Modeling Snag Dynamics in Northern Arizona Mixed-Conifer and Ponderosa Pine Forests

Joseph L. Ganey and Scott C. Vojta
Abstract

Snags (standing dead trees) are important components of forested habitats that contribute to ecological decay and recycling processes as well as providing habitat for many life forms. As such, snags are of special interest to land managers, but information on dynamics of snag populations is lacking. We modeled trends in snag populations in mixed-conifer and ponderosa pine (Pinus ponderosa) forests in northern Arizona using a Leslie matrix model developed by Raphael and Morrison (1987). Models were parameterized using data on snag abundance in five decay classes in 2002, transition rates of snags among decay classes from 1997 to 2002, and recruitment of snags into these decay classes from 1997 to 2002. Snags were sampled on randomly located, 1-ha plots (n = 52 and 58 plots in mixed-conifer and ponderosa pine, respectively). These plots covered the entire elevational gradient occupied by these forest types and a wide range of stand conditions in both forest types. Trends were modeled separately for each forest type over a 30-yr time horizon. The models predicted that over this period: 1) overall snag densities would increase in both forest types, 2) densities of large snags would increase in both forest types, 3) despite these increases, densities of large snags would remain below target densities in both forest types, and 4) species composition and decay-class distributions would change only slightly in both forest types. The models described here were derived from snag data averaged over large landscapes and a wide range of stand conditions within forest types. These models thus are not suitable for modeling snag dynamics at the stand level, but rather provide a means for coarse-scale modeling of snag dynamics over large landscapes. Future inventories of snags on these plots (planned at five-year intervals) will provide a means to both test and improve model predictions.

Keywords: snags, forest habitats, mixed-conifer forest, ponderosa pine, Pinus ponderosa, matrix model

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Cover photo: Ponderosa pine snags in varying stages of decay near Roundup Park, Coconino National Forest, Arizona.
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Introduction

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 and others 1979, Davis and others 1983, Raphael and White 1984, Harmon and others 1986, Bull and others 1997, Laudenslayer and others 2002). Most National Forests have regulations requiring the retention of specified types and densities of snags to provide habitat for native wildlife (Morrison and others 1986), and managers therefore are particularly concerned with maintaining snag populations (Mellen and others 2002). Despite these mandates for snag management, data on snag types 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 (e.g., Everett and others 1999), and they typically exhibit large spatial (Harris 1999, Ohmann and Waddell 2002, Skinner 2002, Stephens 2004, Ganey and Vojta 2005) and temporal variability (Morrison and Raphael 1993, Everett and others 1999, Lehmkühl and others 2003).

We established a series of permanent plots in mixed-conifer and ponderosa pine (Pinus ponderosa) forests in north-central Arizona in 1997 to monitor snag populations. Ganey (1999) described initial snag populations in this area, and Ganey and Vojta (2005) reported on changes in snag populations from 1997 to 2002. Here, we (1) estimate transition rates among snag decay classes and recruitment rates into those classes from 1997 to 2002, (2) use these data to parameterize simple matrix models of snag dynamics based on those rates (Raphael and Morrison 1987), and (3) use these models to project trends in snag populations in five-year increments over a 30-year modeling horizon.

Methods

Field Sampling

We sampled snags in 2002 in a set of 1-ha plots originally established and sampled in 1997. Plots were randomly located in mixed-conifer and
ponderosa pine forest \((n = 53 \text{ and } 60 \text{ plots, respectively; see Ganey [1999] for further details on plot selection, location, and establishment})\) in a study area spanning approximately 73,000 ha across two National Forests in north-central Arizona (fig. 1). Three plots experienced severe wildfire, so they were not considered here because the metal tags used to mark the snags (see below) melted, making it impossible to determine fates of individual snags.

![Figure 1](image.png)

**Figure 1.** General location of the study area (top), and locations of 1-ha snag-monitoring plots within the study area (bottom). Snags were sampled in the Coconino (right) and Kaibab (left) National Forests, north-central Arizona. Plots in ponderosa pine forest \((n = 58)\) are indicated by red circles, plots in mixed-conifer forest \((n = 52)\) by blue triangles. The more clumped distribution of mixed-conifer plots reflects the more restricted distribution of mixed-conifer forest within the study area.
Mixed-conifer forests in this area were dominated by Douglas-fir (Pseudotsuga menziesii) and white fir (Abies concolor); other common species included ponderosa and limber (P. flexilis) pine, quaking aspen (Populus tremuloides), and Gambel oak (Quercus gambelii). Ponderosa pine forests were heavily dominated by ponderosa pine, often contained Gambel oak and/or alligator juniper (Juniperus deppeana), and sometimes contained quaking aspen, pinyon pine (P. edulis), 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 and sampled a number of snag characteristics. We searched the plots for all snags in 2002, re-sampled all previously marked snags, and uniquely marked and sampled any new snags encountered (fig. 2). For this paper, relevant snag characteristics sampled included species, diameter at breast height (dbh), height, and decay class. Snag diameter was recorded to the nearest cm using a dbh tape. Snag height was estimated to the nearest m using a clinometer. Decay classes (fig. 3) 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.

