

Changes in Snag Populations in Northern Arizona Mixed-Conifer and Ponderosa Pine Forests, 1997–2002

Joseph L. Ganey and Scott C. Vojta

Abstract: Snags (standing dead trees) are important components of forests that contribute to ecological processes and provide habitat for many life forms. We monitored dynamics of snag populations on 1-ha plots in southwestern mixed-conifer ($n = 53$ plots) and ponderosa pine (*Pinus ponderosa*, $n = 60$ plots) forests in north-central Arizona from 1997 to 2002. Of 2,240 snags marked in 1997, at least 76% remained standing in 2002, 17% had fallen and were relocated as logs, 0.5% were cut down, and the remainder (6%) were unaccounted for. Snag density increased significantly in mixed-conifer forest but not in ponderosa pine forest. Snag density increased mainly in the smaller size classes in both forest types. Density of large snags (≥ 46 cm in diameter and 9 m in height) increased slightly but nonsignificantly from 1997 levels in both forest types, and fell below current targets for retention. Species composition of snags differed between 1997 and 2002 in ponderosa pine forest, but not in mixed-conifer forest, and decay-class distributions differed among years in both forest types. A classification-tree analysis indicated that a ratio of height to diameter, species, and diameter were key variables in predicting whether a snag survived from 1997 to 2002. These results provide empirical data on snag populations and dynamics in this area and establish a basis for longer-term monitoring of snag populations and dynamics. FOR. SCI. 51(5):396–405.

Key Words: Classification tree, coarse woody debris, snag dynamics.

SNAGS (STANDING DEAD TREES) provide important resources for numerous species of native wildlife as well as important contributions to decay dynamics and ecological processes in the forests where they occur (Thomas et al. 1979, Davis et al. 1983, Raphael and White 1984, Harmon et al. 1986, Bull et al. 1997, McComb and Lindenmayer 1999, Laudenslayer et al. 2002). Because of their importance, snags have received considerable attention from land managers and researchers. Most national forests in the United States have regulations requiring the retention of specified numbers of snags to provide habitat for native wildlife (Morrison et al. 1986), and managers therefore are particularly concerned with maintaining snag populations (Mellen et al. 2002). Despite these mandates for snag management, data on snag numbers and densities on national forest lands often are sparse. Further, maintaining target densities of snags is difficult even when current snag densities are known, because snag dynamics are not well understood in most forest types and geographic areas (Everett et al. 1999), and typically exhibit large spatial and temporal variability (Raphael and Morrison 1987, Morrison and Raphael 1993).

To address information needs relative to dynamics of snag populations in southwestern mixed-conifer and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) forests, we established a series of permanent plots in north-central

Arizona in 1997 for the purpose of monitoring snag populations at 5-yr intervals. Ganey (1999) described initial snag populations in this area. Here, we 1) describe changes in snag populations (abundance and composition) from 1997 to 2002, 2) compare existing densities of large snags to current standards for retention of large snags in these forests, and to densities of such snags in 1997, and 3) model and describe characteristics of standing versus fallen snags. These data provide an initial glimpse of the dynamics of snag populations in these forest types, and establish a basis for longer-term monitoring of snag populations and dynamics.

Methods

Field Sampling

We sampled snags in 2002 in square, 1-ha plots established in 1997 in a study area of approximately 73,000 ha spanning six Ranger Districts on two National Forests in north-central Arizona (Figure 1). Plots were randomly located in mixed-conifer ($n = 54$ plots, of which 53 were sampled in 2002) and ponderosa pine ($n = 60$ plots, all sampled in 2002) forest (see Ganey 1999 for further details on plot selection, location, and establishment). Mixed-conifer forests in this area were dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and white fir (*Abies*

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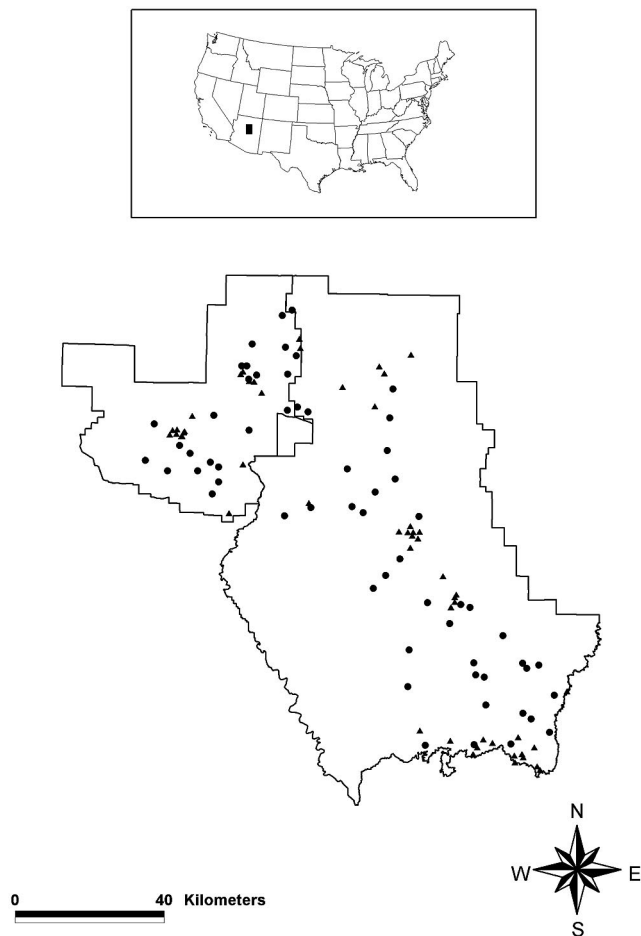


Figure 1. Location of the study area (black box, top) in northern Arizona, USA, and locations of snag-monitoring plots within the study area (bottom). Plots were located in the Coconino (right, 4 Ranger Districts included) and Kaibab (left, 2 Ranger Districts included) National Forests, north-central Arizona. Plots in ponderosa pine forest ($n = 60$) are indicated by circles, plots in mixed-conifer forest ($n = 53$) by triangles. The more clumped distribution of mixed-conifer plots reflects the more restricted distribution of mixed-conifer forest within the study area.

concolor Lindl. ex Hildebr.); other common species included ponderosa and limber (*P. flexilis* James) pine, quaking aspen (*Populus tremuloides* Michaux), and Gambel oak (*Quercus gambelii* Nutt.). Ponderosa pine forests were heavily dominated by ponderosa pine, often contained Gambel oak and/or alligator juniper (*Juniperus deppeana* Steud), and sometimes contained quaking aspen, pinyon pine (*P. edulis* Engelm.), limber pine, Douglas-fir, and other species of junipers.

