



# Ponderosa pine snag dynamics and cavity excavation following wildfire in northern Arizona

Carol L. Chambers\*, Joy N. Mast

*Northern Arizona University, School of Forestry, P.O. Box 15018, Flagstaff, AZ 86011, USA*

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## Abstract

Snags are important components of wildlife habitat, providing nesting and feeding sites for over 75 species of animals in the southwestern United States. Wildfires can increase or decrease the availability of snags to wildlife by killing live trees or incinerating snags. Our objectives were to describe dynamics and spatial patterns of fire-killed snags in ponderosa pine (*Pinus ponderosa*) forests of northern Arizona and predict the probability of snag use by cavity nesters. We established six 1-ha plots following two recent fires that occurred in northern Arizona (Hochderffer fire of 1996 [H96] and Pumpkin fire of 2000 [P00]) to determine ponderosa pine snag availability and use by wildlife as evidenced by presence of excavated cavities. For comparison, six paired 1-ha plots in nearby unburned areas were sampled with burned plots. For the twelve 1 ha plots, field methods included mapping and measuring 15 characteristics for 668 snags (630 in burned and 38 in unburned plots) 4 years post-fire on the H96 fire, and 1010 snags (996 in burned and 14 in unburned plots) 1 year post-fire on the P00 fire. We remeasured characteristics of all snags in 2003. Most burned snags were standing 3 years after fire, but 7 years after fire, 41% had fallen. Snags in burned plots were clumped when initially measured and remeasured. After 7 years, snags in burned plots that were still standing were straight, large diameter trees in denser clumps. Density of excavated cavities was similar between burned ( $3.0 \text{ ha}^{-1}$ ) and unburned ( $2.2 \text{ ha}^{-1}$ ) plots, even though burned areas produced much higher densities of snags. Snags (both burned and unburned) that were most likely to contain excavated cavities were large diameter with broken tops. This evidence of cavity nester use indicates that in ponderosa pine forests in the southwest, retaining large diameter snags is important to cavity nesters regardless of snag origin. If salvage logging is to occur in severely burned ponderosa pine in the southwest, retaining straight, large diameter snags in clumps will help maintain snags for cavity-excavating species.

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## 1. Introduction

Snags provide nesting, roosting, feeding, loafing, and storage sites for many wildlife species in the southwest (Scott, 1979; Cunningham et al., 1980; Rabe et al., 1998). In Arizona and New Mexico, ponderosa

\* Corresponding author.

E-mail address: [carol.chambers@nau.edu](mailto:carol.chambers@nau.edu) (C.L. Chambers).

pine (*Pinus ponderosa*) forests cover about 3.2 million ha (Klemmedson and Smith, 1979) and provide nesting habitat for more cavity-nesting species than any other forest type (Scott and Patton, 1989). Prior to 1870, tree densities were thought to average  $\sim 60 \text{ ha}^{-1}$ , with forests experiencing low intensity but high frequency (e.g., every 4 years) fires. However, fire suppression, logging, and increases in livestock grazing have altered ponderosa pine forest structure and composition over the past century (Cooper, 1960; Cochran and Hopkins, 1991; Covington and Moore, 1994; Saab et al., 1995; Touchan et al., 1996; Grissino-Mayer and Swetnam, 2000). In many areas, density of live trees has increased (e.g., to  $>3000 \text{ trees ha}^{-1}$  today) and average diameter of live trees has decreased (Covington et al., 1994; Mast et al., 1999). As a consequence, wildfires in forests of the southwest have been increasing in size and severity, particularly in the last 25 years (Swetnam and Baisan, 2003).

Wildfires vary in intensity across a landscape and can have both immediate and long-term impacts on snags and snag dynamics (decay and fall rate). Low intensity fires may have little effect on live trees, but may scorch and in some cases, incinerate snags (Gaines et al., 1958; Horton and Mannan, 1988; Boucher et al., 1999). Moderate and high intensity fires may scorch and kill live trees and incinerate snags (Harrington, 1996; McHugh and Kolb, 2003). Fires can therefore affect rates of snag formation, snag density, and distribution among snag size classes. In addition, fire may affect snags by charring boles. Charred snags may decay at slower rates than unburned snags, be more difficult to excavate for some cavity nesting species, and therefore may be less useful as a nesting resource (Gaines et al., 1958).

Many factors can influence wildlife use of snags, including tree species, diameter, height, density, and spatial dispersion. Most wildlife species select large diameter snags ( $\geq 34 \text{ cm}$  diameter at breast height [dbh] in ponderosa pine) (Scott and Oldemeyer, 1983; Rabe et al., 1998; Saab and Dudley, 1998; Lehmkuhl et al., 2003; Ganey and Vojta, 2004). Less is known about selection for other characteristics. Fire alters characteristics of snags and likely affects use by cavity nesters (Saab and Dudley, 1998). Knowing which snags will remain standing longest and are most used by cavity nesters can provide guidance in snag management.

We documented ponderosa pine snag dynamics in northern Arizona from 1 to 7 years following two wildfires that occurred in 1996 and 2000. For each snag, we determined year of origin as live tree, year the tree died and became a snag, physical characteristics (e.g., height, diameter, decay condition, spatial arrangement), and wildlife use (signs of foraging, presence of excavated cavities). Our objectives were to (1) describe characteristics, spatial patterns, density, decay rates, and dynamics of fire-killed snags in ponderosa pine forests of northern Arizona, and (2) predict the probability of fire-killed snag use by cavity nesters based on snag characteristics.

## 2. Methods

### 2.1. Study sites

We selected two areas that had been recently burned by wildfire on the Coconino and Kaibab National Forests (NFs) located in northern Arizona, approximately 26 km northwest of Flagstaff, Arizona. These areas have a mean annual air temperature of 5–6 °C and a mean annual precipitation of 500–600 mm. A drought that occurs seasonally between April and June (Anonymous, 1995) increases probability of fire during that time. The Hochderffer fire (H96) burned about 6500 ha of ponderosa pine on the Coconino NF in June–July 1996. The Pumpkin fire (P00) burned about 5300 ha on the Coconino and Kaibab NFs in May–June 2000. Both fires varied in severity from low (surface) to severe (crown).

