (old + new snags >20 cm dbh) (ANOVA; $F = 5.22$, df = 1, 8; $P = 0.052$), and snags averaged 74 snags/10 ha after treatment on the four burned (BO and T+B) units. Burning led to a shift in the dominant snag class from old to new snags, with new snags representing three-quarters of all snags on these units. Accordingly, burning increased the density of new snags compared with unburned units (ANCOVA; $F = 8.40$, df = 1, 7; $P = 0.023$). The pretreatment covariate in this model (Table 2; $F = 7.73$, df = 1, 7; $P = 0.027$) indicated that pretreatment density of current year snags influenced levels after treatment (i.e., units with high pretreatment abundance tended to have high posttreatment abundance), and when this effect was accounted for, there was still a significant burn effect. Burning had no effect on the density of older snags >20 cm dbh (ANCOVA; $P > 0.1$) (Table 2); rather, units with high old snag abundance before treatment lost more snags over time regardless of treatment (ANCOVA; pretreatment, $F = 26.67$, df = 1, 7; $P = 0.001$).

The basal area of new snags increased (ANCOVA; $F = 10.32$, df = 1, 7; $P = 0.015$) (Table 2) and that of old snags decreased on burned units compared with unburned units (ANCOVA; $F = 4.20$, df = 1, 7; $P = 0.080$); however,

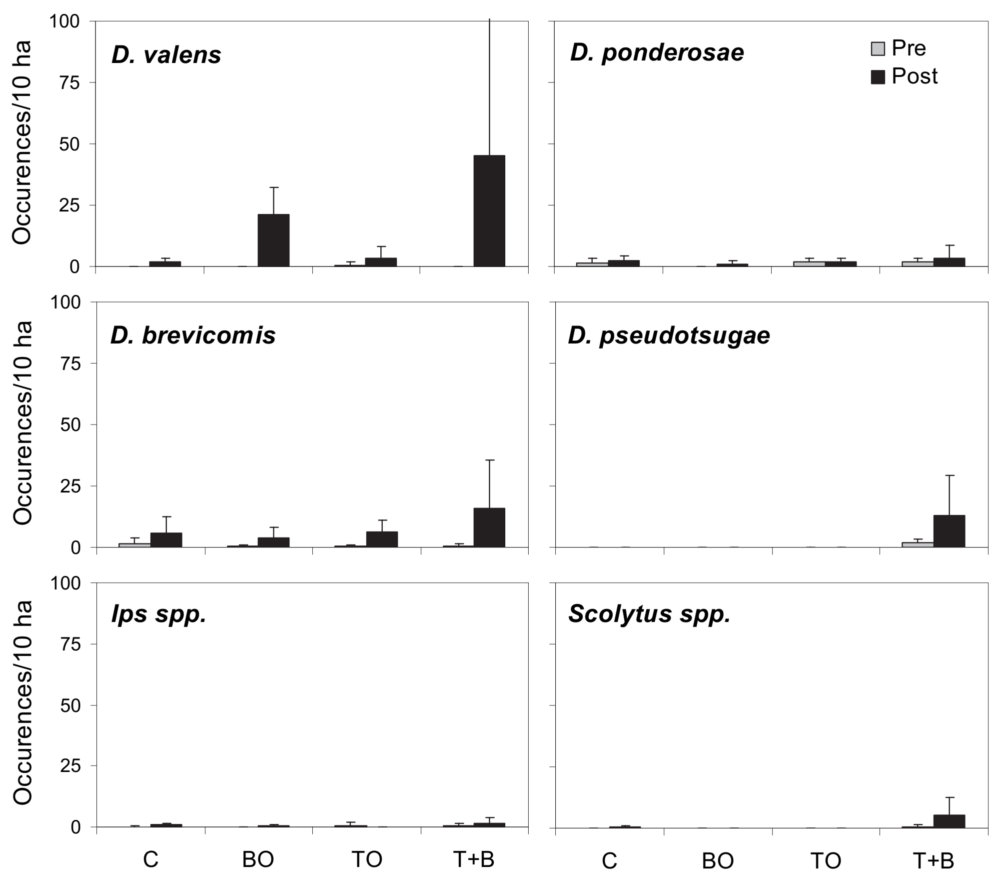

Figure 3. Percentage of total snags attacked by different species of bark beetles before and after fuel reduction treatments at the Northeastern Cascades site of the FFS project in central Washington State. Bark beetle species were recorded in field surveys if evidence of current or prior mass attack was found on dead or dying trees of a treatment unit. Error bars represent mean ± SD.