In 1997, we marked all snags ≥ 2 m in height and ≥ 20 cm in diameter with uniquely numbered aluminum tags attached at the base of the snag. For each snag, we recorded tag number, snag species, diameter at breast height (dbh), (or diameter at root crown [drc] for oaks or junipers with multiple trunks), height, decay class, bark cover, and top condition. Snag diameter was recorded to the nearest cm using a dbh tape. Snag height was estimated to the nearest m using a clinometer. Percent bark cover was estimated visually to the nearest 5%, and top condition was recorded

as broken or intact. Decay classes recognized followed Raphael and White (1984). Snags in decay class 1 retained needles (or leaves), twigs, and intact limbs. Decay-class 2 snags retained twigs and intact limbs but lacked needles. Class 3 snags had limbs that were largely intact, but lacked twigs. Class 4 snags had limbs that were mostly broken, and class 5 snags lacked large limbs entirely.

In 2002, we searched the plots for all snags, re-sampled all previously marked snags, and uniquely marked any new snags encountered. We also searched for numbered tags on logs and stumps within any plots containing snags marked in 1997 but not located in 2002. Despite this search, we were not able to relocate all 1997 snags. We identified at least four possible causes for failure to relocate marked snags. In order from most to least likely, these were: (1) the metal tag melted due to extreme heat during wildfire (see below), (2) the snag had fallen, but the metal tag was on the side against the ground and not visible, (3) the snag was cut down and woodcutters removed the metal tag from the stump, or (4) the tag was removed from standing snags by animals or humans.

We recorded the above data for all snags encountered in 2002, but added several decay classes to account for changes in status of snags marked in 1997. New categories added included: snag cut down, snag fell and was located as a log, and snag not found.

Summarizing Changes in Snag Populations

We summarized data on changes in abundance of snags and composition of snag populations from 1997 to 2002 by forest type. We estimated snag loss and recruitment rates (both overall rates and rates within 10-cm diameter classes) only for plots that did not experience severe wildfire between 1997 and 2002, because the metal tags used to mark snags melted when exposed to extreme heat. As a result, we could not always determine whether a snag was marked previously or newly recruited. We included burned plots ($n = 3$) in analyses of net changes in snag numbers, however, because biases in estimated loss and recruitment rates of snags due to tag loss canceled each other. That is, a snag that lost its tag would be counted both as a snag lost and a snag recruited, resulting in unbiased estimates of net change. We compared snag density between 1997 and 2002 using Wilcoxon signed-ranks tests (Conover 1980) stratified by forest type. We also estimated net change in density of snags from 1997 to 2002 within 10-cm diameter classes. We compared species composition and decay-class distributions between 1997 and 2002, using chi-square tests stratified by forest type.

Density of Large Snags

Because management guidelines in this region emphasize large snags (defined as snags ≥ 46 cm dbh and ≥ 9 m tall; Reynolds et al. 1992, USDA 1996), we focused a series of analyses on such snags. Specifically, we (1) compared 2002 density of large snags with 1997 density (Ganey

1999), using Wilcoxon signed-ranks tests stratified by forest type; (2) compared densities of large snags with current standards for retention of large snags in these forests (4.9 and 7.4 snags/ha in ponderosa pine and mixed-conifer forest, respectively; Reynolds et al. 1992, USDA 1996); (3) estimated proportions of plots meeting guidelines in both forest types; and (4) compared these proportions between 1997 and 2002 using McNemar's test for significance of changes (Conover 1980). Because past timber harvest could influence current densities of large snags (Oliver 2002), we also compared density of large snags between plots with and without evidence of past timber harvest using Mann-Whitney tests (Conover 1980) stratified by forest type.

Modeling Snag Survival

We used classification tree analysis (Breiman et al. 1984) to identify snag attributes that best predicted snag fate. We used the rpart module (Therneau and Atkinson 2004) in R software (R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. 2004 <http://www.R-project.org>.) to develop the classification tree. Variables entered included forest type and snag species, dbh, height, a height-to-diameter ratio (computed as height/diameter in m), decay class, bark cover, and top condition (broken or intact). We used cross-validation to assess prediction accuracy of the resulting tree, and estimated the importance of variables used to develop the tree based on a relative importance score. This score was computed by summing improvement values for each variable across all nodes within the tree, then scaling all scores relative to the variable with the highest score. Thus, the importance value for a particular variable was based both on how many nodes included that variable as a primary or surrogate splitting variable, and on how significant that variable was at those nodes.

Following the classification tree analysis, we conducted univariate comparisons between snags that stood from 1997 to 2002 and those that fell. We compared continuous variables (dbh, height, height-to-diameter ratio, bark cover) using Mann-Whitney tests (Conover 1980), and compared survival rates of snags across categories of categorical variables (species, decay class, top condition) using a comparison of multiple proportions (Goodman 1964).

Results

None of the plots sampled in 2002 experienced commercial timber harvest or precommercial thinning during the interval 1997–2002, but three plots (2.7%) experienced severe wildfire during this interval. Two of these plots were in ponderosa pine forest (3.3% of pine plots), with the third in mixed-conifer forest (1.9% of mixed-conifer plots). It was frequently impossible to determine fates of individual snags in these plots (see above).