To evaluate snag dynamics, we compared snags in severely burned and unburned areas. Selected sites had: (1) high severity burn patches ( $>95\%$  of trees killed by fire) with nearby or adjacent unburned patches, (2)  $>1 \text{ km}$  between plot pairs, (3) similar terrain, elevation, and pre-fire tree densities, (4) unburned snag densities of  $\geq 5 \text{ snags ha}^{-1}$  (based on Ganey (1999) median snag density of  $5 \text{ snags ha}^{-1}$  in unburned ponderosa pine forest in northern Arizona), and (5) a range of snag diameter classes to determine effect of diameter on decay and fall rate. Sites were randomly chosen from those meeting the criteria. Plots were paired, with one plot in ponderosa pine burned by wildfire and the second plot located in unburned forest  $<0.8 \text{ km}$  from its pair. We placed three pairs of plots in

each of the two wildfire-burned areas for a total of twelve 1-ha plots. Distance between H96 and P00 fires was >10 km, and within a fire boundary, pairs were 1.2–3.9 km apart. Plots in the H96 fire were established in 2000 (4 years post-fire); whereas those in the P00 fire were established in 2001 (1 year post-fire). Because the wildfires were selected opportunistically, the post-fire monitoring periods for the two fires were not the same.

All snags and live trees in plots were ponderosa pine. Plots were on relatively flat slopes ( $9 \pm 1\%$  standard error [S.E.]), at elevations between 2300 and 2550 m, with pre-fire tree basal area of  $30 \pm 2 \text{ m}^2 \text{ ha}^{-1}$ . Average diameter of smallest snags in all plots was  $17 \pm 2 \text{ cm}$ ; largest snags averaged  $67 \pm 4 \text{ cm}$ .

## 2.2. Snag measurements

We sampled all snags >1.8 m in height and >10 cm dbh on rectangular 50 m  $\times$  200 m (1 ha) permanent plots. Snag locations were mapped (to the nearest 0.5 m) for spatial analysis and to assist relocation in subsequent measurements. We collected baseline data for all snags on the H96 fire 4 years post-fire (2000) and on the P00 fire 1 year post-fire (2001). As baseline data, we recorded the following for each snag: dbh (taken at 1.4 m above ground), height (measured with a clinometer), top condition (intact or broken), bark cover (percent of bole with bark cover, to the nearest 5%), char (percent of bole with burn, to the nearest 5%), number of excavated cavities (circular openings large and deep enough to appear to the observer on the ground as adequate for the smallest cavity nester in the area to use as a nest site), number of natural cavities (naturally created openings of adequate size for nesting), foraging sign (irregular openings created by cavity-nesting birds on the surface of the snag; recorded as present, absent), dead limbs (number of dead limbs >10 cm diameter and >30 cm length), lean (degrees) of the snag from perpendicular to ground using a clinometer, and decay class (Table 1). We measured slope (%) by taking two measurements from each snag to 20 m distant in two opposite directions and averaged measurements for the snag, aspect (degrees) of slope on which the snag stood by using the natural line of travel that water would follow, and basal area (using a 20 BAF prism) of live and dead trees surrounding each snag.

Table 1

Criteria used to classify ponderosa pine snags into decay classes in southwestern conifer forests (after Raphael and White, 1984)

Decay class	Needles	Twigs	Limbs
1	Present	Present	Intact
2	Absent	Present	Intact
3	Absent	Absent	Mostly intact
4	Absent	Absent	Mostly broken
5	Absent	Absent	Gone

All snags were remeasured in 2003. All independent variables except dbh, char, slope, and aspect were remeasured. In addition, we assessed standing condition to categorize snags as either standing, fallen (uprooted or broken), cut, or missing (i.e., under other fallen snags thus unable to relocate the snag). We categorized snags into four dbh class (<25, 25–50.9, 51–75.9,  $\geq 76 \text{ cm}$ ) for comparison with other studies of fire-killed ponderosa pine (Keen, 1929; Dahms, 1949; Bull, 1983; Everett et al., 1999) but combined the two largest size classes because our sample size for  $\geq 76 \text{ cm}$  dbh snags was small ( $n = 2$ ).

## 2.3. Dendrochronological methods

We collected two tree core samples near the ground from all snags (unless they were too decayed) when we collected baseline data on snag characteristics. Tree cores were mounted, sanded, and crossdated following standard dendrochronological procedures (Stokes and Smiley, 1968) to determine age and year of death (Mast and Veblen, 1994). Rings were counted using a binocular microscope to determine marker years which are annual rings with very narrow ring widths or signatures (Visser, 1995). Ring counts were corrected for false and missing rings by use of marker years.

## 2.4. Data analysis

We described snag baseline (Time 0) and remeasurement (Time 1) data using means and standard errors. For the H96 fire, Time 0 was 4 years post-fire; Time 1 was 7 years post-fire. For the P00 fire, Time 0 was 1 year post-fire; Time 1 was 3 years post-fire. We used  $\chi^2$  tests for independence to test the null hypotheses that there were no differences between burned and unburned snag populations in top

condition, foraging sign, and decay class (Sokal and Rohlf, 1981: 152). We used Wilcoxon two-sample tests to test the null hypotheses that there were no differences between burned and unburned snag populations for dbh, height, bark cover, char, number of excavated and natural cavities, number of dead limbs, slope, and basal area surrounding snag (Sokal and Rohlf, 1981: 433). These comparisons were stratified by fire (H96 versus P00). We compared changes in characteristics of standing snags across time using Wilcoxon signed rank tests (Sokal and Rohlf, 1981: 449) to test the null hypotheses that there were no differences between Times 0 and 1 in height, bark cover, number of excavated and natural cavities, number of dead limbs, and basal area. We compared changes in condition of all snags (standing [standing or leaning] versus not standing [fallen, cut, or missing]) and in proportions of standing snags with broken tops, decay class, or foraging sign across time using McNemar tests for significance of changes (Sokal and Rohlf, 1981: 768) to test the null hypotheses that there were no differences between Times 0 and 1. We used an alpha level of 0.05 for all tests.