Table 2. Summary of ANCOVA model results for the change in snag stocking and size after fuel reduction treatments

Snag class	Response variable	R^2	P	RMSE[a]	Pretreatment P	Thin P	Burn P	Thin × burn P
Total	Density (>20 cm dbh)	0.473	0.144	45.540	X	0.567	**0.052**	0.350
	Density (20–40 cm dbh)	0.499	0.120	31.729	X	0.521	**0.052**	0.260
	Density (40–60 cm dbh)	0.436	0.184	11.662	X	0.889	**0.058**	0.344
	Density (>60 cm dbh)	0.672	0.068	4.100	**0.015**	0.526	0.798	0.524
	Basal area (>20 cm dbh)	0.620	0.108	5.011	**0.071**	0.271	0.644	0.128
	QMD (cm)	0.852	**0.005**	4.389	**0.001**	0.031	0.257	0.604
New[b]	Density (>20 cm dbh)	0.722	**0.040**	0.886	**0.027**	0.181	**0.023**	0.705
	Density (20–40 cm dbh)	0.197	0.603	1.378	X	0.490	0.274	0.989
	Density (40–60 cm dbh)	0.517	0.105	0.909	X	0.611	**0.021**	0.867
	Density (>60 cm dbh)	0.801	**0.004**	0.399	X	0.471	**0.001**	0.920
	Basal area (>20 cm dbh)	0.773	**0.021**	0.488	**0.079**	0.397	**0.015**	0.553
	QMD (cm)[c]	0.179	0.735	8.601	X	0.643	0.858	0.316
Old[d]	Density (>20 cm dbh)	0.871	**0.003**	16.472	**0.001**	0.866	0.200	0.135
	Density (20–40 cm dbh)	0.734	**0.035**	19.467	**0.013**	0.309	0.611	0.968
	Density (40–60 cm dbh)[c]	0.750	**0.028**	4.618	**0.022**	0.564	0.656	0.345
	Density (>60 cm dbh)	0.845	**0.006**	2.322	**0.001**	0.790	**0.022**	0.894
	Basal area (>20 cm dbh)	0.839	**0.007**	1.795	**0.003**	0.795	**0.080**	0.139
	QMD (cm)[e]	0.810	**0.012**	4.890	**0.004**	0.016	0.185	0.206

The response is the change in condition (posttreatment minus pretreatment values). An X indicates instances for which an insignificant pretreatment covariate was eliminated ($P > 0.1$) from the model resulting in an ANOVA. Values in bold are significant at $P \leq 0.10$.
[a] RMSE is a measure of the within-treatment SD.
[b] New snags refer to snags created <1year ago.
[c] The response variable in these models were slightly non-normal (Shapiro-Wilk's test, $P < 0.08$).
[d] Old snags refer to snags created >1year ago.
[e] The pretreatment covariate was slightly non-normal (Shapiro-Wilk's test, $P = 0.04$).

burning had no effect on the change in total basal area (ANCOVA; $F = 0.23$, df = 1, 7; $P = 0.644$). For total snag basal area, the pretreatment covariate was significant (ANCOVA; $F = 4.53$, df = 1, 7; $P = 0.071$) (Table 2) in this model and indicated that areas with low pretreatment snag basal area tended to be in BO and control units, which experienced increases in snag basal area after treatment. This result contrasted with that for thinned units, which tended to have higher pretreatment levels and experienced the largest declines.

Increases in snag densities on burned (BO and T+B) units were largest in the small (20–39.9 cm)- and medium (40–59.9 cm)-diameter classes (Figure 2). Burning increased the density of small-diameter snags by 32 snags/10 ha on average (ANOVA; $F = 5.20$, df = 1, 8; $P = 0.052$, Table 2), of which more than half were ponderosa pine. Similar trends were observed for medium-diameter snags, which increased by ~10 snags/10 ha (ANOVA; $F = 4.91$, df = 1, 8; $P = 0.058$), and more than 80% of these were ponderosa pine.