Changes in Snag Populations

Plots sampled in 2002 contained 2,240 snags originally marked in 1997. At least 1,710 (76.4%) of these were still standing in 2002. Twelve snags (0.5% of total snags) were cut down between 1997 and 2002. Another 383 snags (17.1%) fell and were relocated as logs, and 133 snags (5.9%) could not be found. Among the snags that could not be found, 99 (74.4%) occurred on the three severely burned plots. Many of these snags likely remained standing but could not be identified because the metal tags melted. In contrast, we suspect that most or all of the 34 missing snags on unburned plots (1.5% of total snags) had fallen or been cut down.

Snags that were cut down were not necessarily large (mean dbh = 37.6 cm, range = 21–67 cm; mean height in 1997 = 9.1 m, range = 3–25 m). They included at least five species (alligator juniper [$n = 2$], ponderosa pine [$n = 4$], quaking aspen [$n = 2$], Douglas-fir [$n = 1$], Gambel oak [$n = 2$], and unknown species [$n = 1$]) and most decay classes (25% class 1, 17% class 2, 8% class 4, and 50% class 5).

Absolute loss rates of snags were approximately three times greater in unburned mixed-conifer forest than in unburned ponderosa pine forest (Table 1), although proportionally more snags were lost in ponderosa pine forest (24.1% of total snags) than in mixed-conifer forest (17.4%). Recruitment rates were approximately five times greater in mixed-conifer forest, however, with the result that overall snag abundance increased more in mixed-conifer than in ponderosa pine forest (Table 1). Increases in snag abundance also occurred over more of the landscape in mixed-conifer than in ponderosa pine forest. Most mixed-conifer

Table 1. Changes in snag density (number/ha) from 1997 to 2002 in northern Arizona mixed-conifer and ponderosa pine forest

Burn status	Plots ¹	1997 snag density	Snags lost	Snags recruited	2002 snag density	Net change
Mixed-conifer forest						
Unburned	52	32.9 (3.0)	6.2 (0.7)	10.0 (1.0)	36.7 (3.3)	3.8 (0.7)
Burned	1	52.0			52.0	0.0
Total	53	33.3 (3.0)			37.0 (3.2)	3.7 (0.7)
Ponderosa pine forest						
Unburned	58	7.2 (1.0)	1.8 (0.3)	2.2 (0.3)	7.6 (1.0)	0.4 (0.3)
Burned	2	30.0 (8.0)			82.5 (45.5)	52.5 (53.5)
Total	60	7.9 (1.1)			10.1 (2.3)	2.1 (1.8)

Mean values SE (in parentheses) are shown where applicable.

¹ Numbers of snags lost and recruited were not estimated in severely burned plots. Metal tags used to mark snags melted when exposed to extreme heat, making it impossible to distinguish previously marked snags from newly recruited snags. These plots were included in estimates of net change, however.

plots showed net gains in snags during this interval, whereas ponderosa pine plots were almost as likely to show no change or a net decrease in snag numbers (Figure 2).

Snag density changed little from 1997 to 2002 in unburned ponderosa pine plots (Wilcoxon test, $P = 0.208$), but increased greatly in two ponderosa pine plots that experienced severe wildfire during this interval (Table 1). In contrast, snag density did not change on the single mixed-conifer plot that experienced severe wildfire, but increased significantly in unburned mixed-conifer plots (Table 1; $P < 0.001$). Considering both burned and unburned plots, snag density increased almost twice as much in mixed-conifer forest as in ponderosa pine forest (Table 1; P -values for change = <0.001 and 0.162 for mixed-conifer and ponderosa pine forest, respectively).

Snag density increased significantly in the smallest size classes in both forest types, but not in the largest size classes (Figure 3). Both snag loss and snag recruitment was concentrated in the smallest size classes in both forest types (Figure 4). Species composition differed significantly between 1997 and 2002 in ponderosa pine forest (chi-square test; $P < 0.001$), but not in mixed-conifer forest ($P = 0.489$). Proportional representation increased in ponderosa pine forest for limber pine, ponderosa pine, and Douglas-fir, whereas proportion of Gambel oak snags decreased (Figure 5). Decay-class distributions differed between years in both forest types (both P -values < 0.001). In both forest types, proportions of snags increased in the early decay stages (Figure 6). This appears consistent with the heavy recruitment of small snags, most of which were in early decay classes. For example, 78% of 601 snags <40 cm dbh that were recruited from 1997 to 2002 were in decay classes 1 and 2.

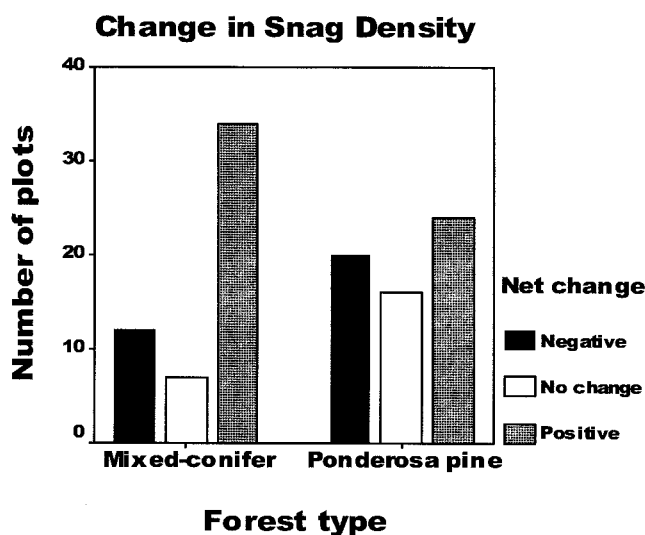


Figure 2. Number of 1-ha plots showing positive, negative, or no change in snag density from 1997 to 2002 in northern Arizona mixed-conifer and ponderosa pine forests ($n = 53$ and 60 total plots, respectively).

