International Journal of Wildland Fire 9(4): 223–234, 1999 ©IAWF 10.1071/WF00011

Snag Dynamics in a Chronosequence of 26 Wildfires on the East Slope of the Cascade Range in Washington State, USA

Richard Everett
USDA Forest Service, Wenatchee Forestry Sciences Laboratory, 1133 N. Western Avenue, Wenatchee, Washington 98801 USA
Phone: +1 509 662 4315 ext. 255; Fax +1 509 664 2742; email: r.everett2@gte.net

John Lehmkuhl
Phone: +1 509 662 4315 ext. 235; email: jlehmkuhl@fs.fed.us

Richard Schellhaas
Phone: +1 509 662 4315 ext. 255; email: rschellhaas@fs.fed.us

Pete Ohlson
Phone: +1 509 662 4315 ext. 255; email:pohlson@fs.fed.us

David Keenum
Phone: +1 509 662 4315 ext. 255; email: dkeenum@fs.fed.us

Heidi Riesterer
Phone: +1 509 662 4315 ext. 255; email:hriesterer@fs.fed.us

Don Spurbeck
Phone: +1 509 662 4315 ext. 255; email:dspurbeck@fs.fed.us

Abstract

Snag numbers and decay class were measured on a chronosequence of 26 wildfires (ages 1–81 years) on the east slope of the Cascade Range in Washington. Snag longevity and resultant snag densities varied spatially across burns in relation to micro-topographic position. Longevity of snags < 41 cm dbh was greater for thin-barked Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*) and lodgepole pine (*Pinus contorta*) than thick-barked Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*). With larger diameter snags, however, Douglas-fir persisted longer than Engelmann spruce. The time period required for recruitment of soft snags > 23 cm dbh was estimated to exceed snag longevity for ponderosa pine, Engelmann spruce, lodgepole pine, and subalpine fir, causing an "on-site gap" in soft snags for these species. Snags of Douglas-fir ≥ 41 cm dbh stood for a sufficient time (40% standing after 80 years) to potentially overlap the recruitment of soft snags ≥ 23 cm dbh from the replacement stand. Providing continuity in soft snags following stand-replacement events would require a landscape-scale perspective, incorporating adjacent stands of different ages or disturbance histories. Results suggest that standards and guidelines for snags on public forest lands need to be sufficiently flexible to accommodate both disturbance and stand development phases and differences in snag longevity among species and topographic positions.

Keywords:

Snag density
Snag decay
Wildlife habitat
Soil organic matter.

Introduction

Snags and logs are important components of wildlife habitat (McClelland and Frissell 1975, Thomas et al. 1979, Raphael and White 1984), and are critical for the maintenance of soil organic matter and long-term site productivity (Harmon et al. 1986, Graham et al. 1994). Different biophysical environments, with varying potentials for amounts and types of snags and disturbance events, provide a mosaic of snag density across the landscape. Snags within developing stands are produced by chronic disturbance (endemic insect and disease) and continuous successional processes (Spies et al. 1988, Oliver et al. 1997). Episodic and severe disturbance events (fire, insect epidemics) create different-aged stands and provide pulses of snags at specific landscape locations.

Snag numbers do not continually increase over time because the process of tree mortality and snag recruitment are balanced by the processes of snag decay and fall. As an example, Dahms (1949) reports 50% of fire-killed ponderosa pine (*Pinus ponderosa*) was standing after 10 years, but this declined to 22% standing after 22 years. Snag fall rates are a function of snag size, tree species, cause of mortality, season of mortality, and the micro-environment. Smaller snag diameter is associated with more rapid snag fall. Keen (1929) reports that, 7 years following fire, 42% of ponderosa pine 25–46 cm (10–18 in.) diameter at breast height (dbh) were standing compared to 57% for those 51–71 cm (20–28 in.) dbh, and 78% for trees larger than 102 cm (40 in.) dbh. Similarly, Dahms (1949) reports that 75% of ponderosa pine snags between 20 and 51cm (8 and 20 in.) dbh fell within a 10 year post-fire period compared to 35% and 15% for 51–76 cm (20–30 in.) and 76–107 cm (30–42 in.) dbh snags, respectively.

Snags of different tree species fall at varying rates and have unique fall characteristics. Average annual fall rate for fire-killed ponderosa pine snags was given at 14–19% among all size classes 4–38 cm (1.5–15 in.) dbh (Harrington 1996), 2.5% for Douglas-fir (*Pseudotsuga menziesii*) (Hinds et al. 1965), and 8.4% for > 8 cm (3 in.) dbh lodgepole pine (*Pinus contorta*) (Lyon 1977). Average fall rates can be misleading as the relationship is curvilinear over time and snags can fall at an increasing rate when critical decay levels are reached. As an example, approximately 85% of fire-killed snags fell in a 5-year period 18–23 years after fire in California (Morrison and Raphael 1993). Raphael and Morrison (1987) report that Jeffrey pine (*P. jeffreyi*) decay faster than white fir (*Abies concolor*), with the latter falling entirely from the stump and the former falling as a series of tree topping events. Snag longevity was enhanced by larger bole diameter, shorter height (topping action) and being in the genus *Abies*. Bull (1983) reports broken tops occur more often (70%) for > 50 cm dbh than smaller diameter ponderosa pine snags (40%) and only 10% of lodgepole pine were topped 8 years after fire. Snag fall rates have been defined for different tree species and sites, but snag longevity is a site-specific process that needs to be determined for each area of interest (Keen 1929).

Tree densities have increased on the east slope of the Cascades and elsewhere in interior western forests since Eurosettlement (Agee and Edmonds 1992, Covington et al. 1994, Lehmkuhl et al. 1994). Fire suppression activities limited the number and extent of fires over the past century and the results of altered fire regimes are increased stand density and changed species composition. Starting in the 1970s, several large (> 20 000 ha) wildfires on the east side of the Cascade Range in Washington have created a pulse of snags in excess of estimated historical conditions (Everett et al. 1996). As the size of stand-replacement fires increase, there is potential for 'boom and bust' cycles of snags and logs and the species that are dependent on them. Should post-fire snag fall exceed snag recruitment, then 'on-site gaps' in snag habitat can occur over time (Bull 1983, Harmon et al. 1986). Gaps in snags of specific sizes or decay class for significant time periods and over extensive areas could have adverse impacts on viability of species dependent on that habitat (Washington Department of Fish and Wildlife 1995). To estimate if gaps in snag availability will occur within these large burns, we need data on snag decay rates, longevity of snags, and the recruitment and growth period for replacement snags. Information on wildlife species dependent on snag habitat also is needed but is not covered in this study. Information on snag distributions and conditions is not currently available for the eastside of the Cascade Range. In this study we tested the null hypotheses:

(1) That post-fire snag density and fall rates are similar among species, snag diameter classes, and micro-topographic positions;
(2) That snag density is homogeneous within burns (coefficients of variation [CV] < 50% among plots); and
(3) That snag longevity is equal to or exceeds the period required for the occurrence of replacement soft snags (Decay Class 3 or higher, Cline et al. 1980) that are important for cavity-nesting species.