We used logistic regression to identify characteristics of burned and unburned snags that were associated with excavated cavities. Because our sample size of snags with excavated cavities was small ( $n = 31$ ), but about equal between burn types ( $n = 18$  on burned plots,  $n = 13$  on unburned plots) we combined all snags with excavated cavities for analysis. We used a randomly selected subset of snags without cavities ( $n = 59$ , 29 unburned and 30 burned snags) for comparison. We also used logistic regression as a means of selecting variables that separated standing from fallen snags at Time 1. We used the Hosmer and Lemeshow goodness-of-fit test to determine whether the distribution of probabilities produced by our model fit the logistic probability distribution (Hosmer and Lemeshow, 1989).

### 2.5. Spatial statistical analyses

We used spatial statistical tests to determine within and between patch patterns. Patches were 1–20 m diameter clumps around snags that increased in 1 m diameter increments. Ripley's  $K(t)$  was used to determine snag pattern with clumped distributions indicated by high values of  $K(t)$ , random pattern

indicated by values within the confidence intervals, and dispersed (or uniform) distributions indicated by low values (Ripley, 1977, 1981; Diggle, 1983). Ripley's  $K_{12}(t)$  was used to determine spatial association between groups of standing versus fallen snags, with high values of  $K_{12}(t)$  indicating attraction between the two groups, values within the confidence interval indicating no spatial relation (independence), and low values indicating negative spatial association between the two groups (Lotwick and Silverman, 1982; Diggle, 1983; Upton and Fingleton, 1985). Moran's  $I$ , a measure of spatial autocorrelation, was computed for tree height and tree diameter sizes for all snags (Moran, 1950; Cliff and Ord, 1973, 1981; Upton and Fingleton, 1985; Odland, 1988; Legendre and Fortin, 1989). Significant positive spatial autocorrelations indicated patches of similar snags (same height or same dbh), whereas negative spatial autocorrelation indicated patches of dissimilar snags (mixed heights or mixed dbh) (Legendre, 1993; Haase, 1995; Mast and Veblen, 1999; Mast and Wolf, 2004). Duncan's (1990) spatial statistics program was used for these computations. Statistical significance for each test was determined by computing 95% confidence intervals using 99 simulations (Besag and Diggle, 1977; Marriott, 1979). Since a sample size of  $>30$  was needed to run the statistical program, only the burned plots were analyzed.

## 3. Results

### 3.1. Snag characteristics

#### 3.1.1. Baseline data (Time 0)

We tagged and measured 1678 standing snags: 668 snags on the H96 fire plots, 1010 snags on the P00 fire plots. Most snags were on burned plots (H96 fire: 630 on burned plots, 38 on unburned plots; P00 fire: 996 on burned plots, 14 on unburned plots). We cored and aged 70% of snags on the H96 fire plots (29 of 38 on unburned plots, 436 of 630 on burned plots) and 96% of snags on the P00 fire plots (6 of 14 on unburned plots, 960 of 996 on burned plots). We were unable to obtain a usable core on some snags on the unburned H96 plots because of advanced decay. Most snags in burned plots were 60 to 90 years old when fire-killed (Table 2); as live trees they likely originated from 1910

Table 2

Mean ages of live trees before conversion to snags determined from 2 cores per snag on twelve 1-ha plots on the Coconino and Kaibab National Forests, northern Arizona

Location	Number of snags in plot	Percentage of snags cored	Mean age (years)	S.E.	Minimum age (years)	Maximum age (years)
P00 1B	327	92	73.7	0.5	42	136
P00 1UB	5	20	76	NA	76	76
P00 2B	279	99	61.7	1.3	35	169
P00 2UB	6	33	201.5	103.5	98	305
P00 3B	390	98	71.9	0.7	39	185
P00 3UB	3	100	59	5.1	49	66
H96 1B	102	64	69.8	1	52	103
H96 1UB	7	86	97.2	18.6	51	167
H96 2B	210	73	68.4	0.9	23	106
H96 2UB	5	60	54.3	9.8	44	74
H96 3B	318	68	79.2	1.1	35	140
H96 3UB	25	80	90.4	8.9	27	164

Location is Pumpkin fire (P00) or Hochderffer fire (H96), plots are burned (B) or unburned (UB). The H96 fire occurred in 1996; the P00 fire in 2000. Trees were cored in 2000 (H96 fire) or 2001 (P00 fire). S.E. is standard error.

to 1940. Snags in unburned plots varied in age from 54 to 202 years old. Snags ranged from 11 to 88 cm dbh and 2 to 27 m tall. We found few leaning snags. We detected differences ( $P < 0.05$ ) between snags in burned versus unburned plots on both fires in that snags in burned plots were taller, had more bole char, fewer cavities, and were on flatter slopes than those in unburned plots (Table 3). Snags in the P00 unburned

plots were larger diameter than in P00 burned plots. They also had less bark remaining than in the burned plots, likely due to more advanced decay condition (9 of 14 snags were decay class 4 or 5) (Table 4). Snags in the H96 unburned plots had more limbs and higher surrounding basal area than in H96 burned plots (Table 3). For both fires, snags were predominantly in decay class 1 or 2, especially in the burned plots.

Table 3

Means and standard errors (S.E.) for characteristics of snags in six burned and six unburned 1-ha plots on two fires (H96 = Hochderffer fire; P00 = Pumpkin fire; three burned plots and three unburned plots in each fire) in northern Arizona

Variable <sup>a</sup>	Burned P00 ( $n = 996$ )		Unburned P00 ( $n = 14$ )			Burned H96 ( $n = 629$ )		Unburned H96 ( $n = 38$ )		
	Mean	S.E.	Mean	S.E.	$P$	Mean	S.E.	Mean	S.E.	$P$
Dbh (cm)	27.4	0.2	44.8	5.1	0.0002	28.9	0.4	28.3	2.6	0.1
Height (m)	13.6	0.1	9.5	1.2	0.0009	11.6	0.2	10.3	0.9	0.05
Bark (%)	98.4	0.1	51.4	11.7	0.0001	91.2	0.5	91.4	2.8	0.1
Char (%)	95.7	0.4	6.1	4.9	0.0001	91.4	0.5	22.6	4.8	0.0001
# Excavated cavities	0.01	0.01	1.07	0.5	0.0001	0.03	0.01	0.92	0.45	0.0001
# Natural cavities	0	0	0.2	0.2	0.0001	0	0	0.2	0.1	0.0001
# Limbs	0.2	0	0	0	0.5	1	0.2	2.7	0.8	0.004
Lean (°)	0.9	0	3	1.1	0.1	1.4	0.2	3.1	1.3	0.6
Basal area ( $\text{m}^2 \text{ha}^{-1}$ )	29.6	0.5	28.2	3.0	0.8	28.7	0.5	34.7	2.8	0.04
Slope (%)	5.4	0	11.3	3.8	0.001	5.8	0.1	13.7	1.5	0.001

The H96 fire burned in 1996 and the P00 fire burned in 2000. Snags were measured 4 years post-fire (H96 fire) or 1 year post-fire (P00 fire).  $n$  is the number of snags measured in plots.  $P$  is probability that there were no detectable differences between burned and unburned snag populations within fires using Wilcoxon two-sample tests.