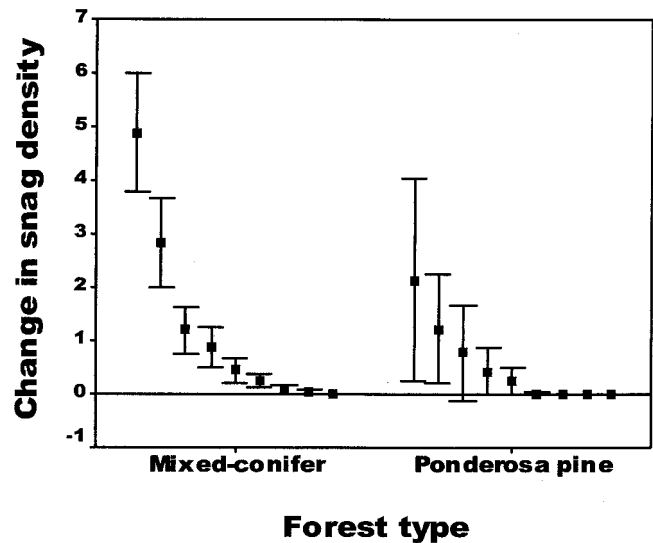


Figure 3. Change in snag density (snags/ha) by size class in northern Arizona mixed-conifer and ponderosa pine forest, 1997–2002 ($n = 53$ and 60 plots, respectively). Shown from left to right are means ($\pm 95\%$ confidence intervals) for 10-cm size classes, beginning with snags 20–29 cm dbh. Density increased significantly in the smaller size classes in both forest types, whereas the largest size classes showed no change.

Density of Large Snags

Density of large snags in 2002 was similar to density in 1997 in both forest types (mixed-conifer forest: 4.7 ± 0.6 [SE] snags/ha in 1997 versus 5.1 ± 0.6 snags/ha in 2002, $P = 0.223$; ponderosa pine forest: 1.4 ± 0.3 snags/ha in 1997 versus 1.7 ± 0.5 snags/ha in 2002, $P = 0.119$). Confidence intervals (95%) around mean densities (3.9–6.2 and 0.7–2.6 snags/ha in mixed-conifer and ponderosa pine forest, respectively) did not include the target for snag retention in either forest type (7.4 and 4.9 snags/ha, respectively). Two large snags were cut down between 1997 and 2002, including a ponderosa pine snag 47 cm in dbh and 18 m tall, and an aspen snag 51 cm in dbh and 25 m tall.

Spatial variation in density of large snags was high, particularly in ponderosa pine forest (Figure 7). Only 20.8 and 5.0% of plots in mixed-conifer and ponderosa pine forest, respectively, met or exceeded standards for retention of large snags in 2002. These proportions did not differ between 1997 and 2002 (McNemar's tests, $P = 0.16$ and 0.32 for mixed-conifer and ponderosa pine forest, respectively). Only 11.3% of mixed-conifer plots lacked large snags entirely, whereas 36.7% of ponderosa pine plots contained no large snags as defined by current USFS standards (Figure 7).

Density of large snags differed significantly between plots with and without evidence of past timber harvest in both forest types (Table 2). Mean density of large snags in unlogged plots either approached (mixed-conifer forest) or exceeded (ponderosa pine forest) targets for large-snag retention (Table 2). This was largely due to high densities of large snags in a few unlogged plots, however, especially in ponderosa pine forest. Only 20 and 40% of unlogged plots

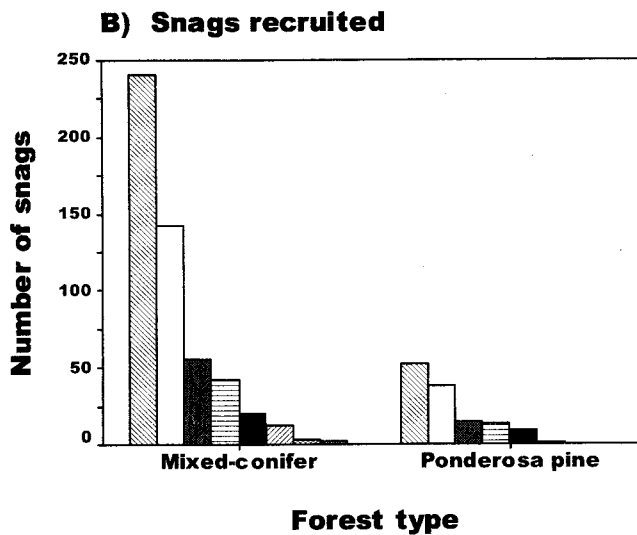
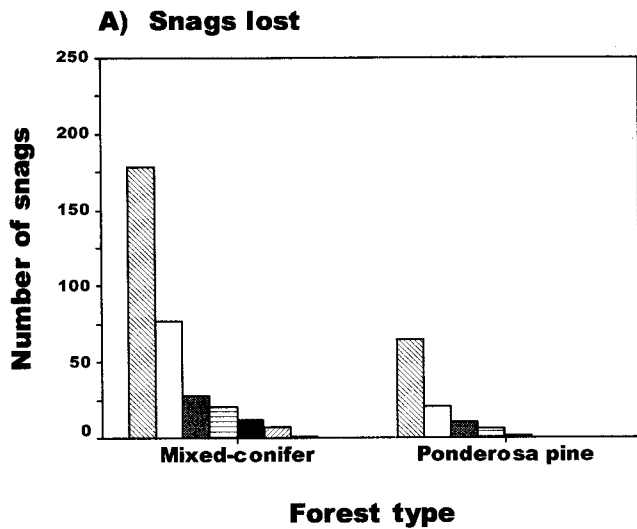


Figure 4. Number of snags lost (A) and recruited (B) by size class in mixed-conifer and ponderosa pine forests in northern Arizona from 1997 to 2002. Shown from left to right are 10-cm size classes, beginning with snags 20–29 cm dbh. Only unburned plots ($n = 52$ and 58 in mixed-conifer and ponderosa pine forest, respectively) were included, because the metal tags used to mark snags melted in burned plots, making it impossible to estimate snag loss and recruitment rates accurately. Both snag loss and recruitment were concentrated in the smaller size classes in both forest types.

met or exceeded targets for retention of large snags in ponderosa pine and mixed-conifer forest, respectively.