The abundance of large-diameter (>60 cm) snags was low (<10 snags/10 ha) on most treatment units before and after treatment (Figure 2). Burning affected large-diameter snag populations in two ways: burning increased the density of new snags in this size class (ANOVA; $F = 31.57$, df = 1, 8; $P = 0.001$) and reduced the density of old snags (ANCOVA; burn, $F = 8.62$, df = 1, 7; $P = 0.022$). However, when mortality classes were combined, burning had no affect on the total density (new + old) of large snags (ANCOVA; $F = 0.07$, df = 1, 7; $P = 0.798$) (Table 2). Rather, the pretreatment covariate explained the change in large snag densities in the combined mortality class in this model (ANCOVA; $F = 10.34$, df = 1, 7; $P = 0.015$).

Treatment Effects on Snag Abundance—Thinning

Thinning treatments (TO and T+B) had no effect on snag densities in any size or mortality class (Table 2). Few new snags were created by the thinning operation (Figure 2), and thinning led to insignificant declines in old and total (new + old) snag abundance in all diameter classes ($P > 0.25$) (Table 2, Figure 2). Thinning led to small but significant increases in QMD of old snags (ANCOVA; $F = 10.05$, df = 1, 7; $P = 0.016$) and total snags (ANCOVA; $F = 7.29$, df = 1, 7; $P = 0.031$), whereas QMD on unthinned units tended to decline after treatments. In both models, the pretreatment covariate was significant (ANCOVA; $P < 0.005$), indicating that thinning led to a reduction after accounting for pretreatment variation in snag QMD.

Treatment Effects on Bark Beetle Occurrences

Burning increased bark beetle activity as observed by a significant increase in the density of new snags with signs of beetle attack on burned units compared with unburned units (ANCOVA; $F = 5.97$, df = 1, 7; $P = 0.045$). The majority of new snags with evidence of bark beetle attack were between 20 and 39.9 cm dbh after treatment across all units (Table 3). Indicator species analysis showed that the red turpentine beetle, found exclusively on ponderosa pine in our study, was a strong indicator in burned units (BO and T+B) compared with unburned (control and TO) units after treatment (ISA; $IV = 92.7$; $P = 0.024$). Accordingly, the density of new snags attacked by the red turpentine beetle increased on burned units, which had 62% of new snags attacked by the beetle compared with 21% on unburned units after treatment (ANOVA; $F = 8.87$, df = 1, 8; $P =$

Table 3. Pre- and posttreatment density of new snags (<1 year) attacked by bark beetles and wood-boring insects at the Northeastern Cascades site of the Fire and Fire Surrogate project in central Washington State

	Snags/dbh											
	Control			Burn-only			Thin-only			Thin + burn		
	20–40	40–60	>60	20–40	40–60	>60	20–40	40–60	>60	20–40	40–60	>60
	(cm)											
Pretreatment												
Total	2.5	0.5	0.0	1.0	0.0	0.0	1.9	0.7	0.0	2.0	2.0	1.5
1 spp. bark beetle	1.8	0.2	0.0	1.0	0.0	0.0	1.5	0.2	0.0	2.0	1.5	1.5
>1 spp. bark beetle	0.5	0.2	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.5	0.0
≥1 spp. woodborer	1.7	0.5	0.0	0.5	0.0	0.0	1.2	0.2	0.0	2.0	2.0	1.5
Posttreatment												
Total	10.3	1.2	0.5	18.7	6.2	4.8	4.9	2.4	0.7	53.7	20.9	7.6
1 spp. bark beetle	7.1	0.7	0.0	12.9	5.7	4.8	2.7	1.0	0.5	31.7	16.3	6.1
>1 spp. bark beetle	2.5	0.0	0.5	3.4	0.0	0.0	2.2	1.5	0.2	10.7	4.1	1.0
≥1 spp. woodborer	5.5	0.7	0.5	4.8	0.5	0.5	4.4	2.2	0.5	38.4	6.1	4.0

Snags are classified as attacked by only one species of bark beetle, attacked by more than one species of bark beetle, and attacked by at least one species of wood-boring insects.

0.0176) (Figure 3). Douglas-fir beetle was also indicative of burned units (ISA; $IV = 50.0$; $P = 0.086$), but this trend was largely driven by a single T+B unit (Camas). On the remaining units, evidence of trees (snags) attacked by this species was absent or rare, and there were no treatment effects ($P > 0.1$). The abundance of trees attacked and killed by the western and mountain pine beetles was unchanged ($P > 0.3$).