<sup>a</sup> Dbh is diameter at breast height, bark cover (percent of bole with bark cover, to the nearest 5%), char (percent of bole with burn, to the nearest 5%), number of excavated cavities per snag, number of natural cavities per snag, number of dead limbs (number of dead limbs >10 cm diameter and >30 cm length), lean (degree of snag lean from perpendicular to ground), basal area ( $\text{m}^2 \text{ha}^{-1}$ ) of live and dead trees surrounding each snag, percent slope averaged from two directions at 20 m from each snag.

Table 4

Percentage of snags in six burned and six unburned 1-ha plots on two fires (H96 = Hochderffer fire, P00 = Pumpkin fire) in northern Arizona by decay class, with broken or intact tops, with excavated or natural cavities, or with evidence of foraging by cavity-nesting birds

	Burned P00 ( <i>n</i> = 996)	Burned H96 ( <i>n</i> = 630)	Unburned P00 ( <i>n</i> = 14) <sup>a</sup>	Unburned H96 ( <i>n</i> = 38)
Decay class				
1	21	27	7	42
2	79	48	29	29
3	0	12	0	11
4	0	10	14	16
5	0	3	50	3
Top condition				
Broken	1	28	64	29
Intact	99	72	36	71
Snags with excavated cavities				
0	99	98	50	84
≥1	1	2	50	6
Snags with natural cavities				
0	99.9	99.5	91.7	91.9
≥1	0.1	0.5	8.3	8.1
Evidence of foraging				
No	2	1	14	8
Yes	98	99	86	92

The H96 fire burned in 1996 and the P00 fire burned in 2000. Snags were measured 4 years post-fire (H96 fire) or 1 year post-fire (P00 fire). *n* is the number of snags measured in plots.

<sup>a</sup> For snags with natural cavities, *n* = 12.

Most snags had intact tops and showed evidence of foraging by birds (Table 4).

Few snags contained excavated or natural cavities (Table 4). We found 13 snags in unburned plots (30%)

and 18 snags in burned plots (1%) with excavated cavities. Of these 31 snags, 20 had 1 cavity: 6 (14%) snags in unburned plots, 14 (1%) in burned plots. Eleven snags had multiple cavities: 7 snags (16%) had >1 cavity in unburned plots, 4 (0.3%) had >1 cavity in burned plots. In both fires the proportion of snags with ≥1 cavity was much greater in unburned plots than burned plots. However, the average number of snags per ha with cavities was similar between unburned (2.2 ha<sup>-1</sup>) and burned (3 ha<sup>-1</sup>) plots. We found few snags in burned or unburned plots with natural cavities (Table 4).

Snags were significantly clumped (95% CI) at all distances (up to 20 m plot diameter) using Ripley's *K(t)*. Spatial autocorrelation, using Moran's *I*, found patches of same-sized (dbh) snags as well as patches of same-height snags (95% CI). There was only 1 patch of mixed-size and mixed-height snags.

### 3.1.2. Remeasurement data (Time 1)

Fewer snags fell between Times 0 and 1 on the P00 (14%) than the H96 (41%) burned plots when we remeasured them 3- and 7-years post-fire, respectively. No snags fell on P00 unburned plots; 26% of snags were no longer standing on H96 unburned plots. On burned plots, larger snags were less likely to fall than smaller snags (Fig. 1). Most loss was due to snags falling (breaking at base or uprooting) as opposed to being missing (cut or not found) (1–4% of total snags on burned plots, 0–8% on unburned plots). Some snags were leaning in all plots (1–2% of total snags on burned plots, 7–11% on unburned plots).

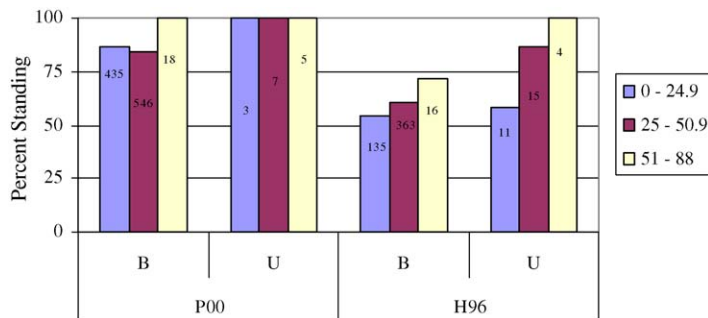


Fig. 1. Percent of ponderosa pine snags in 3 size classes (<25, 25–50.9, ≥51 cm dbh) still standing when remeasured on burned (B) and unburned (U) plots. Data are from Pumpkin fire that burned in 2000 (P00), and Hochderffer fire that burned in 1996 (H96). Snags were measured in 2000 for H96 fire and 2001 for P00 fire. All snags were remeasured in 2003. Data are from snags measured on twelve 1 ha plots (six pairs: three burned and three unburned on each fire), Coconino and Kaibab National Forests. Numbers in bars are the total number of snags measured by burn class, location, and size class.