Study Area and Methods

Field Sampling

We sampled snags, logs, and live trees in a chronosequence of 26 stand-replacement burns (without salvage logging or subsequent reburns) 1–81 years after fire occurrence (Figure 1). Burn sites were selected without discernible reburns to reduce confounding effects of episodic reburns on snag longevity. However, the reader is cautioned that the absence of reburns may support snag and log densities different from 'historical' conditions prior to Eurosettlement activities.

The objective of the sampling design was to identify differences in snag densities within burns based on aspect, slope, and micro-topography; the design was not constructed to define mean or total snag amounts for an entire burn area. Each burn was mapped by aspect polygons based on north versus south aspects and sloped versus flat terrain. We used current and historical aerial photos to delineate 'snag stands' that differed in snag density, size, or species (when possible)

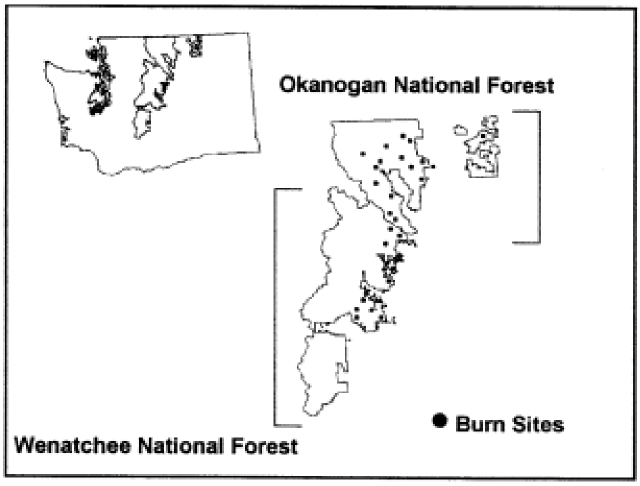

Figure 1. Location of burn sites on the east slope of the Cascade Range in Washington, Wenatchee and Okanogan National Forest sites.

within the aspect polygons. A single stand representative of each 'snag stand type' was randomly selected for sampling from the available array of snag stands within each aspect polygon present on the burn. Also, sample sites were identified by micro-topographic position (convex, concave, straight, and undulating).

We sampled one to four sites within each selected snag stand with two concentric circular plots of 0.02 ha (1/20 acre) and one 0.1 ha (1/4 acre) plot. The 0.02 ha plot size was smaller than some previous snag studies (Raphael and Morrison 1987), but is comparable to the 0.04 ha plots of Cline et al. (1980). Our rationale was to stratify the burn to identify the different snag stand types present and then sample within uniform snag stands rather than capture undefined heterogeneity in snag density within larger sample plots. Sample plots were selected for within-plot homogeneity in burn severity (similar trunk and branch scorch and snag decay conditions) to reduce confounding effects of partial burns and lingering tree mortality. At the center of each 0.02 ha plot, three sampling procedures were completed: (1) vegetation type characterization; (2) forest regeneration; and (3) snag assessment.

The vegetation type in which the sample plot occurred was classified to plant association level (Lillybridge et al. 1995) by using presence of herbaceous and shrubby understory indicator species, the species of snags present, and identification of regeneration species composition. In sampling post-fire regeneration tree species, height and stocking level (tree density/ha) were recorded for each of five diameter classes: 3–13 cm (1–5 in.), 13–23 cm (5–9 in.), 23–41 cm (9–16 in.), 41–64 cm (16–25 in.) and ≥ 64 cm (≥ 25 in.) dbh. Trees < 3 cm dbh were group tallied by species. Two trees in each size class and species were cored at ground level to determine age distribution. All snags and all remnant live trees were recorded in 0.02 ha plots, and all snags ≥ 23 cm (≥ 9 in.) dbh were recorded in the 0.1 ha plot. Tree species, dbh, height, and the presence of a broken top and cavity-use were recorded for each snag. Decay class of snags was determined by using the drawing and descriptions by Cline et al. (1980) that show increasing loss of bark, stems, and then branches and sections of bole as decay increases over time. As an example, Decay Class 3 is characterized by the absence of bark and branches, but the bole appears intact with a minimum of top breakage. Stumps and logs were identified by species by experienced field crews (more than 25 years experience in the area).

Analysis

Snag data were grouped into diameter classes for analysis. Data from the 0.02 ha plots were used to estimate initial (post-fire) snag densities, percent standing snags over time (by species and size classes), and snag density by micro-topographic position. The 0.1 ha plots contained greater numbers of snags ≥ 23 cm dbh than 0.02 ha plots and were sampled to estimate proportion of snags in a specific decay class and change in snag height over time. Because of the potential to underestimate the number of small diameter stems (< 23 cm dbh) initially present on older burns due to decay loss, the data analysis emphasizes snags and logs ≥ 23 cm dbh. We used a minimum snag height of 1.8 m (6 ft.) to estimate snag density. This minimum value is similar to that used by Raphael and Morrison (1987) and 96% of the wildlife cavities occurred in snags greater than 1.8 m in height in our study. The initial, or immediate post-fire, snag density was estimated by combining the number of all current standing snags and the number of stumps or logs present within the 0.02 ha plot. Percent standing snags was computed ([currently standing/ initial]*100) for each sample plot.

Tree rings on sampled regeneration cores were analysed to determine the time required for tree re-establishment following the fires and time required to achieve ≥ 23 cm dbh class. Tree age information from adjacent research sites (Everett et al. 1997) was used to estimate time required for species to achieve a 41 cm dbh size class because no live regeneration trees of this size class occurred on sampled burns (< 81 years old). Data from all plots in a snag stand were averaged to describe stand conditions (i.e. stands were the sample units).

Total numbers of snags and rate of snag fall (snag longevity) were compared among aspects and micro-topographic positions for burns 3–15 years, 15–40 years, and > 40 years old in regression analysis (Neter and Wasserman 1974, Table Curve 1992). Percent standing snags by size class and species was regressed on age of burn (x) and a curve was fitted (Table Curve 1992) that maximized the coefficient of determination (R^2) and minimized the standard error of the estimate (SE). The exponential regression equation, $Y = a + b \exp(-x/c)$, yielded the highest R^2 values and SE values were comparable to other regression equations generated from Table Curve. Conservatively adjusted R^2 values (based on number of data points in the regression) are reported. For the statistical comparison of regression lines among species and size classes, snag density data were log-transformed and transformed data were regressed by using the linear regression equation, $Y = a + bx^c$. Differences in the slope and intercept of paired linear regression lines were tested by using methods described by Neter and Wasserman (1974, pp. 146–171). Analysis results are reported by species and for two species groups: (1) thick-bark species Douglas-fir and ponderosa pine and (2) thin-bark species Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine.

Snag decay class values (a discrete variable) for each sampled snag ≥ 23 cm dbh was combined with all other snags of the same species to derive a mean snag decay condition for the species on a given burn (a continuous variable). Species decay condition was analysed separately or in combination with other species within the burn by using the regression analysis described above.