Most wood borer attacks were relegated to smaller diameter snags (Table 3). ANCOVA results suggested that wood borer abundance increased over the course of the experiment with larger increases occurring in areas with the highest abundance before treatment (ANCOVA; pretreatment, $F = 6.87$, df = 1, 7; $P = 0.034$). Wood borer incidence increased 10-fold on one T+B treatment unit where tree mortality was highest among all study units after treatments.

Treatment Effects on the Spatial Point Pattern of Snags

Treatments had a variable affect on the spatial distribution of snags. Snags in control units were generally clustered, with little change observed over the course of the experiment (Figure 4). On the basis of FDA, snags in control units were clustered from 7 to ~36 m (Figure 5). Maximum snag clustering on control units at both time periods was between 10 and 15 m, suggesting that snag clumps were generally between 20 and 30 m in diameter. Before treatments, snags on TO units showed a clustered distribution at distances >5 m. Thinning alone retained snag clustering at all spatial scales, but variability in the spatial distribution increased after treatment (Table 4, Figures 4 and 5). The maximum cluster radius on TO units changed very little after treatment and clusters were ~50 m in diameter. These results were generally consistent for the main thinning (TO and T+B) effect (Figure 5). Snag abundance in BO units was low before treatment, and snags were randomly distributed at almost all spatial scales, mostly because of the large critical envelopes associated with the sparse populations (Figure 5). The BO treatment increased snag numbers, and snags were clustered from 10 to 50 m after treatment (Table 4, Figure 5).

The T+B treatment had a variable effect on the spatial distribution of snags. Snags on one unit (Camas) were abundant before treatment and clustered at several scales. After treatment, snag density more than doubled, and clustering was significant at all tested spatial scales (Table 4, Figure 4). Before treatment, snag abundance at the Tripp T+B unit was low, and snags were randomly distributed. Treatments at this unit caused a net reduction in snag abundance and had little effect on snag spatial distribution (Table 4). FDA showed little effect of the treatments on the estimated $L(d)$ curve, but treatments led to larger critical envelopes, which reduced the significance of snag clustering at distances >20 m.

Discussion

In this study we investigated the effects of common fuel reduction treatments on snag abundance and spatial point pattern and bark beetle activity. Burning (BO and T+B) tended to increase snag abundance, and mortality was highest in but not restricted to the smallest size classes (20–39.9 cm dbh). Burning had the additional effect of retaining or increasing snag clumpiness at several scales, whereas thinning caused a more random distribution. Incidences of attacks by the red turpentine beetle, a species found exclusively on ponderosa pines in this study and generally not considered an important agent of tree mortality, increased after prescribed burns, but no other important trends in posttreatment bark beetle activity were found.