Table 5

Mean difference (mean *D*; indicates decrease in variable) in characteristics of standing ponderosa pine snags at remeasurement (Time 1)

Variable <sup>a</sup>	Burned P00 ( <i>n</i> = 839)			Unburned P00 ( <i>n</i> = 13)			Burned H96 ( <i>n</i> = 368)			Unburned H96 ( <i>n</i> = 24)		
	Mean <i>D</i>	S.E.	<i>P</i>	Mean <i>D</i>	S.E.	<i>P</i>	Mean <i>D</i>	S.E.	<i>P</i>	Mean <i>D</i>	S.E.	<i>P</i>
Height (m)	−0.15	0.04	0.0001	−0.13	0.08	0.3	−1.6	0.2	0.0001	−0.7	0.7	0.5
Bark (%)	−2.2	0.2	0.0001	−2.1	1.2	0.1	−2.8	0.5	0.0001	−0.9	0.4	0.06
# Excavated cavities	0.02	0.01	0.08	0.15	0.61	0.6	−0.02	0.0	0.3	0.07	0.09	1.0
# Natural cavities	−0.002	0.002	1.0	0.09	0.08	1.0	−0.003	0.0	1	0	0	–
# Limbs	0	0	–	0	0	–	−0.4	0.1	0.0001	−1.4	0.7	0.06
Lean (°)	0.5	0.2	0.4	−0.7	0.7	1.0	0.6	0.2	0.6	1.2	0.9	0.2
Basal area (m <sup>2</sup> ha <sup>−1</sup> )	−8.4	0.7	0.0001	3.7	3.9	1.0	−30.9	1.8	0.0001	−15	11.5	0.3

Snags on Pumpkin (P00) fire were measured 1 (Time 0) and 3 (Time 1) years post-fire. Snags on Hochderffer (H96) fire were 4 (Time 0) and 7 (Time 1) years post-fire. Fires occurred in northern Arizona in 1996 (H96 fire) and 2000 (P00 fire). Snags were measured on 12 paired plots (one plot of each pair in burned area, the other in unburned area; three pairs per fire).

<sup>a</sup> Bark cover (percentage of bole with bark cover, to the nearest 5%), number of excavated cavities per snag, number of natural cavities per snag, number of dead limbs (number of dead limbs >10 cm diameter and >30 cm length), lean (degree of snag lean from perpendicular to ground), basal area of live and dead trees surrounding each snag.

In burned plots, height, percent bark, and basal area of trees surrounding snags had significantly decreased ( $P < 0.0001$ ). Snags in burned plots on the H96 fire had lost a significant number of limbs ( $P < 0.0001$ ) but not in P00 fire plots. In unburned plots, we did not

detect any significant changes in snag characteristics ( $P > 0.06$ ) (Table 5). We found changes in snag top condition in burned plots on both H96 and P00 burned plots ( $P < 0.0001$ ), but not in unburned plots ( $P = 0.3$ ). More snags in burned plots had broken

Table 6

Difference in percentage of ponderosa pine snags in six burned and six unburned 1-ha plots on two fires (H96 = Hochderffer fire that burned in 1996, P00 = Pumpkin fire that burned in 2000) in northern Arizona at remeasurement (Time 1) by decay class, with broken or intact tops, or with evidence of foraging by cavity-nesting birds

	Burned P00		Burned H96		Unburned P00		Unburned H96	
	%	<i>P</i>	%	<i>P</i>	%	<i>P</i>	%	<i>P</i>
All snags	<i>n</i> = 996		<i>n</i> = 630		<i>n</i> = 14		<i>n</i> = 38	
Standing	85		58		100		74	
Not standing	15	0.0001	42	0.0001	0	0.3	26	0.007
Standing snags	<i>n</i> = 850		<i>n</i> = 368 <sup>a</sup>		<i>n</i> = 14		<i>n</i> = 28	
Decay class								
1	12		10		7		25	
2	88		57		29		46	
3	0		9		0		11	
4	0		10		14		14	
5	0	0.0001	14	0.0001	50	1	4	0.7
Top condition								
Broken	3		53		71		39	
Intact	97	0.0001	47	0.0001	29	0.3	61	0.3
Evidence of foraging								
No	1.6		0.5		7		4	
Yes	98.4	0.4	99.5	1	93	–	96	0.3

Baseline data for snags was taken in 2000 for H96 and 2001 for P00. Snags were remeasured in 2003 (Time 1) which was 7 years post-fire for H96 fire or 3 years post-fire for P00 fire. *P* is the probability that no change was detected between Times 0 and 1 in number of standing snags, decay class, top condition, or evidence of foraging.

<sup>a</sup> For burned H96, *n* = 366 for evidence of foraging.

tops 3 or 7 years post-fire than when they were first measured 1 or 4 years post-fire, respectively. Snags in burned plots were in more advanced decay classes when re-measured on both the H96 and P00 fires ( $P < 0.0001$ ) but not in unburned plots ( $P \geq 0.7$ ) (Table 6).

We did not detect differences in number of excavated or natural cavities between Times 0 and 1 (Table 5). We found evidence of foraging by woodpeckers in most snags when we measured them initially, so did not detect a difference when we re-measured them ( $P \geq 0.3$ ) (Table 6).

Snags were significantly clumped (95% CI) at all distances up to 20 m diameter using Ripley's  $K(t)$ . Using Ripley's  $K_{12}(t)$ , we found significant negative spatial association between fallen snags at Time 1 versus those still standing at Time 1.

### 3.1.3. Characteristics of burned snags that remained standing

We were unable to develop a model for burned snags using H96 and P00 plots combined (goodness-of-fit  $P < 0.01$ ), so we developed separate models for each fire. Our sample size was too small to develop a logistic regression model explaining which snags remained standing in unburned plots.

Whether a ponderosa pine snag remained standing ( $n = 850$ ) or not ( $n = 145$ ) 3 years post-burn on the Pumpkin fire could be predicted by a logistic regression model that included basal area of live and dead trees surrounding the snag at Time 0 (likelihood ratio  $P < 0.0001$ , goodness-of-fit  $P = 0.06$ ). Three-year-old fire-killed snags were more likely to remain standing if they had higher surrounding basal area at Time 0. This model accurately classified 52% of standing snags. However, the best model predicting whether a ponderosa pine snag remained standing included both basal area of live and dead trees surrounding the snag at Time 0 and basal area of live and dead trees surrounding the snag when re-measured at Time 1 (likelihood ratio  $P < 0.0001$ , goodness-of-fit  $P = 0.4$ ). Three-year-old fire-killed snags were more likely to remain standing if they had higher surrounding basal area (live and dead trees) (Fig. 2). This model accurately classified 87% of standing snags.