Characteristics of Standing versus Falling Snags

The classification-tree analysis identified height-to-diameter ratio, dbh, and species as key variables in determining whether a snag stood from 1997 to 2002 (Figure 8, Table 3). Cross-validated model prediction accuracy was 76.4%, with cross-validated prediction accuracies of 36.6 and 86.1% for falling and standing snags, respectively.

The classification tree first split snags based on height-to-diameter ratio, and predicted greater probability of survival for snags that were short relative to their diameter than

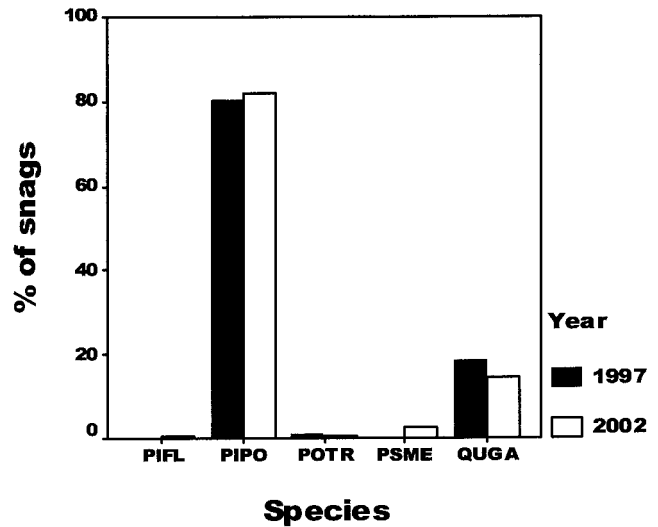


Figure 5. Species composition of snags in ponderosa pine forest in northern Arizona in 1997 and 2002. PIFL, limber pine; PIPO, ponderosa pine; POTR, quaking aspen; PSME, Douglas-fir; QUGA, Gambel oak. Proportions of snags increased slightly in limber pine, ponderosa pine, and Douglas-fir, and decreased slightly in Gambel oak. Snags were sampled on 60 1-ha plots.

for snags with greater height-to-diameter ratios (Figure 8). The second node split the remaining snags based on snag diameter, with predicted survival greater for snags with $\text{dbh} \geq 43.5$ cm than for smaller snags. The third node split remaining snags based on species, and predicted greater survival of aspen, Douglas-fir, Gambel oak, and “other” snags than of white fir or ponderosa pine snags. Approximately 32% of snags in the “other” category ($n = 60$ total snags) were limber pine, another 23% were unknown species, and the remainder were primarily various species of junipers and deciduous hardwoods. A fourth node split the remaining snags based on decay class, and predicted greater probability of survival for snags in later decay classes than in early decay classes. This node had little predictive power, however (overall accuracy 51.5% at this node; Figure 8), indicating that decay class was not an effective predictor of survival for these remaining snags. Importance values (Table 3) suggested that rank order for these variables was similar but not identical to the order in which they appeared in the tree.

Empirical results generally agreed with the tree predictions. Observed snag survival was greater in snags with a height-to-diameter ratio < 33.33 (89.7% survival) than for snags with a greater height-to-diameter ratio (69.8%). Among snags with height-to-diameter ratios ≥ 33.33 , snags with $\text{dbh} \geq 43.5$ cm survived at higher rates (85.1%) than did smaller-diameter snags (66.3%). Among these remaining smaller-diameter snags, survival was greater collectively for aspen, Douglas-fir, Gambel oak, and “other” snags (66.3%) than for white fir and ponderosa pine snags (58.7%). Finally, among the remaining snags, survival was slightly greater for snags in decay classes 3–5 (64.2%) than for snags in decay classes 1 and 2 (55.6%).

In univariate comparisons, snags that survived from 1997

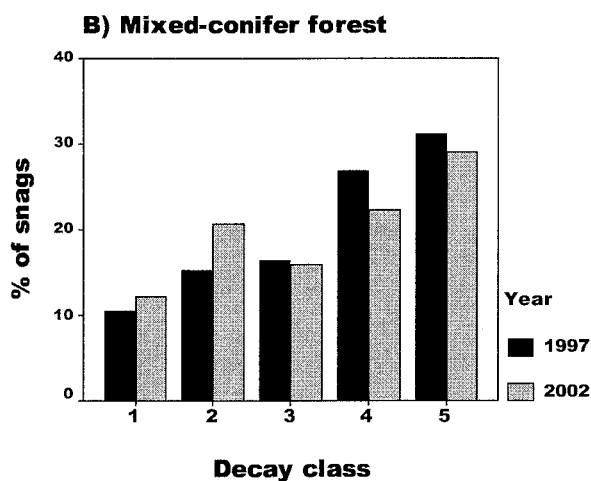
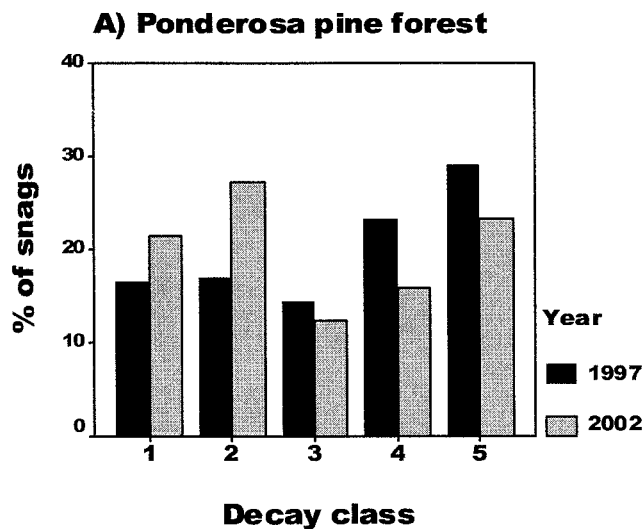