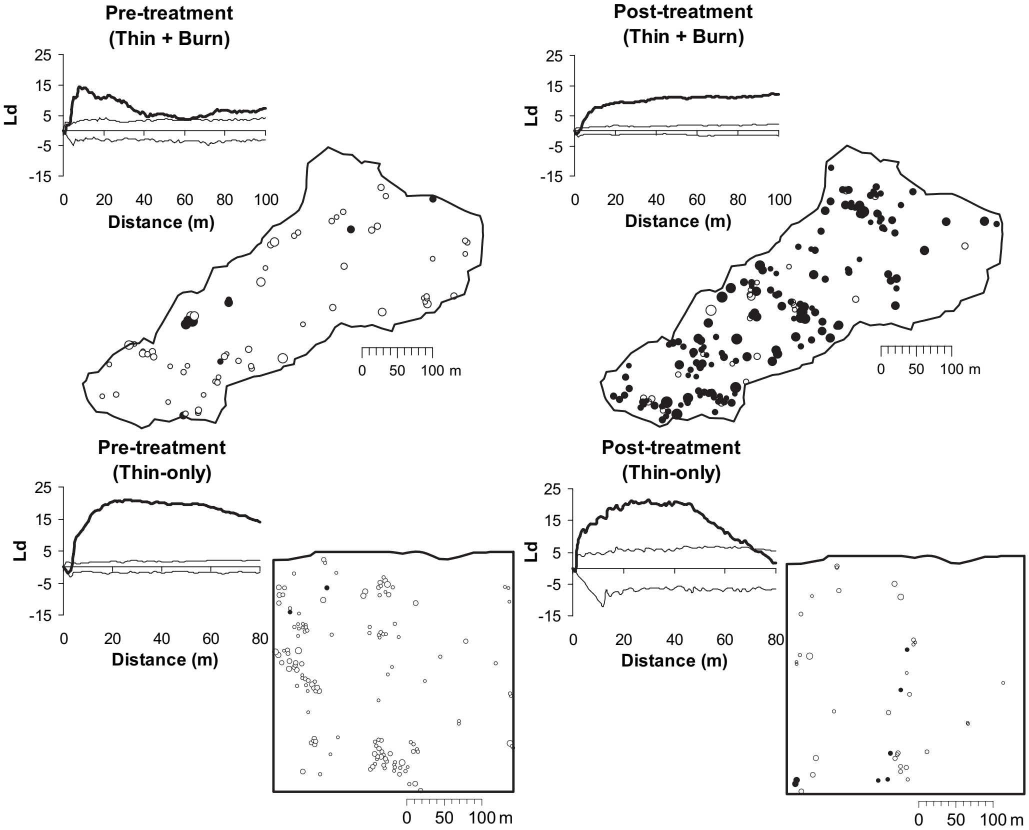

Figure 4. Spatial distribution and adjusted Ripley's *K* function (*L*(*d*)) for snags before and after treatment in a thin + burn unit (top frame; Camas) and a thin-only unit (bottom frame; Crow 1) at the Northeastern Cascades site of the FFS project in central Washington State. The graphs show the adjusted Ripley's *K* (dark line) and the 95% critical envelope (thin lines). Open and closed circles on the stem maps represent old snags and new snags, respectively. Circles are graduated by dbh and enlarged for clarity.

Burn treatments had a variable effect on snag abundance, largely because of the low burn intensity of the spring prescribed burns (Agee and Lolley 2006). However, previous studies have shown that prescribed burns conducted early in the growing season can be effective at reducing live-tree stocking and surface fuels and increasing snag abundance (Swezy and Agee 1991, McHugh et al. 2003, Schwilk et al. 2006). For example, Schwilk et al. (2006) found no differences in tree mortality between early- and late-season burns but did find that the probability of bark beetle attack on firs was greater after early season burns. Other studies investigating late-season prescribed burns reported burn coverages and snag creation rates similar to those observed in this study (Stephens and Moghaddas 2005, Innes et al. 2006, Saab et al. 2006, Youngblood et al. 2006). For example, Innes et al. (2006) reported fall burns in Sequoia National Park, California, covering 20–70% of burned (BO and T+B) units, and increases in snag density were restricted to smaller diameter classes (<45 cm dbh).

Other studies have reported declines in snag densities after single prescribed burns (Horton and Mannan 1988, Machmer 2002, Randall-Parker and Miller 2002, Bagne et al. 2007), a result that differs from ours. In these studies, fires consumed >20% of snags existing before treatment, and losses were not offset by new snag creation. In the current study, on average 3.0 and 8.2 snags/ha were created by the BO and T+B treatments, respectively, and few existing snags were consumed by the fires. This result is probably due to the fact that initial snag abundance was low, and early-season burning generally did not consume extant snags.

Burning treatments (BO and T+B) tended to increase snag density in our study area, although they were often small-diameter (e.g., 20–39.9 cm dbh) snags. The retention time for small bark beetle-killed snags tends to be quite brief owing to minimal heartwood development and high sapwood basal area, the latter of which is typically rotted in the first 5 years by saprotting fungi (e.g., see Harrington 1980). However, recent evidence suggests that trees of this size class can be used by certain bird species (Bagne et al. 2007), and in the current study, snags as small as 20 cm dbh were attacked by bark beetles and wood borer larvae. This finding suggests that even small-diameter snags may be useful to wildlife in the short term. However, as these structures fall down and add to surface fuel levels, further treatments may be required to reduce fire hazard in these stands (Stephens and Moghaddas 2005). Conversely, large-diameter new snags (>60 cm dbh) increased significantly on burned units, but populations in this size class were still very low (<1/ha). Regardless, preparatory treatments, such as raking potential combustibles away from individual tree boles, may be required before the prescribed burn to protect