Whether a ponderosa pine snag remained standing ( $n = 368$ ) or not ( $n = 258$ ) in burned stands 7

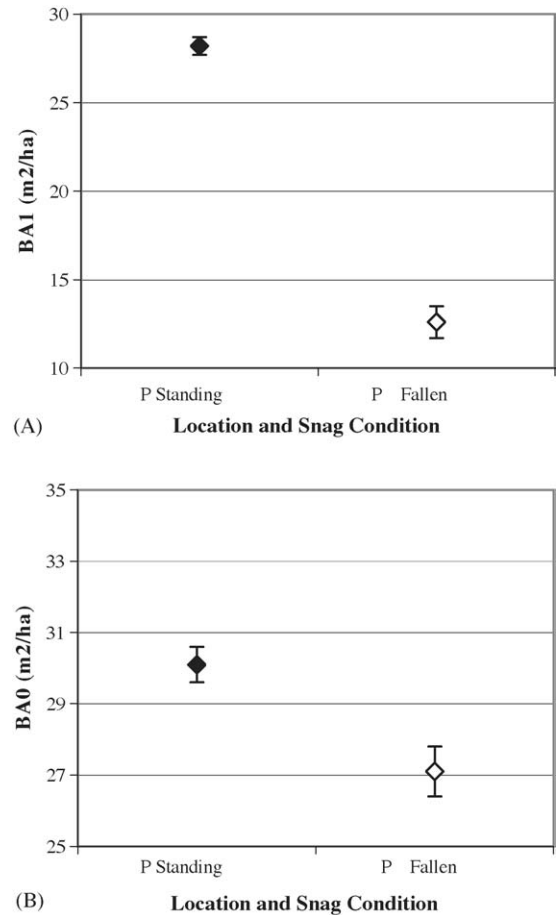


Fig. 2. Characteristics of 3-year-old fire-killed ponderosa pine snags that helped distinguish standing from fallen snags. Snags were measured on Pumpkin fire (P) which burned in 2000. Snags were measured in 2001 (996 standing snags) and 2003 (839 standing and 157 fallen snags). (A) BA1 and (B) BA0 were basal area of surrounding trees (live and dead) when snags were re-measured at 3 years post-fire (BA1) and 1 year post-fire (BA0).

years post-burn at the Hochderffer fire was best predicted by a logistic regression model that included dbh at Time 0, height at Time 0, lean at Time 0, basal area of surrounding live and dead trees at Time 0, and basal area of surrounding live and dead trees at Time 1 (likelihood ratio  $P < 0.0001$ , goodness-of-fit  $P = 0.4$ ). Snags most likely to persist on the H96 fire were straight, short, large diameter, and in clumps of live and/or dead trees (Fig. 3). This model accurately classified 79% of standing snags.



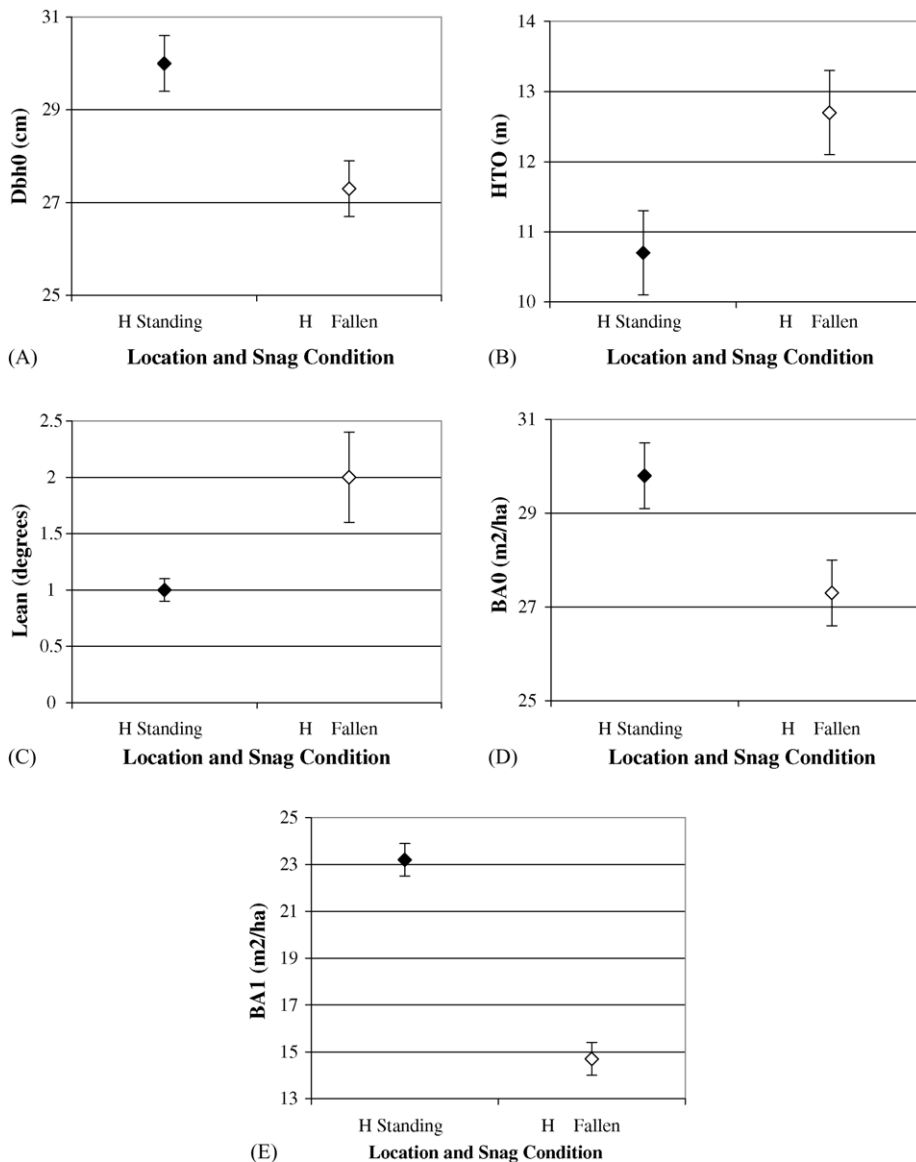


Fig. 3. Characteristics of 7-year-old fire-killed ponderosa pine snags that helped distinguish standing from fallen snags. Snags were measured on the Hochderffer fire (H) which burned in 1996. Snags were measured in 2000 (629 standing snags) and 2003 (359 standing and 270 fallen snags). (A) Diameter at breast height (Dbh0), (B) height (ht0), (C) degree of lean (lean0), and (D) initial basal area of live and dead surrounding trees (BA0) were measured at Time 0. (E) BAI is basal area of live and dead surrounding trees when snags were remeasured at Time 1 (7 years post-fire).