Results and Discussion

Vegetation Series

In the chronosequence of the 26 wildfires, sample plots occurred mostly in Douglas-fir (121 plots) and subalpine fir (82 plots) series with fewer plots in subalpine larch (*Larix lyallii*—8), whitebark pine (*Pinus albicaulis*—7), grand fir (*Abies grandis*—5), ponderosa pine (4), silver fir (*A. amabilis*—4), and western hemlock (*Tsuga heterophylla*—1) series (Table 1). Snags of Douglas-fir, subalpine fir, Engelmann spruce, lodgepole pine, and ponderosa pine predominated and occurred on 25, 16, 13, 12, and 10 of the 26 burn sites, respectively. Snags of other species, such as western larch (*Larix occidentalis*), whitebark pine, subalpine larch, grand fir, and western red cedar (*Thuja plicata*) were present but in total represented less than 8% of the snags recorded. Snag density varied greatly among plots of the same tree series occurring on the different burns. Coefficients of variation in snag density (> 23 cm dbh) for the same tree series was greater than 50% in 65% of the comparisons using immediate post-fire snag conditions and in 92% of the comparisons of current snag conditions (Table 1).

Snag Density Over Time and Topography

We estimate that approximately 3944 snags were present immediately following fires on the burn plots (Table 1). In 1995, the number of snags present on these plots was about 1953. As many as 170 snags ≥ 23 cm dbh occurred per ha on burns less than 10 years old, whereas fewer than 50 snags per ha in this size class occurred on burns greater than 60 years old (Figure 2). The percentage of standing snags ≥ 23 cm dbh declined to less than 30% on the 81 year-old burn.

We suggest that the greater abundance of snags on recent burns relative to older burns is the combined result of less time for snag fall and greater pre-fire tree densities due to the reduced fire effects over the last century (Covington et al. 1994, Everett et al. 1997). The current snag densities reported here may reflect decades of fire suppression and may not be indicative of these forest types under unaltered fire regimes.

Significant differences in snag densities among burns demonstrate the combined effects of variations in tree densities among sites and differences in time since burn. Reduced breadth in confidence bands for snag densities associated with older burns may indicate that snag densities become more homogeneous across burns over time or reflect inherent differences in immediate post-fire snag densities between younger and older burn sites.

In analysing immediate post-fire snag density, there was a trend toward increased numbers of snags > 23 cm dbh on north (321/ha) than south aspects (259/ha). During the initial 3–15-year period following each burn, snags fell rapidly with smaller snags falling more rapidly than larger snags of the same species in most instances (Figure 3). On burns 3–15-years old, snags ≥ 23 cm dbh were again more abundant ($P = 0.05$) on north (338 snags/ha) than south aspects (188 snags/ha). More ($P = 0.05$) post-fire snags occurred on flat (328 snags/ha) and moderate slopes (415 snags/ha) than occurred on steep (> 50%) slopes (143 snags/ha). Snag numbers tended to be greater ($P = 0.1$) on concave (343 snags/ha) than straight (240 snags/ha) slopes. In this study, 21 and 79% of sample plots occurred on flat and sloped topography, respectively, with the following percentage in each micro-topographic position: 20% concave, 36% convex, 11% undulating, and 33% straight.

Sufficient information was available on snags of Douglas-fir and subalpine fir to predict differences in snag longevity among micro-topographic positions (Figure 4, a and b). Snag longevity was predicted to be reduced on undulating terrain and greater on straight or convex micro-topography for both species. There was a trend for convex slopes to maintain subalpine snags longer than concave slopes.

Our data show that an array of aspects, slopes, and micro-topography occurs within large stand-replacement burns and that these sites have different snag densities and snag longevity rates. The large coefficients of variation (> 50%) in snag densities for individual series (Table 1) and broad confidence bands for total snag densities (all species combined) (Figure 2) on any given burn supports the hypothesis of heterogeneous post-fire snag densities across large stand-replacement burns.

Table 1. Snag density by tree series and fire year for immediate post-fire and current conditions. ABAM, Pacific silver fir; ABGR, grand fir; ABLA2, subalpine fir; LALY, subalpine larch; PIAL, whitebark pine; PIPO, ponderosa pine; PSME, Douglas-fir; TSHE, western hemlock.

Series	Elevation (m)	Fire year	Immediate post-fire snag numbers					Current snag numbers		
			3–23 cm # / ha	3–23 cm CV%	>23 cm # / ha	>23 cm CV%	3–23 # / ha	3–23 cm CV%	>23 cm # / ha	>23 cm CV%
ABAM	1280–1798	1920	50	0	200	35.4	0		30	141.4
		1935	230	78.6	180	60.6	0		80	47.1
ABGR	1052–1487	1988	2910	117	250	69.3	2390	113.1	200	66.1
ABLA2	1189–2097	1919	410	72.4	370	33.6	30	167.3	70	36.9
		1929	150	60.9	130	74.8	10	200	10	245
		1935	200	30.6	420	33.6	40	163	110	72.8
		1949a	360	41.2	430	64.1	40	127.7	210	80.1
		1958	150	47.1	280	12.9	0		100	70.7
		1970a	1100	104.1	220	58.1	340	90.4	140	57.3
		1970b	1540	49.9	190	83.3	420	79.9	20	173.2
		1970c	680	79.6	440	64	80	143.9	160	71.3
		1970d	1400				600			
		1973b	700	80.8	300	23.6	50	141.4	150	0
		1984	720	38.4	230	15.7	120	24.7	80	47.1
		1986	780	77.6	250	28.3	300	141.4	130	28.3
		1988	2700	69.9	390	32.8	2140	76.2	390	32.8
		1992	1690	76.2	410	56.5	1390	80.7	360	51.4
		1993	2980	53.5	430	25	2480	55.7	380	28.3
		1994b	1230	37.1	400	34.5	880	58.2	390	37.4
LALY	1783–2066	1935	220	113.8	350	28.6	0		70	173.2
		1986	930	37.9	470	34.1	360	50.5	430	26.8
PIAL	1826–2103	1919	450		700		0		150	
		1929	280	64.3	430	8.3	0		0	
		1970a	500	56.6	600	47.1	250	56.6	230	15.7
		1970b	550	0	680	15.7	100	70.7	200	0
PIPO	786–1103	1968	230	15.7	100	0	0		0	
		1970a	1280	69.3	300	70.7	0		30	141.4
PSME	594–1838	1914			330	119.7			180	141.4
		1919	500		170	75.5	0		20	173.2
		1929	110	52.4	220	44.5	0		80	86.3
		1949b	50		200		0		100	
		1958	250	80	330	31.4	0		190	34.3
		1968	860	108.5	200	54	10	200	10	200
		1970a	520	105.8	240	43.7	10	254.3	80	79.7
		1970b	430	63	220	62.4	80	77.1	140	83.5
		1973a	980	39.9	180	101	350	121.2	100	141.4
		1973b	300	129.1	200	31.6	20	245	50	109.5
		1976			200				100	
		1977	470	69.3	230	56.8	80	173.6	160	48.9
		1980	350		550		0		200	
		1985	370	28.4	340	57.3	150	88.2	240	78.5
		1988	1020	76.1	260	77.6	73	85.5	220	87.7
		1994a	2240	45.9	270	80.3	2100	47.8	240	72.8
TSHE	1341	1988	550		800		500		650	

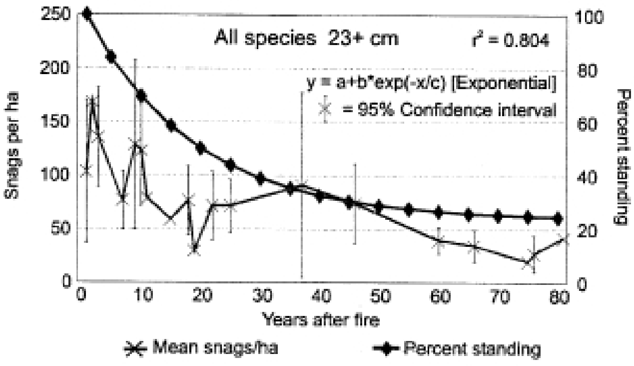

Figure 2. Mean number and 95% CI of snags (all species) per ha and percentage standing on the chronosequence of burn sites.