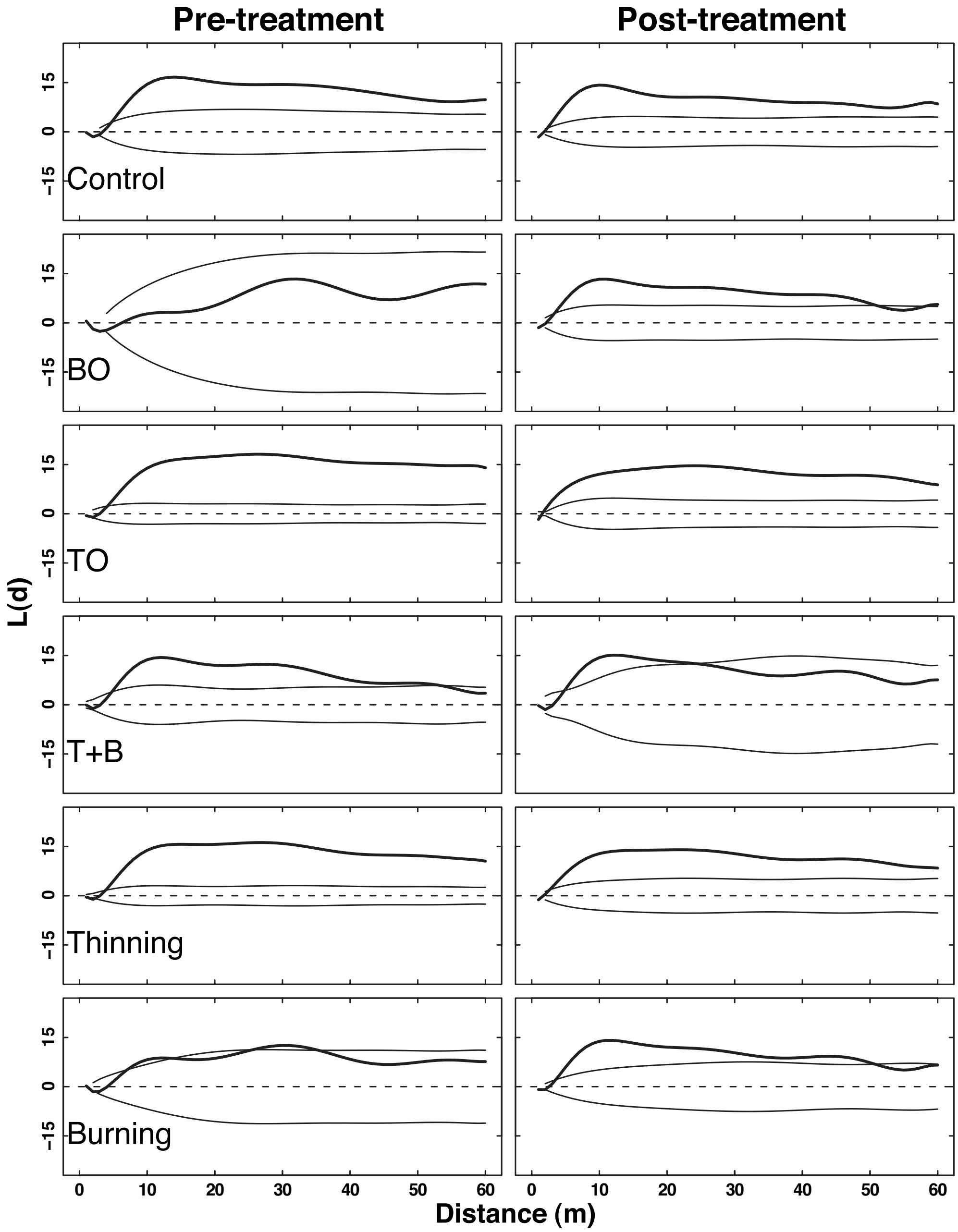

Figure 5. Summary of the spatial distribution of snags at the Northeastern Cascades site of the FFS project in central Washington State using FDA. Ripley's *K* analyses were averaged for each treatment before and after treatments. Confidence envelopes are ±2 SE.

large-diameter stems from severe scorching during the burn (Swezy and Agee 1991).