#### 3.1.4. Characteristics of snags containing excavated cavities

Whether a snag contained excavated cavities ( $n = 31$ ) or not ( $n = 59$ ) was best predicted by dbh and top condition measured at Time 0 (likelihood ratio

$P < 0.0001$ ; goodness-of-fit  $P = 0.3$ ). The probability of a ponderosa pine snag containing excavated cavities increased if the top was broken and as dbh of the snag increased (Fig. 4). This model accurately classified 83% of standing snags with excavated cavities.

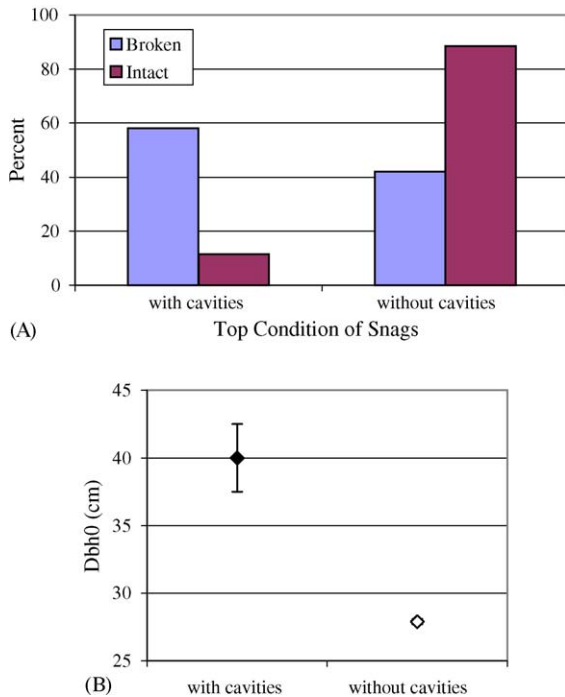


Fig. 4. Characteristics of burned and unburned ponderosa pine snags with and without excavated cavities. Snags were measured on twelve 1-ha plots from two fires in northern Arizona (H = Hochderffer fire, Coconino National Forest, fire burned in 1996, snags first measured in 2000, remeasured in 2003; P = Pumpkin fire, Coconino and Kaibab National Forests, fire burned in 2000, snags first measured in 2001, remeasured in 2003) (six pairs: three burned and three unburned on each fire). Data represent a subset of snags measured;  $n = 31$  for snags with excavated cavities,  $n = 59$  for snags without excavated cavities. (A) Top condition for snags is intact or broken, (B) dbh0 is diameter at breast height of snag.

## 4. Discussion

### 4.1. Snag dynamics

Wildfire can dramatically increase snag density across a landscape, creating a pulse of new snags and altering vegetation class from mature forest to open grasslands with snags. The burned snags in severely burned areas that we monitored were much denser (17–70 times) than unburned snags in ponderosa pine forests that had not burned. We found that snags in Hochderffer burned plots most likely to remain standing were straight, large diameter, broken-topped snags in denser clumps. We suspected that wind affected top condition of snags in our study by

breaking snags at heights  $>1.8$  m which then contributed to their stability. Raphael and Morrison (1987) similarly reported that snag longevity for pine species (*Pinus* spp.) was greater for larger diameter, less decayed, shorter height snags with broken tops. However, in our study wind also felled snags (breaking to  $<1.8$  m height or uprooting them). Having higher basal area of live or dead trees surrounding a snag appeared to protect them by slowing fall rate; most likely these clumps helped block wind. Ponderosa pine snags appeared to be stable for 3–4 years post-fire, but began to fall at higher rates after this time. We suspected that unburned snags would persist longer than burned snags, especially in smaller size classes. Because of our small sample size for unburned snags, we were unable to test this.

Ponderosa pine snag dynamics in severely burned areas have been described in other parts of the western United States. We observed remarkably similar fall rates to these areas, with high losses of snags within a short time period (4–7 years). For example, Bull (1983) found that 11% of burned ponderosa pine snags fell within 4 years. She also found that top breakage occurred rapidly, possibly because the thick bark of ponderosa pine retained moisture that promoted decay. We found a similar fall rate on the P00 fire; with 14% of burned snags fallen 3 years after fire (Fig. 5).

Other studies examined fall rate by dbh size class. Keen (1929) reported that 42% of smaller (25–46 cm

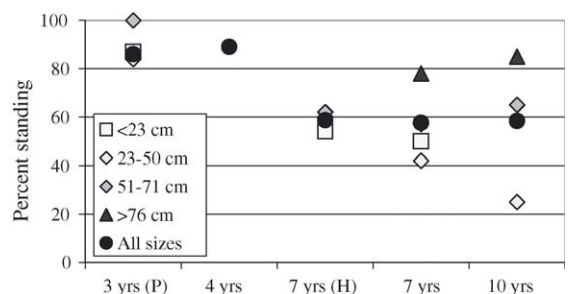


Fig. 5. Percent of fire-killed ponderosa pine snags by dbh size class ( $<23$ , 23–50, 51–71,  $>76$  cm dbh, and all size classes combined) standing post-fire on the Pumpkin (P00) and Hochderffer (H96) burned plots from northern Arizona, compared with studies by Keen (1929), Dahms (1949), Bull (1983), and Everett et al. (1999). Bull's (1983) data were for 4 years post-fire, Keen (1929) and Everett et al. (1999) were for 7 years post-fire, and Dahms (1949) for 10 years post-fire. The P00 burned plots are for 3 years post-fire (P) and the H96 for 7 years post-fire (H).