Standards and guidelines for snags on public forest lands need to be flexible enough to accommodate differences in snag density across landscapes and between periods of disturbance and subsequent stand development. The numbers of snags reported here should be used with caution in developing standards and guidelines as they may reflect forest structure created and supported by altered disturbance regimes. Existing snag densities may be in excess of those sustainable over time under existing fire regimes or if historical fire regimes or fire effects are restored to the landscape. Also, the reader is cautioned that numbers of snags estimated from small homogeneous plots (used here to demonstrate heterogeneity in snag density within burns) may overestimate or underestimate actual snag densities over an entire burn area.

Snag Longevity Among Species

Small diameter (< 23 cm dbh) snags of thin-barked species (subalpine fir, lodgepole pine) fell less rapidly than those of thick-barked species (Douglas-fir, ponderosa pine) (Figure 3, a). Approximately 50% of the ponderosa pine, Douglas-fir, lodgepole pine, and subalpine fir snags < 23 cm dbh fell or broke to the minimum (1.8 m) snag height during the first 7–12 years after fire. While the observed snag fall seems rapid, the fall rates reported may actually be less than what would occur if historical fire-return intervals were present.

Larger snags (23–41 cm dbh) of some thin-barked species continue to stand longer than thick-barked species, but other thin-barked species fell at the same rate (Figure 3, b). Regression predicted that approximately 50% of snags of thin-barked Engelmann spruce and subalpine fir fell within 25 years after fire, but 50% of similar size snags of Douglas-fir and lodgepole pine fell within 15 years.

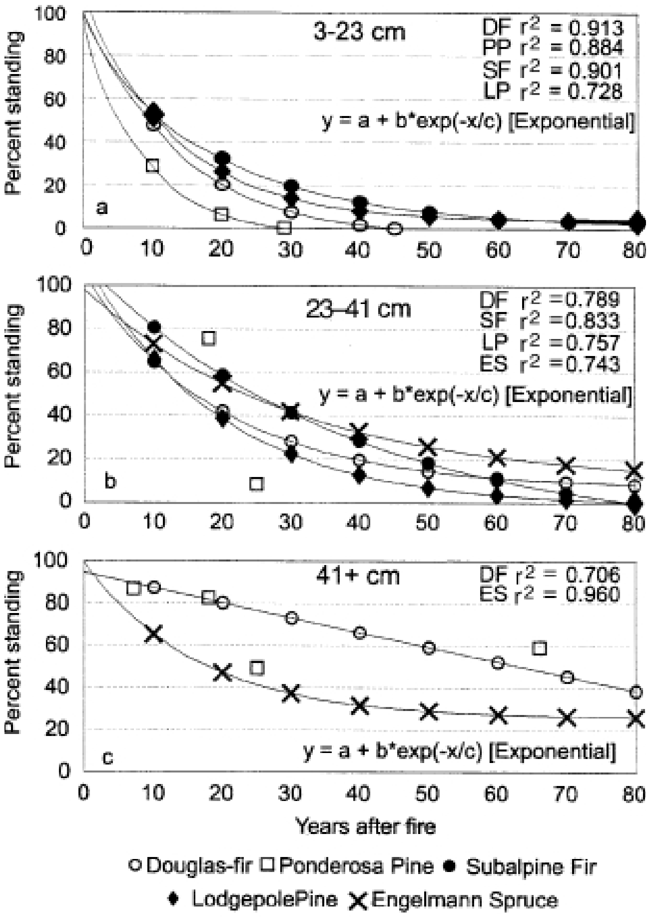

Figure 3. Snag longevity of thick (Douglas-fir) and thin (Engelmann spruce, lodgepole pine and subalpine fir) barked species of (a) 3–23 cm dbh, (b) 23–41 cm dbh and (c) > 41 cm dbh size classes. There was insufficient data for regression of ponderosa pine > 23 cm dbh, but observed values are provided for reader information.

In contrast to smaller snag size classes, a greater proportion (40%) of thick-barked Douglas-fir snags ≥ 41 cm dbh remained standing on the oldest burns than thin-barked Engelmann spruce (Figure 3, c). Large diameter ponderosa pine snags occurred too infrequently on sampled burns (10 out of 26 burns) and in too few numbers for statistical comparison with other species, but 79% (37.7% CV) of the initial snags were present on the two burns greater than 60 years of age. Although similar size snags of Engelmann spruce initially fell rapidly (50% in 20 years), the species is predicted to maintain 30% of its initial snag density up to 80 years following fire. Subalpine fir and lodgepole pine snags ≥ 41 cm dbh were rarely found. If snag populations are to be maintained over long periods of time following stand-replacement fires on similar sites, it will be necessary to retain snags ≥ 41 cm dbh of Douglas-fir and Engelmann spruce when possible.

We compared snag longevity of similar species, snag size, and sampling periods between our results and others in the

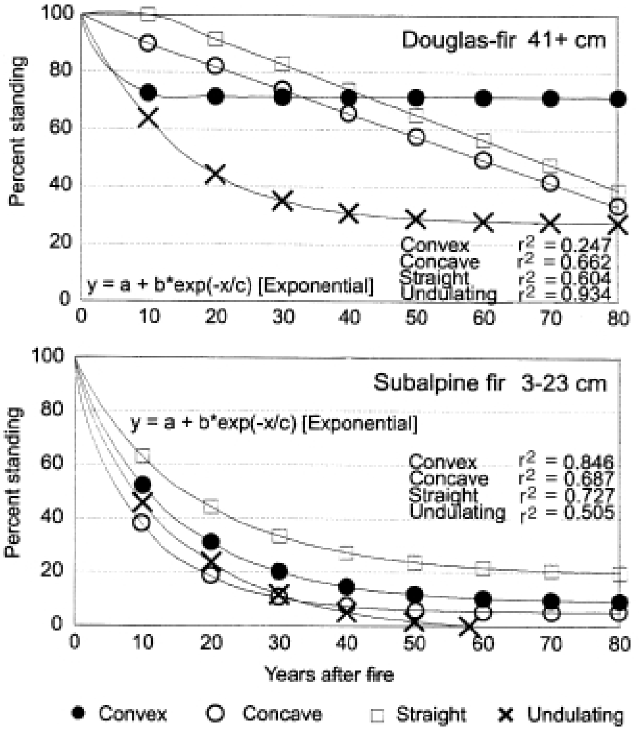

Figure 4. Predicted snag longevity for Douglas-fir and subalpine fir by micro-topographic position (convex, concave, straight, or undulating).

literature. The mean number of lodgepole pine snags ≥ 23 cm dbh standing 8 years after fire was estimated at 70% (range 45–100) compared to 55% reported by Bull (1983). We estimate the mean number of Douglas-fir snags ≥ 41 cm dbh standing at 60 years to be 50% (range 40–60), compared to 50% standing at 40 years in western Oregon (Cline et al. 1980). Differences in mean snag longevity rates among sites may be the result of different snag height criteria. However, we used similar snag height criteria to those of Raphael and Morrison (1987) and did not see the decline in snag densities 18–23 years after burn they report for lodgepole pine (62%, 15–23 cm dbh) nor did our ponderosa pine snag densities decline by 65% (23–38 cm dbh) as they report for Jeffrey pine. These differences in snag longevity between studies support the claim by Keen (1929) that snag longevity is area-specific.