Figure 6. Decay-class distributions of snags in (A) ponderosa pine forest ($n = 60$ plots) and (B) mixed-conifer forest ($n = 53$ plots). Proportions of snags increased in early decay stages and decreased in later decay stages in both forest types. This is consistent with the heavy recruitment of small snags observed (Figure 3), because most of these smaller snags were in early decay stages.

to 2002 were larger in diameter and shorter (both overall and relative to diameter) than snags that fell (Table 4). Snag survival rates also differed among species, across decay classes, and with top condition (Table 5). Gambel oak and “other” snags survived at higher rates than all other species, and snags with broken tops survived at higher rates than snags with intact tops. Surprisingly, snags in later decay classes generally survived at higher rates than did snags in earlier decay classes. We suspect that this reflects interactions between decay class and other factors influencing snag survival (especially height-to-diameter ratio, species, and diameter; Figure 8).

Mean height generally declined slightly for snags that stood from 1997 to 2002 (Wilcoxon test, $P < 0.001$), with the extent of that decline related to both snag species and whether the snag had an intact top in 1997. Snags with intact tops in 1997 generally declined more in height than did snags with broken tops (Mann–Whitney test, $P < 0.001$),

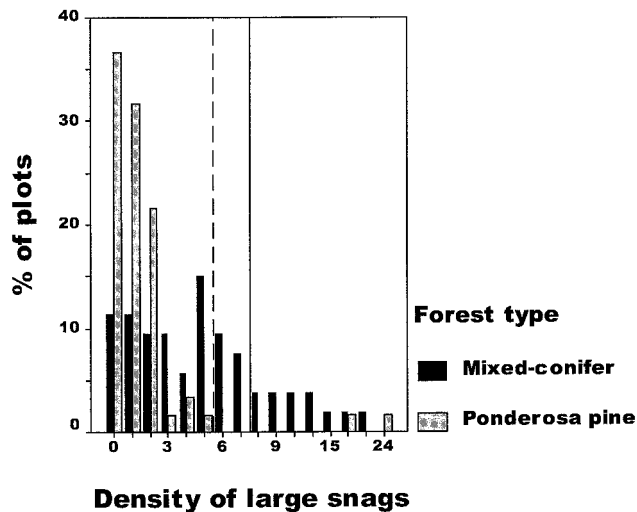


Figure 7. Percent of plots in northern Arizona mixed-conifer and ponderosa pine forest by density (number/ha) of large snags (note that x-axis is not linear above 9). Current standards for retention of large snags (defined as snags ≥ 46 cm dbh and 9 m in height; Reynolds et al. 1992, USDA 1996) denoted by vertical lines (solid line, mixed-conifer forest standard; dashed line, ponderosa pine standard). Most plots in both forest types fell below standards for density of large snags.

Table 2. Density (snags/ha) of large snags (≥ 46 cm dbh and ≥ 9 m tall; Reynolds et al. 1992, USDA 1996) in northern Arizona mixed-conifer and ponderosa pine plots with and without evidence of past timber harvest

Forest type	Plot status						P^1
	Logged			Unlogged			
	N	Mean	SE	N	Mean	SE	
Mixed-conifer	28	3.4	0.5	25	6.9	1.0	0.006
Ponderosa pine	50	0.9	0.1	10	5.7	2.5	0.001

¹ P -value from Mann–Whitney test comparing density between logged and unlogged plots.

and declines were largest in white fir and ponderosa pine snags (Figure 9). Of 699 snags with intact tops in 1997 that stood until 2002, 35% had broken tops by 2002. Many surviving snags (60.4%) showed no change in bark cover from 1997 to 2002. On average, bark cover declined by only 6.5% (± 0.3) for surviving snags (range = 0–97%).

Discussion

Characteristics of Standing versus Falling Snags

Our results with respect to characteristics of surviving snags generally were similar to previous results in that surviving snags were larger in diameter, shorter (both overall and relative to diameter), likely to have a broken top, and survival rates differed among species (Keen 1955, Raphael and Morrison 1987, Morrison and Raphael 1993, Parks et al. 1999, Landram et al. 2002, but see Schmid et al. 1985, Mitchell and Preisler 1998). Our results were not directly comparable to these studies, however, due to differences in geographic areas and forest types represented. In addition,

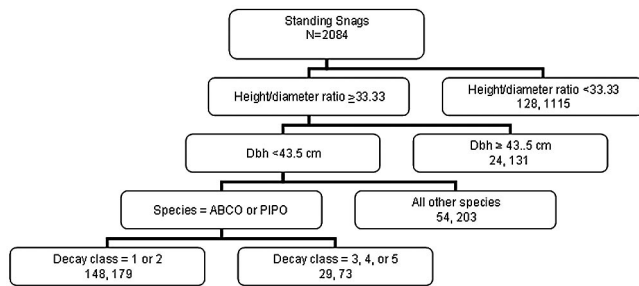


Figure 8. Classification tree predicting snag fate for snags sampled in northern Arizona mixed-conifer and ponderosa pine forest, 1997–2002. Numbers at terminal nodes indicate number of snags falling (on the left) versus standing (on the right). Height-to-diameter ratio was a unitless variable computed as (height in m/diameter in m). ABCO, white fir; PIP0, ponderosa pine. Decay classes followed Raphael and White (1984), and are described in the text.

some of these studies either included only one or a few mortality agents (Keen 1955, Schmid et al. 1985, Mitchell and Preisler 1998, Parks et al. 1999), or included only limited spatial replication (Raphael and Morrison 1987, Morrison and Raphael 1993).