Thinning alone was the only treatment that consistently reduced snag populations, created few new snags, and had no affect on bark beetle attack incidence. Posttreatment snag density in these units was among the lowest recorded across all treatment units and in all size classes. Because snag retention was not the primary focus of this treatment, snags were often removed because of the safety hazard that exists with operation of mechanized equipment. Further, the accumulation of fuels after the TO treatment, as reported by Agee and Lolley (2006), did little to increase bark beetle populations, as bark beetles attacked <1 new snag/ha after thinning. The unbalanced experimental design precluded analyses of individual treatment effects and probably the finding of significant reductions in snags on TO units.

Bark beetles are important mortality agents in western forests, particularly after disturbances that weaken residual tree defenses to attack (Parker et al. 2006). The use of spring burns in the current experiment meant that the burning was concurrent with bark beetle flight of the newly emergent adults in the spring. Injury to trees during a period when bark beetles are active can be detrimental to the operation, causing unexpected rates of tree mortality (McHugh et al. 2003, Parker et al. 2006). Results from our study revealed that beetle activity increased after the prescribed burns; however, this increase was largely due to a single species, the red turpentine beetle, which comprised >60% of the

Table 4. Adjusted Ripley's *K* analysis of the spatial point pattern of snags before and after fuel reduction treatments

Treatment unit	Intertree distance																				Total trees (n)[a]
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	
	(m)																				
Crow 3 (C)[b]																					
Before	C	C	C	C	C	r	r	r	r	r	r	r	r	r							39
After	C	C	C	C	C	C	**C**	**C**	**C**	**C**	**C**	**C**	r	r							38
Pendleton (C)																					
Before	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C			130
After	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	**r**	**r**	**r**			97
Sand 19 (C)																					
Before	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r					19
After	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r					22
Sand 2 (C)																					
Before	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C			26
After	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C			60
Poison (B)																					
Before	r	r	r	r	r	r	r	r	r	r	r	r									10
After	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**	**C**									68
Spromberg (B)																					
Before	C	C	C	C	C	C	C	C	C	C	C	C									17
After	C	C	C	C	C	C	C	C	C	**r**	**r**	**r**									36
Crow 1 (T)																					
Before	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C					137
After	C	C	C	C	C	C	C	C	C	C	C	C	C	C	**r**	**r**					39
Crow 6 (T)																					
Before	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C			114
After	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	**r**	**r**	**r**			52
Ruby (T)																					
Before	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	r			43
After	C	C	C	C	C	C	C	C	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	r			35
Slawson (T)																					
Before	C	C	C	C	C	C	C	C	C	C	C	r									34
After	C	**r**	C	**r**	**r**	**r**	**r**	**r**	**r**	C	C	r									24
Camas (TB)																					
Before	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	68
After	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	178
Tripp (TB)																					
Before	r	C	C	C	C	C	C	r	r	r	r	r	r	r	r	r	r	r			32
After	**C**	C	**r**	C	C	**r**	**r**	r	r	r	r	r	r	r	r	r	r	r			15

L(*d*) results are summarized for 5-m intervals. Snag distributions were clumped (C) when *L*(*d*) values were greater than the 95% critical envelope constructed using 99 Monte Carlo simulations, and random (r) for values within the envelope. Bold values indicate significant changes after treatments.
[a] The number of snags surveyed.
[b] Treatment codes: C, control; B, burn-only; T, thin-only; TB, thin + burn.

beetles attacking new snags. Red turpentine beetle is not considered to be a primary mortality agent on ponderosa pine; rather these beetles tend to predispose trees to other lethal beetle attacks or contribute to the demise of low-vigor or injured trees (Bradley and Tueller 2001). Other studies have shown similar high levels of red turpentine beetle attacks after prescribed burns (Ganz et al. 2003, Schwilk et al. 2006, Fettig et al. 2008), but incidence of red turpentine beetle-induced mortality was low. Because of the short time between burn treatments and the snag survey, further inspections of the trees classified as "new snags" attacked by the red turpentine beetle will be needed to definitively determine whether these trees truly died as a direct result of the prescribed burns and subsequent red turpentine beetle or other *Dendroctonus* spp. attack or whether these trees were misclassified as snags and eventually recover from their injuries. For instance, Breece et al. (2008) found only two-thirds of trees initially attacked by bark beetles after late-season burns in northern Arizona succumbed to attack after three growing seasons.