Snag Longevity Among Size Classes

In a linear regression comparison of snag longevity among size classes within a species, we found the slope of the regression line to significantly decrease ($P = 0.05$) and snag longevity to increase from < 23, 23–41 and ≥ 41 cm dbh size classes in Douglas-fir (Figure 3). Snag longevity for subalpine fir < 23 cm dbh was significantly ($P = 0.05$) less than for the 23–41 cm dbh size class of this species (Figure 3). However, we could not determine any significant differences in snag longevity among size classes for lodgepole pine or Engelmann spruce. There were too few large diameter snags of ponderosa pine for statistical comparisons among size classes.

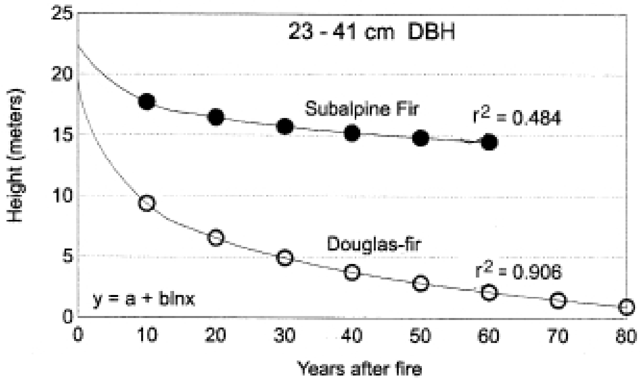

Figure 5. Snag height of thick-barked (Douglas-fir) and thin-barked (subalpine fir) tree species over time.

Snag Height

Height of thick-barked Douglas-fir (shown in Figure 5) and ponderosa pine snags declined incrementally with top breakage, whereas thin-barked Engelmann spruce, lodgepole pine, and subalpine fir (shown in Figure 5) snags fell entirely. Snag height of Douglas-fir (23–41 cm dbh) on the 15-year-old burn was approximately 50% of that on the most recent burns and mean height continued to decline to approximately 2 m on the oldest burns. Snag height of subalpine fir was approximately 70% of that on the most recent burns after 60 years. Over 95% of all Douglas-fir snags had broken tops on burns greater than 35 years old. Bull (1983) reports that top breakage of ponderosa pine snags occurs rapidly, within 4 years, and a significant portion of the snags (11%) convert into down logs by that time. Bull suggests that snags of thin-barked species, such as lodgepole pine, dry rapidly because thin or scaled bark allows rapid moisture loss, and the low moisture content retards decay except at ground level. The decay class assigned to the bole of the thin barked species does not reflect the decay class of the roots or the snag base, hence solid, thin-barked snags can fall entire. Further, Bull states that the thicker bark of ponderosa pine allows moisture to be retained which promotes decay and results in breakage along the bole. More rapid decay rates for Douglas-fir and ponderosa pine snags relative to the other species may in part explain the predominance of top breakage rather than falling entire. A softening of wood at Decay Class 3 was apparent by an increase in wildlife cavities (Lehmkuhl et al., in prep). Bull (1983) previously reported that woodpeckers excavated

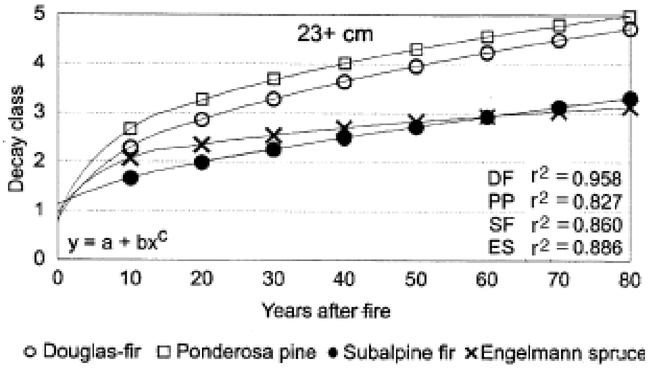

Figure 6. Predicted snag decay class with time since burn for thick-barked species Douglas-fir and ponderosa pine, and thin-barked species subalpine fir and Engelmann spruce.

cavities within 2 m of the broken top because of increased wood decay. Apparently, decay creates conditions conducive to top breakage, and broken tops increase decay rates for the remaining bole that, in turn, hasten top breakage.

Snag Decay

Sufficient numbers of Douglas-fir, ponderosa pine, subalpine fir, and Engelmann spruce snags were found on the chronosequence of burns to estimate the time required for snags to reach a mean decay class. Thick-barked species ponderosa pine and Douglas-fir snags ≥ 23 cm dbh reached Decay Class 3 (soft snags) 15–25 years after fire mortality, significantly shorter than thin-barked species, which attained Decay Class 3 approximately 65 years after fire mortality (Figure 6). Slopes of regression lines for decay of thick-barked species were significantly ($P = 0.05$) greater than for thin-barked species, but there were no significant differences within thick-barked or thin-barked groups. Regression equations predicted ponderosa pine snags decayed slightly faster than those of Douglas-fir and snags of Engelmann spruce were predicted to decayed slightly faster than subalpine fir. Determining the causal factors for differences in decay rates among species exceeds the scope of this study.

Regression lines in Figure 6 reflect mean decay class (snags ≥ 23 cm dbh), but both lesser and greater decay class snags were present at any one point in time (Figure 7, a, b, and c). In thick-barked (ponderosa pine and Douglas-fir) species, hard snags (Decay Classes 1 and 2) predominate immediately following fire, but soft snags (greater than Decay Class 3) were also present. Soft snags had increased representation on the 11-year-old burn and predominated on burns greater than 18 years old (Figure 7, a). Decay Class 5 snags were well represented on burns 60 years or older. Snags (≥ 23 cm dbh) of thin-barked species subalpine fir, lodgepole pine, and Engelmann spruce had not reached Decay Class 3 on burns less than 46 years old. On any of the sampled burns, only a minor proportion of thin-barked snags were in Decay Classes 4 or 5 (Figure 7, b), suggesting that a majority of snags fall entire prior to reaching this decay state.