dbh) ponderosa pine snags remained standing 7 years post-fire. Although we found a higher percentage (60%) of our 7-year-old snags in this dbh class standing, we initially undercounted snags on the H96 fire since we did not tag snags until 4 years after the H96 fire occurred. We monitored only standing snags, so it is likely that some snags had already fallen (e.g., 14% as we found on P00 fire plots), especially in these smaller size classes. However, we did find similar fall rates for larger snags; 62% of snags 51–71 cm dbh were standing 7 years post-fire compared with 57% described by Keen (1929) (Fig. 5). Dahms (1949) reported that only 25% of ponderosa pine 20–51 cm dbh snags were standing 10 years post-fire but larger burned snags persisted longer (65% of 51–76 cm and 85% of 76–107 cm dbh snags remained standing) (Fig. 5). We found 60, 62, and 100% of snags on our burned plots in these size categories were standing 7 years post-fire (although we only had two snags in the largest size category) and will continue to monitor snag fall with the expectation that larger dbh burned snags will persist longer than smaller snags.

Everett et al. (1999) found that about 50% of ponderosa pine snags <23 cm dbh fell or broke to minimum 1.8 m height during the first 7–12 years post-fire. We found 46% of <23 cm dbh snags had fallen 7 years post-fire; however, only 13% of 4-year-old burned snags had fallen (Fig. 5). Raphael and Morrison (1987) also reported high fall rates for pine species with most fall (68%) occurring within the first 5 years of burn. Fall rates for ponderosa pine snags appear to greatly increase 4 years post-burn, especially for smaller dbh size classes (Raphael and Morrison, 1987). Everett et al. (1999) also reported that most burned ponderosa pine snags  $\geq 23$  cm dbh reached decay class 3 (soft snags, bark and branches absent, bole intact, minimum of top breakage) 15–25 years post-fire. Seven years post-fire our snags were primarily in decay class 2, suggesting a similar progression in decay over time.

#### 4.2. Use by cavity excavators

Cavity excavators used large diameter (e.g., 40 cm) burned snags within 3–4 years of creation by wildfire, suggesting the importance of retaining large diameter snags, regardless of origin, to wildlife. Although we

did not have large numbers of unburned snags for comparison, the high mean density of cavities (1 per snag) reflected their importance to cavity nesters.

Snags were not a limiting factor for cavity nesters in severely burned areas; instead, territoriality of birds may explain the similar cavity densities of 2.2–3 ha<sup>-1</sup> that we observed in burned and unburned plots. Hairy woodpeckers (*Picoides villosus*) and Lewis's woodpeckers (*Melanerpes lewis*) nested and northern flickers (*Colaptes auratus*) foraged in burned areas in and around our plots. These species could account for the creation of cavities in recently-burned snags since they have been found to be more abundant in recent wildfire-burned areas (hairy woodpecker, Covert, 2003), have higher reproductive success in crown-burned ponderosa pine forests (Lewis' woodpecker, Saab and Vierling, 2001), or are suspected to respond positively to high severity, stand replacement fire (Saab and Dudley, 1998).

Saab and Dudley (1998) also found that primary cavity nesters selected nest sites in clumps of snags and that nest trees were larger diameter, more heavily decayed snags with broken tops. Thus, both burn severity and spatial arrangement of snags affected cavity nester use. These findings are markedly similar to ours. Snags in burned and unburned plots used by cavity excavators were more likely to be large diameter and broken topped or shorter in height. We did not find a relationship with decay class but many of the cavities we found were in 1–4-year-old burned snags in early stages of decay.

Ganey and Vojta (2004) compared cavity density and characteristics of snags containing excavated cavities in unburned ponderosa pine and mixed conifer forests in northern Arizona. Cavities were more often found in large dbh ponderosa pine that were in more advanced decay classes and had broken tops. The similarity of their findings in unburned snags with our findings in burned and unburned snags indicates that retaining large diameter snags across the landscape, regardless of burn severity, is important to cavity nesters.

## 5. Conclusions

Wildfire can alter snag density across a landscape, creating pulses of snags of similar decay class. The

availability of snags in larger size classes will therefore depend on the size classes of live trees that were fire-killed. We had a range of size classes in our burned plots. Habitat remaining will affect cavity-nesting species. Burned and unburned snag plots in our study differed because qualities of fire-killed snags differed from those of “naturally” killed snags. Burned and unburned snags were created through different disturbances, and differed in spatial and temporal distribution. Cavity nester use of both burned and unburned snags suggested that even though snags were created by different processes, both are important as wildlife habitat. Burned snags benefit species such as hairy, Lewis’s, and black-backed woodpeckers because of the type of habitat created (high density of burned snags that are used for both nesting and foraging) (Hutto, 1995; Saab and Vierling, 2001; Kotliar et al., 2002; Covert, 2003). Other species select unburned over burned snags or snags in unburned areas (Kotliar et al., 2002). Thus, resource managers should retain both unburned and burned snags. Larger diameter snags will be useful for nesting, both large and small diameter snags for foraging.

Retaining large diameter snags surrounded by higher basal area of live and/or dead trees should help retain fire-killed snags longer. Bird responses to fire were influenced by a number of factors (e.g., burn size, burn severity, pre- and post-fire cover types, time since fire), and salvage logging could alter species’ use of burns (Kotliar et al., 2002). Many cavity nesting birds do not use heavily salvaged burns, but some can likely persist in partially salvaged burns (Hutto, 1995; Kotliar et al., 2002). Raphael and Morrison (1987) suggested that models of snag dynamics must include species, condition of trees becoming snags, and factors causing trees to die. Burn condition appeared to be a factor affecting snag longevity. Burned ponderosa pine snags may not last as long as unburned snags, so it will be important to track how snags created by different methods are used by cavity nesters.

Our findings are very similar to other studies of snag dynamics and cavity nesting bird use following fire that have been conducted throughout the western United States. Severely burned areas experience a large pulse of snags that may be followed by a long interval of little to no recruitment of large snags. Because burned snags may not last as long, but are

important to some cavity nesters, it will be important to track snag replacement over time so a landscape does not become devoid of snags.

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