Few studies have compared the effects of burning and thinning treatments on the spatial distribution of snags. Our results suggest that thinning (TO and T+B) retained snag clumpiness but increased the variability in CSR as shown by larger posttreatment confidence intervals. Whereas snag density tended to decline on thinned units, remaining snags maintained a clumped distribution on the basis of the Ripley's *K* analysis. Burning (BO + TB) in most units retained or increased snag clumpiness. This finding was particularly apparent in the BO units where pretreatment snag density was low, yet burning increased both snag abundance and clumpiness.

Chambers and Mast (2005) found that after wildfires in ponderosa pine forests, snags were distributed in pockets over the burned area. However, in the context of prescribed burnings, Innes et al. (2006) observed that single prescribed burns in the eastern Sierras had no effect on the spatial distribution of snags, despite significant fire-related recruitment after treatment. Prescribed burning effects on snag spatial distributions is difficult to predict and is probably dependent on burning conditions, fuel loading and continuity, and bark beetle activity after treatments, among other factors.

The spatial distribution of snags is important for certain wildlife species. For example, the Lewis's woodpecker (*Melanerpes lewis*), listed as a sensitive species by the US Forest Service, prefers snags >20 cm dbh arranged in small clumps on the landscape, rather than areas with uniformly or randomly dispersed snags (Saab and Dudley 1998). Snag utility to certain wildlife species native to dry forests is also apparently dependent on snag size, species, and decay class. For example, Lyons et al. (2008) found large snags to be an important component of foraging habitat for cavity-nesting birds within our study stands. Lehmkuhl et al. (2003) found that large (>40 cm dbh), well-decayed snags with broken tops were more likely to contain cavities used by animals. In a subsequent study, Lehmkuhl et al. (2006) showed that bushy-tailed woodrat (*Neotoma cinerea*) abundance could be predicted by the type and amount of cover provided by large snags (>40 cm dbh), mistletoe brooms, and soft downed logs. Woodrat (*N. cinerea, N. fuscipes*) abundance, consequently, has been linked to the foraging behavior, habitat selection, and demography of the northern spotted owl (*S. occidentalis* caurina) (Carey et al. 1992, Zabel et al. 1993, Franklin et al. 2000).

These considerations have important implications for future silvicultural prescriptions and snag management. By directly influencing the spatial patterns of surface fuels and fuel concentrations, managers may protect existing large snags and recruit new large snags to the landscape. Similarly, during thinning operations, managers may achieve tree stocking and fuel reduction objectives using variable-density spacing methods in low and free thinning such as those suggested by Harrod et al. (1999). Such an approach has many merits. First, it addresses the silvicultural goals of stocking reduction, increased intertree spacing, and improved fire tolerance by virtue of increased residual tree diameters and discrimination against shade-tolerant and fire-intolerant trees, whenever it is reasonable to do so. Second, surface and ladder fuels are reduced by posttreatment prescribed burning. Finally, the clumped distribution of residual trees improves the likelihood that future prescribed or natural fires and bark beetle-caused tree mortality will produce high-quality and durable large snags. This is so for several reasons: surface fuels tend to concentrate near clumps of large-diameter trees (≥40 cm dbh), which can increase the likelihood of fire-related mortality (Swezy and Agee 1991); some trees growing in clumps will show poor vigor because of increased competition for light, water, and nutrients in these areas and are therefore more susceptible to bark beetle mass attack; and snags created in these clumps may be protected from the wind, thereby increasing their longevity.

An underlying goal of fuel reduction treatments is to alter forest structure and composition such that it falls within the broad range of conditions that were present before European settlement. These conditions were in better synchrony with the native fire regimes. Live tree density and spacing objectives for the thinning operation were modeled after the recommendations of Harrod et al. (1999), but stocking of dead standing trees was more difficult to estimate because of inherently uneven distribution, temporal transience, and lack of historical census (Harrod et al. 1998). Nonetheless, researchers have estimated historical snag densities in low-elevation mixed conifer forests of the eastern Cascade Range, and those estimates range from 5 (Agee 2002) to 35 (Harrod et al. 1998) snags/ha. Snag inventories at Northeastern Cascades after treatment indicated that only 5 of the 12 treatment units (2 controls, 1 BO, 1 TO, and 1 T+B unit) had >5 snags/ha of >20 cm dbh, suggesting that snag abundance after treatment was lower than historical averages and that snag protection and creation could be emphasized in prescriptions.

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