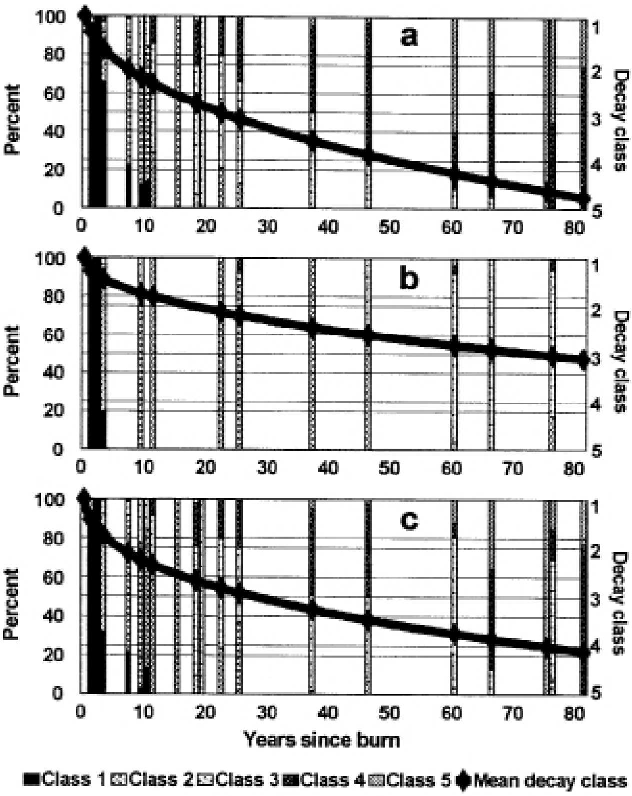

Figure 7. Percentage of snags in each decay class for (a) thick-barked (Douglas-fir, ponderosa pine), (b) thin-barked (Engelmann spruce, subalpine fir and lodgepole pine), and (c) all species combined in the chronosequence of burn sites. The regression of mean decay class over time is shown.

The mix of thin- and thick-barked species on these burns provided greater diversity in snag decay classes over time than if only thick or thin-barked species were present (Figure 7, c). In mixed species post-fire snag stands, Decay Class 1 snags predominated on burns 1 and 2 years of age, but on the 3- to 15-year-old burns, Decay Class 2 made up greater than 50% of the snags and Decay Class 3 snags were present in small amounts. By the 18-year-old burn, the majority of snags were Decay Class 3, but Decay Class 4 was also present. Class 5 snags occurred as small components on burns as early as 18 years old, rapidly increased on the 37-year-old burn, and predominated on the greater than 75-year-old burns. In the absence of fire, the proportion of severely decayed snags would increase over time if not for the recruitment of new snags derived from post-fire regeneration.

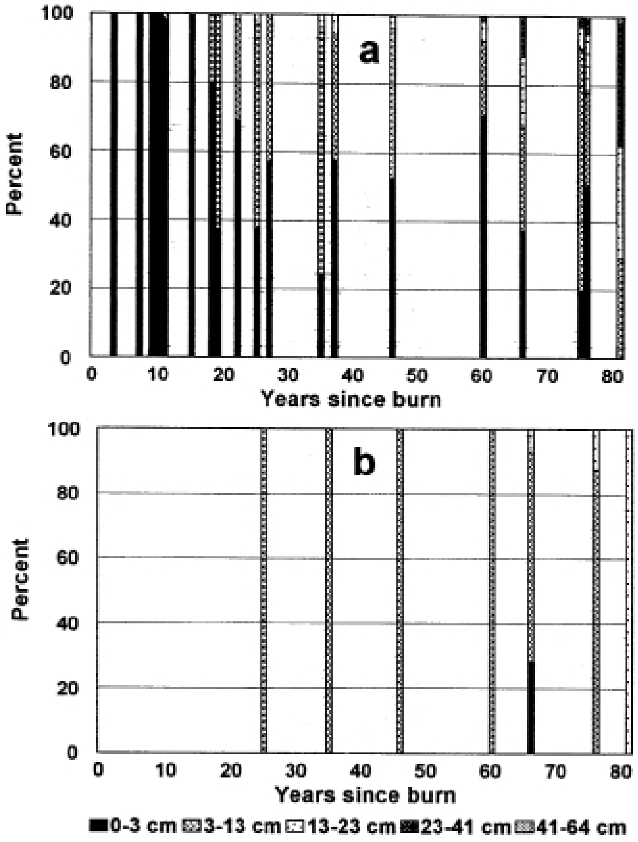

Figure 8. Percentage of (a) tree regeneration and (b) regeneration snags by size classes on the chronosequence of burns.

Regeneration Trees and Snags

Mortality of trees that regenerated following stand replacement fires, 'regeneration snags', provides new snags to replace the initial snags that have fallen over time. Regeneration trees 0–3 cm dbh pre-dominated on burns less than 15 years old, and remained a significant portion of regeneration for all but the oldest burn (Figure 8, a). Live trees 3–13 cm dbh occurred on burns greater than 18 years old. Live trees 13–23 cm dbh occurred on the 22-year-old burn, but remained a small component (5–20%) of regeneration until the 81-year-old burn. Live trees 23–41 cm dbh were found on the 46-year-old burn, but made up less than 10% of the regeneration except on the oldest burn (25%). Regeneration trees 41–64 cm dbh were present on the oldest burns, but regeneration remained dominated by stems < 13 cm dbh.

There were differences among species, with subalpine fir having regeneration > 3 cm dbh within 11 years compared to 18–25 years for other species. Regeneration trees > 13 cm dbh of lodgepole pine first occurred on a 22-year-old burn while the same size class of Engelmann spruce occurred first on a 60-year-old burn. Douglas-fir regeneration trees ≥ 23 cm dbh occurred on a 46-year-old burn, but this size class was not present for other species until the 60- to 75-year-old burns.

Regeneration trees 13–23 cm dbh numbered approximately 230 per ha on the 35-year-old burn and the numbers increased to 800 trees per ha on the 81-year-old burn. Regeneration trees 23–41 cm dbh numbered 49 per ha on the 46-year-old burn and 680 per ha on the 81-year-old burn. Regeneration tree densities reported here reflect the absence of reburn within sampled plots and may not be similar to sites where reburns have occurred. These regeneration tree densities may not be sustainable if fire effects are restored to these sites.

Tree establishment and growth was sufficiently rapid to result in regeneration trees ≥ 23 cm dbh that could become replacement snags (Figure 8, a). However, tree mortality had not yet occurred and regeneration snags in the ≥ 23 cm dbh size class were not found on the burn sites (Figure 8, b). Regeneration snags of 0–3, 3–13, and 13–23 cm dbh first occurred on burns of 7, 25, and 66 years of age, respectively, but on numerous burns there were no regeneration snags. Where the 13–23 cm dbh size class occurred on older burns, an average of 35 snags per ha were present. Regeneration snags < 23 cm dbh were already in Decay Class 2 on the 81-year-old burn.

Soft Snag Recruitment and Gaps in Snag Availability

The sum of the establishment time, tree age at 23 and 41 cm dbh, and decay period to reach Decay Class 3 gave a coarse estimate of the time required to produce a soft snag for each species (Table 2). Gaps in the presence of soft snags in the 23–41 and 41–64 cm dbh size classes were estimated to occur for all species, with the exception of Douglas-fir, if larger diameter trees of the species were well represented prior to the burn (Table 2). Regressions predicted that 18, 10, and 3% of Engelmann spruce, Douglas-fir, and subalpine fir snags 23–41 cm dbh, respectively, would be present 80 years after a burn occurred. Similar diameter lodgepole pine snags would have completely fallen by 78 years after fire. No ponderosa pine snags of this diameter were found on burns older than 25 years. The recruitment period required to provide a 23–41 cm dbh soft (Decay Class 3) snag of subalpine fir (124 years), lodgepole pine (109 years), and ponderosa pine (81 years) exceeds the predicted or actual snag longevity period for each species (80, 80, and 25 years) by an estimated 44 (124–80), 29 (109–80), and 56 (81–25) years, respectively.