Classification-tree analysis identified height-to-diameter ratio, species, and diameter as key variables in predicting whether snags stood or fell from 1997 to 2002. Although we agree with the relative importance of these variables, we recognize that the situation is more complex than this analysis indicates. There are numerous interactions among snag characteristics that come into play in determining snag fate, and modeling snag fate will never be a simple matter as a result.

Most documented snag loss from 1997 to 2002 occurred when snags fell entirely, and many surviving snags lost their tops during the sampling interval. Both factors suggest the importance of wind as a factor in both snag damage and loss in this area. Wind also created snags, however, by breaking off live treetops.

The importance of wind as an agent of snag loss likely explains many of our findings regarding characteristics of surviving snags. Larger-diameter snags, especially those with diameter large relative to height, are more resistant to wind throw than smaller-diameter snags or snags with greater height-to-diameter ratios, and shorter snags with

Table 3. Relative importance scores for variables used in developing a classification tree for snag fate in mixed-conifer and ponderosa pine forests, northern Arizona. Importance scores were computed by summing improvement values for individual variables across nodes within the tree, then scaled relative to the highest ranking variable

Variable	Relative importance score
Height/diameter ratio	100
Species	92
Diameter at breast height (cm)	57
Decay class (1–5)	47
Top condition (broken or intact)	42
Forest type	16
Height (m)	0
Bark cover (%)	0

broken tops offer less resistance to high wind gusts than do taller snags with intact tops. Similarly, species that might be expected to have harder wood (e.g., Gambel oak and various species of junipers and other hardwoods) generally survived at higher rates than species with weaker wood (white fir, ponderosa pine, Douglas-fir, and quaking aspen; Table 5). Also, deciduous trees may offer less resistance to strong winter winds once they lose their leaves. This also could foster greater snag survival in these species.

Morrison and Raphael (1993) also identified wind as an important factor in snag loss, along with cause of death. Cause of death may be an important influence on snag survival in our study area as well. For example, snags resulting from root disease may have weakened root systems and be more susceptible to wind throw than snags caused by other mortality agents (Bull et al. 1997). We lack information on cause of death of most snags, however.

Cutting of snags was not a major source of snag loss, accounting for only 3.1% of known snag loss in this study. We acknowledge that cutting of snags can be a problem in some areas and/or for particular snag species, however (e.g., Gambel oak; May and Gutiérrez 2002). We further acknowledge that historical cutting of snags may have influenced current snag distributions in unknown ways.

Density of Large Snags

Densities of large snags increased slightly but nonsignificantly from 1997 levels in both forest types, but remained below standards for retention of large snags (Reynolds et al. 1992, USDA 1996) in both forest types. Spatial variation in density of large snags was high, particularly in ponderosa pine forest, where almost 40% of plots sampled lacked large snags entirely (Figure 7). Ganey (1999; see also Oliver 2002) suggested that the standards for retention of large snags in these forest types might be unreasonably high, however, given current knowledge of natural fire regimes (Covington et al. 1994, Fulé et al. 2003) and the susceptibility of snags to fire (Gaines et al. 1958, Horton and Mannan 1988, Gordon 1996, Randall-Parker and Miller 2002, Skinner 2002). Therefore, the failure to achieve target densities of large snags may not be cause for concern. Similarly, we are not necessarily alarmed by the lack of large snags in many ponderosa pine plots. Snags, and particularly large snags, are and always will be patchily distributed (e.g., Harris 1999, Ohmann and Waddell 2002, Skinner 2002). Consequently, it would be unreasonable to expect large snags to occur everywhere.

Past management appeared to influence current density of large snags, as Oliver (2002) also noted in California. Mean densities of large snags on unlogged plots approached (mixed-conifer forest) or exceeded (ponderosa pine forest) targets for retention of large snags, and were significantly greater than densities of large snags on logged plots in both forest types (Table 2). The mechanism underlying this difference is unknown. Possible explanatory hypotheses include: 1) large snags were cut down on logged plots, 2) the pool of large trees from which large snags are recruited was

Table 4. Selected characteristics of surviving versus falling snags in northern Arizona mixed-conifer and ponderosa pine forests, 1997–2002

Characteristic	Snag fate				P ¹
	Standing (n = 1,701)		Fallen (n = 383)		
	Mean	SE	Mean	SE	
Height to diameter ratio ²	27.9	0.5	41.2	1.0	<0.001
Dbh (cm)	38.5	0.4	32.1	0.6	<0.001
Height (m)	9.8	0.2	12.2	0.3	<0.001

¹ P-values from Mann–Whitney test.

² A unitless variable computed as (height/diameter in meters).

Table 5. Survival rates of snags in northern Arizona mixed-conifer and ponderosa pine forests, 1997–2002, as a function of various categorical variables

Variable	N	% survival	P ¹	Group ²
Species			<0.001	
Gambel oak	520	92.3		A
“Other” ³	60	86.7		A
Douglas-fir	207	81.6		B
White fir	380	74.9		B
Ponderosa pine	762	74.4		B
Quaking aspen	155	72.8		B
Decay class			<0.001	
1	246	71.8		AB
2	332	68.0		A
3	335	79.6		BC
4	535	81.9		CD
5	631	87.9		D
Top condition			<0.001	
Intact	932	72.4		A
Broken	1147	86.1		B

¹ P-value from omnibus test of no difference among categories within variable (comparison of multiple proportions; Goodman 1964).

² Categories followed by different letters are significantly different ($P < 0.05$).

³ The “other” category included limber pine, pinyon pine, alligator juniper, unknown species, and various other species of junipers and deciduous hardwoods.

smaller on logged plots, 3) mortality of large trees was greater on unlogged plots (see below), or 4) various combinations of these factors operated to increase densities of large snags. At present we cannot rule out any of these hypotheses.