The lengthy recruitment period for soft ≥ 23 cm dbh Engelmann spruce snags (141 years) suggests that a gap in snag availability would occur for this species if the snags remaining on the oldest burn fell within the next 61 years. A gap in availability of soft 23–41 cm dbh Douglas-fir snags is less likely with its 89 year snag recruitment period and 10% of the snags still standing on the 81-year-old burn. Caution is

Table 2. Estimated years required to produce soft snags >23 or >41 cm in dbh. SF, subalpine fir; DF, Douglas-fir; LP, lodgepole pine; PP, ponderosa pine; ES, Engelmann spruce. — indicates that snags 41–64 cm dbh were not present for SF or LP.

	A	B		C	Recruitment period (A+B+C)		Snags remaining at 80 years	
	Establishment^{B} period	Tree age^{A} 23–41 cm dbh	Tree age 41–64 cm dbh	Decay^{C} period	23–41 cm dbh	> 41 cm dbh	23–41 cm dbh	41–64 cm dbh
Species	Years						Percentage	
SF	12	48	—	64	124	—	3	0
DF	20	46	109	23	89	152	10	40
LP	10	54	—	45	109	—	0	0
PP	15	51	150	15	81	180	0	49
ES	20	56	119	65	141	204	18	25

^{A}Mean tree age for size class. ^{B}Time period for establishment. ^{C}Time period to reach Decay Class 3.

needed in application of these results as regression predictions are only estimations. Snag gaps for species and size class may occur contrary to the average condition when only a few large snags of a species are initially present. Data showed gaps in soft snag > 23 cm dbh availability for both Engelmann spruce (3 of 13 sites) and Douglas-fir (3 of 25 sites) when only 1 or 2 snags of this size class were present immediately after the fire.

Larger diameter (41–64 cm dbh) snags were present only for Engelmann spruce, Douglas-fir, and ponderosa pine. Regression equations estimated 25 and 40% of the original number Engelmann spruce and Douglas-fir snags would be standing after 80 years. Given that 58% of large diameter ponderosa pine snags remained standing on a 66-year-old burn, and assuming a similar fall rate, we estimated 49% would remain standing 80 years following a burn. The recruitment period for Douglas-fir, ponderosa pine, and Engelmann spruce snags 41–64 cm dbh was estimated at 152, 180, and 204 years, respectively (Table 2). Snags of these species would need to persist for an additional 72, 100, and 124 years from the present for no gaps in snag availability to occur for this size and to achieve Decay Class 3 or greater. There were no observed gaps in snag availability for this size class of Douglas-fir at sample sites, but there were gaps for ponderosa pine (1 of 10 sites) and Engelmann spruce (1 of 13 sites) where only 1–3 snags were initially present on the sample plots.

Gaps in snag availability following stand-replacement disturbance are occurring for Douglas-fir, Engelmann spruce, and ponderosa pine in undisturbed post-fire stand conditions. 'The rapid loss without replacement of snags on a severely burned site is to be expected because there are few remaining trees to recruit into the snag populations' (Lambert et al. 1980). Attempts to maintain a constant on-site availability of 23–41 and 41–64 cm dbh snags through natural processes may not be possible given observed snag longevity, decay rates, and natural regeneration time frames for most species. For Douglas-fir, the ability to continually maintain snags ≥ 23 cm dbh on a site may require 'structure relay' where large snags (41–64 cm dbh) remain a sufficient time for the development of the smaller snags (23–41 cm dbh) from regeneration. Overlap is more tenuous between the recruitment period for 23–41 cm dbh snags and the longevity of ≥ 41 cm dbh snags for Engelmann spruce (requires maintenance of 41–64 cm dbh snags for 141 years), and may not be feasible for ponderosa pine, subalpine fir, and lodgepole pine on burn sites. Following stand-replacement events, continuous snag availability for the latter species may need to be derived from adjacent stands on a landscape basis rather than on a continual on-site basis. Also, the potential for within-stand 'soft snag gaps' may be ameliorated by continuous snag recruitment from remnant individual trees that escaped the fire. Implementation of silvicultural practices that reduce time frames for species establishment (reforestation) and diameter growth (thinning and fertilization) following fire may reduce or eliminate 'on-site' snag gaps for other conifer species if selective mortality is used to produce snags. Wildlife cavity habitat can also be created in living trees (Baker et al. 1996, Parks et al. 1996) to reduce wildlife dependency upon snag occurrence.

Although we have focused on large, soft snags as potential opportunities for wildlife cavities, it is important to emphasize that small and hard snags have significant value for wildlife or other ecological benefits such as nutrient cycling. However, the description of the many roles snags play in forest ecosystems is complex and beyond the scope of this paper.

Conclusions

We rejected our null hypothesis that snag density was uniform across burns. Burns were comprised of an array of aspects, slopes, micro-topographic configurations, and tree series. The number of snags and snag longevity varied among sample plots within the same burn in response to aspect, slope, micro-topography, and species composition. Topographic differences in snag density and snag fall were most apparent on burns 1–15 years of age when snag fall was most rapid. Snag dispersion was more homogeneous among micro-topographic sites on older burns.

We suggest that snag management standards and guidelines should be flexible to accommodate differences in snag densities associated with diverse landscape heterogeneity and species composition. Also, standards and guidelines for snags should accommodate both periods of disturbance and periods of stand recovery as defined by the disturbance regimes of the area (Everett and Lehmkuhl 1996). 'Forest managers must consider this episodic creation of snags when developing snag management guidelines' (Morrison and Raphael 1993). Land managers are cautioned that current snag density in stand-replacement burns in the inland west (USA) may reflect inflated pre-fire tree densities resulting from altered fire regimes (Everett et al. 1996) and would be of limited value in establishing standards and guidelines for future snag management. The standard(s) for snag amounts, dispersion, and conditions should be supportable under the disturbance regimes of the area, otherwise management is working against disturbance processes on site and this may require additional management inputs to maintain elevated snag levels.

We rejected our null hypotheses that snag longevity is equal to or exceeds the period required for the occurrence of replacement soft snags (Decay Class 3 or greater) for all tree species evaluated. Although stand-replacement fire provides a pulse of hard snags to forest environments, it disrupts the continuous process of snag production and decay that occurs during development of unburned stands. Fire interruption of continuous snag production has been the normal process in higher elevation lodgepole pine and subalpine fir forests, but we are starting to see this phenomenon become the norm in lower elevation Douglas-fir and ponderosa pine forests as well.

Continuous on-site snag availability appears possible for some species, but not others, following stand replacement fires. In the absence of reburns, large (> 41 cm dbh) snags of thick-barked Douglas-fir are estimated to have sufficient longevity (40% standing after 80 years) to overlap the recruitment of regeneration snags ≥ 23 cm dbh (89 years). Large diameter snags of thin-barked Engelmann spruce have similar longevity, but longer growth and decay periods delay recruitment of soft snags ≥ 23 cm dbh until 141 years following fire. The recruitment period for ponderosa pine, lodgepole pine, and subalpine fir snags ≥ 23 cm dbh exceeds snag longevity for these species and an on-site gap in soft snag availability could occur within portions of stand-replacement burns. Continuous availability of soft snags ≥ 23 cm dbh in complete stand-replacement burns would have to be met from adjacent unburned stands of different ages and disturbance histories rather than on site.