Changes in Snag Populations

Our results indicated that overall snag numbers increased in both forest types in this area from 1997 to 2002 (Table 1). Snag density increased significantly in mixed-conifer forest but not in ponderosa pine forest. Snags also increased in abundance across much of the landscape in mixed-conifer forest, whereas increasing abundance was less consistent spatially in ponderosa pine forest (Figure 2). Most of the increase in snag abundance occurred in the smaller size classes (Figure 3), where both snag loss and recruitment were concentrated in both forest types (Figure 4), and in early decay classes (Figure 6). Species composition of snag populations differed between 1997 and 2002 in ponderosa pine forest (figure 5), but not in mixed-conifer forest.

Although snags were recruited in all size classes in

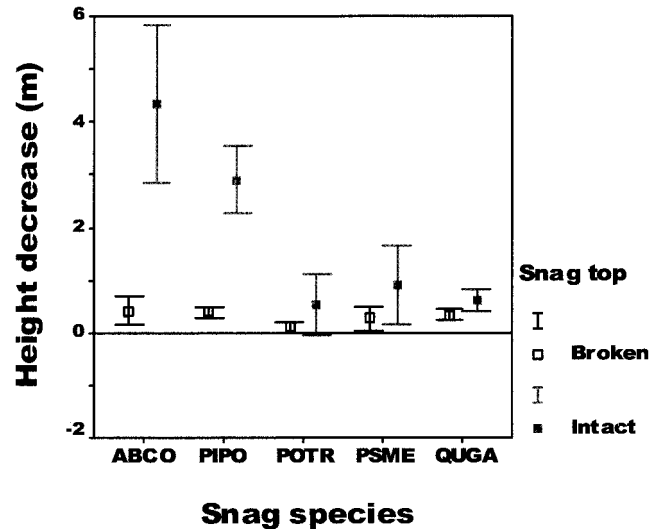


Figure 9. Decrease (mean \pm 95% confidence interval) in snag height for snags marked in 1997 and re-sampled in 2002, by species and top condition. ABCO, white fir (186, 111); PIPO, ponderosa pine (342, 238); POTR, quaking aspen (41, 74); PSME, Douglas-fir (103, 72); QUGA, Gambel oak (317, 172) (Numbers in parentheses are snags with broken and intact tops, respectively). Note that the y-axis shows the decline in snag height, so that larger values indicate greater declines. Snags with intact tops in 1997 generally showed greater decline in height over the next 5 years than snags with broken tops, with the difference most pronounced in white fir and ponderosa pine snags.

mixed-conifer forest and most size classes in ponderosa pine forest, the vast majority of snags recruited were in the smaller size classes (<40 cm dbh; Figure 4). Thus, these were not large, old trees that were dying. They were either young trees or older trees that were suppressed and grew slowly. Fiedler and Morgan (2002) noted similar patterns in tree mortality in ponderosa pine and ponderosa pine/Douglas-fir/western larch (*Larix occidentalis*) forests in Montana, and suggested that suppression was the leading cause of mortality in many stands.

Suppression may be an important cause of mortality in our study area as well. Tree density has increased greatly in southwestern mixed-conifer and ponderosa pine forests since the advent of effective fire-suppression tactics (Covington et al. 1994, Fulé et al. 2003). This increased density results in increased competition for water and nutrients, which can weaken trees and ultimately predispose them to various mortality factors. Increased competition for moisture currently is exacerbated by a severe, long-lasting

drought in this area. Annual precipitation in 2002 was only 38% of mean annual precipitation for this area, and cool-season (Nov.–Apr.) precipitation from 1999 to 2003 averaged only 68% of long-term average precipitation for this season (Drought fact sheet, Arizona climate division 2; www.ispe.arizona.edu/climas/).

Drought conditions and resultant moisture stress also contributed to a serious outbreak of bark beetles throughout the southwest in recent years. This outbreak involved multiple species of beetles, but the primary species attacking ponderosa pine in Arizona were *Ips* spp. (USDA 2002, 2003). U. S. Forest Service aerial surveys conservatively estimated that millions of ponderosa pine trees died on 570,000 acres affected by this outbreak across Arizona and New Mexico in 2002 alone (USDA 2003).

Consequently, snag numbers should continue to increase in this area in the near future. If the drought cycle continues, these increases may be dramatic, driven by a combination of overstocked stands, moisture stress, bark beetles, and wild-fire (e.g., McHugh et al. 2003). Given the extensive mortality observed in ponderosa pine forests throughout Arizona (see above), we were surprised that increases in snag density were not larger in our plots. This likely indicates considerable spatial heterogeneity in levels of both moisture stress and bark beetle activity. It may also reflect the timing of our sampling, however. A great deal of ponderosa pine mortality caused by bark beetles occurred late in 2002 (USDA 2003), after our sampling period. Consequently, we probably missed much of this mortality in 2002, and thus may see large increases in snag numbers when these plots are re-sampled in 2007.

Conclusions

A better understanding of all aspects of snag dynamics would be helpful to resource managers working in southwestern mixed-conifer and ponderosa pine forests. The results presented here provide empirical data on snag populations and provide a basis for continued monitoring of snag populations, which may change dramatically if current drought conditions and fire risk persist. Future inventories will include information on populations of live trees as well as snags. This will provide information on source pools for snags and a basis for modeling snag dynamics.

This study provides the ability to follow fates of individual snags at relatively frequent intervals, but that level of detail necessarily restricts the geographic scope of sampling. It would be desirable to extend the assessment of snag populations to broader spatial scales. This could perhaps best be accomplished using data from systematic ongoing forest inventory efforts such as the Forest Inventory and Analysis program (Harris 1999, Ohmann and Waddell 2002). Data from inventories conducted under this program could be used to evaluate current levels of snags across broad geographic areas and multiple land ownerships, and data from repeated inventories could be used to track changes in snag populations. Such large-scale assessments

would greatly further our understanding of trends in snag populations in southwestern forests.

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