Snag gaps across large, discontinuous burns are unlikely if well dispersed remnant (unburned) trees remain and the period of tree mortality is prolonged. Conservation of green trees in partial or unburned sites within large burns may increase continuity in snag availability for conifer species that do not overlap regeneration snag recruitment. However, the increased size and severity of fire events in the inland western United States (Agee 1994, Covington et al. 1994) suggests there is the realistic potential for soft snag deficits across extensive portions of wildfire burns for extended periods. Conservation of large (≥ 41 cm dbh) Douglas-fir snags following stand-replacement fires is of particular importance as these snags had the maximum longevity of the species studied and have the potential to provide on-site continuity in snags over time. Established management practices are available to reduce the potential of on-site snag gaps following continuous stand-replacement fires. Artificial regeneration to accelerate establishment, silviculture procedures to enhance growth rates, and induced regeneration tree mortality may reduce or eliminate gaps in snag availability.

Acknowledgments

The authors thank Martin Raphael, PNW Research Station; Jim Furlong, Wenatchee National Forest; John Townsley, Okanogan National Forest; and two anonymous journal reviewers for their helpful critiques and comments on the manuscript.

References

Agee J (1994) 'Fire and weather disturbances in terrestrial ecosystems of the eastern Cascades.' United States Department of Agriculture, Forest Service, General Technical Report PNW-GTR-320, Portland, Oregon.

Agee J, Edmonds RL (1992) Forest protection guidelines for the northern spotted owl, Appendix F. In 'Recovery plan for the northern spotted owl—draft'. pp. 419–480. (United States Department of the Interior, Fish and Wildlife Service, Washington, D.C.)

Baker FA, Daniels SE, Parks CA (1996) Inoculating trees with wood decay fungi with rifle and shotgun. *Western Journal of Applied Forestry* 11, 13–15.

Bull E (1983) 'Snag habitat management.' United States Department of Agriculture, Forest Service, General Technical Report RM-99, Fort Collins, Colorado.

Cline S, Berg A, Wight H (1980) Snag characteristics and dynamics in Douglas-fir forests, Western Oregon. *Journal of Wildlife Management* **44**, 773–787.

Covington WW, Everett RL, Steele R, Irwin LL, Daer TA, Auclair AN (1994) Historical and anticipated changes in forest ecosystems of the inland west of the United States. *Journal of Sustainable Forestry* **2**, 13–64

Dahms W (1949) 'How long do ponderosa pine snags stand?' United States Department of Agriculture, Forest Service, Research Note Number 57, Portland, Oregon.

Everett RL, Camp AE, Schellhaas R (1996) Building a new forest with fire protection in mind. In 'Proceedings of the Society of American Foresters National Convention'. pp. 253–258. (Society of American Foresters Bethesda MD).

Everett RL, Lehmkuhl JF (1996) An emphasis-use approach to conserving biodiversity. *Wildlife Society Bulletin* **24**, 192–199.

Everett RL, Schellhaas R, Spurbeck D, Ohlson P, Keenum D, Anderson T (1997) Structure of northern spotted owl nest stands and their historical conditions on the eastern slope of the Pacific Northwest Cascades, USA. *Forest Ecology and Management* **94**, 1–14.

Graham R, Harvey A, Jurgensen M, Jain TB, Tonn JR, Page-Dumroese DS (1994) 'Managing coarse woody debris in forest of the Rocky Mountains.' United States Department of Agriculture, Forest Service, Research Paper INT- RP-477, Ogden, Utah.

Harmon M, Franklin J, Swanson F, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Cummins KW (1986) Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* **15**, 133–276.

Harrington M (1996) 'Fall rates of prescribed fire-killed ponderosa pine.' United States Department of Agriculture, Forest Service, Research Paper INT-RP-489, Ogden, Utah.

Hinds T, Hawksworth F, Davidson R (1965) Beetle-killed Engelmann spruce: its deterioration in Colorado. *Journal of Forestry* **63**, 536–542.

Keen F (1929) How soon do yellow pine snags fall? *Journal of Forestry* **27**, 735–737.

Lambert R, Lang G, Reiners W (1980) Loss of mass and chemical change in decaying boles of a subalpine balsam fir forest. *Ecology* **61**, 1460–1473.

Lehmkuhl JF, Everett RL, Schellhaas R, Ohlson P, Keenum D, Riesterer H, Spurbeck D [In Prep.]. Cavity excavation in snags across a chronosequence of wildfire burns in the eastern Washington Cascades.

Lehmkuhl JF, Hessburg PF, Everett RL, Huff MD, Ottmar RD (1994) 'Historical and current forest landscapes of eastern Oregon and Washington.' United States Department of Agriculture, Forest Service, General Technical Report PNW-GTR-328, Portland, Oregon.

Lillybridge TR, Kovalchick BL, Williams CK, Smith BG (1995) 'Field guide for Forest Plant Associations of the Wenatchee National Forest.' United States Department of Agriculture, Forest Service, General Technical Report PNW-GTR-359, Portland, Oregon.

Lyon J (1977) 'Attrition of lodgepole pine snags on the Sleeping Child Burn, Montana.' United States Department of Agriculture, Forest Service, Research Note INT-219, Ogden, Utah.

McClelland R, Frissell S, (1975) Identifying forest snags useful for hole-nesting birds. *Journal of Forestry* **73**, 414–417.

Morrison M, Raphael M (1993) Modeling the dynamics of snags. *Ecological Applications* **3**, 322–330.

Neter J, Wasserman W (1974) 'Applied linear statistical models'. (Richard Irwin, Inc.: Homewood IL)

Oliver C, Osawa A, Camp A (1997) Forest dynamics and resulting animal and plant population changes at the stand and landscape levels. *Journal of Sustainable Forestry* **6**, 281–312.

Parks CA, Bull EL, Filip GM (1996) Using artificially inoculated decay fungi to create wildlife habitat. In 'Wildlife tree/stand-level biodiversity workshop'. (Eds P Bradford, T Manning and B. l'Anson). Pp. 87–89. (British Columbia Environment: Victoria, B.C)

Raphael M, Morrison M (1987) Decay and dynamics of snags in the Sierra Nevada, California. *Forest Science* **33**, 774–783.

Raphael MG, White M (1984) Use of snags by cavity-nesting birds in the Sierra Nevada. *Wildlife Monograph Number* 86, pp. 1–66.

Spies TA, Franklin JF, Thomas TB (1988) Coarse woody debris in Douglas-fir forests of western Oregon and Washington. *Ecology* **69**, 1689–1702.

Table Curve (1992) 'Table Curve 2D automated curve fitting software for Windows.' (Jandel Scientific: San Rafael CA)

Thomas J, Anderson R, Masser C, Bull E (1979) Snags. In 'Wildlife habitats in managed forests, the Blue Mountains of Oregon and Washington.' (Ed. J Thomas) pp. 60–77.(United States Department of Agriculture, Forest Service, Agriculture Handbook Number 553, Washington D.C.)

Washington Department of Fish and Wildlife (1995). 'Priority habitat recommendations: snags.' Washington Department of Fish and Wildlife, Olympia.