Modeling Snag Population Dynamics

We estimated transition rates among and recruitment into decay classes between 1997 and 2002 for snags in each forest type. These transition matrices summarize information on progression of snags among decay classes. Snag fall rates differed among some species over this time period (Ganey and Vojta 2005), and recruitment and transition rates likely differed among species as well. Therefore, we estimated recruitment and transition rates for individual species where sample sizes allowed.
Figure 3. Illustrations of five decay classes of snags recognized (after Raphael and White 1984). Snags in decay class 1 retained needles (or leaves, for broadleaved trees). Snags in decay class 2 retained twigs but not 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 (next page) lacked large limbs entirely.
We modeled the dynamics of snag populations in each forest type using a Leslie matrix model developed by Raphael and Morrison (1987). This model took the form:

$$ N_{t+1} = D \cdot N_t + R, $$

where

- $N_{t+1}$ is the 5 x 1 matrix denoting snag abundance by decay class at time $t + 1$,
- $D$ is the 5 x 5 decay transition matrix (with zeroes above the diagonal) denoting the probability $P_{ij}$ of a snag moving from decay class $i$ at time $t$ to decay class $j$ at time $t + 1$,
- $N_t$ is the 5 x 1 matrix of the total number of snags in each decay class at time $t$, and
- $R$ is the 5 x 1 matrix of the number of snags recruited into each decay class during the time period from $t$ to $t + 1$.

The models were parameterized using observed transition rates among snag decay classes from 1997–2002, information on snag abundance in these decay classes in 2002, and recruitment rates into these decay classes from 1997 to 2002. Models were run separately for individual species within forest types (see below), and then results were summed across species within forest type. We ran models through 2032, as we suspected that there was little point in modeling longer time frames with the available data. The model requires an assumption that transition and recruitment rates remain constant, and that assumption becomes increasingly untenable as the time frame considered increases.
Management guidelines in this region emphasized large snags (defined as snags ≥46 cm dbh and ≥9 m tall; Reynolds and others 1992, U.S. Forest Service 1996). Consequently, we also modeled dynamics of large snags in each forest type. Because numbers of large snags were low in most combinations of forest type, species, and decay class, we parameterized large-snag models using transition rates averaged across species and forest types, as well as recruitment rates averaged across species within forest type.

**Results and Discussion**

We sampled 1,902 and 446 snags in 2002 in mixed-conifer and ponderosa pine forest, respectively. Of these, 254 and 77 snags met criteria for large snags in mixed-conifer and ponderosa pine forest, respectively. Absolute abundance of both all snags and large snags increased in both forest types from 1997 to 2002, although snag density differed significantly between years only for all snags in mixed-conifer forest (Ganey and Vojta 2005).

A total of 1,389 and 312 snags marked in 1997 were available for estimating transition rates in mixed-conifer and ponderosa pine forest, respectively (table 1). Models for all snags were parameterized using species-specific data within forest type, whereas models for large snags used transition rates averaged across species and forest types. Therefore, we present transition rates for large snags to illustrate the form of the decay transition matrix (table 1). Patterns were generally similar across species and forest types.

Most class-1 snags transitioned to other decay classes (table 1), suggesting that residence time in this class was relatively short. In contrast, larger proportions of snags in all other decay classes remained in the same class, and this proportion generally increased from class 2 to class 5. This suggests greater residence time in classes 2 through 5 than in decay-class 1, and that residence time within decay class increased from earlier to later decay classes.

<table>
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<th>3</th>
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Table 1. Transition rates of large snags (defined as dbh ≥46 cm and height ≥9 m) among decay classes from 1997 to 2002 in mixed-conifer and ponderosa pine forest in northern Arizona. Decay classes are described in the text. Data presented here were averaged across species and forest types.

1 Values shown are the proportions of snags decomposing from each decay class in 1997 to the observed decay class in 2002. The proportion of snags falling, cut down, or unaccounted for is one minus the column sum.
Numbers of new snags recruited between 1997 and 2002 totaled 513 and 134 in mixed-conifer and ponderosa pine forest, respectively. Most snags recruited from coniferous tree species entered into the earliest decay classes, whereas most snags recruited from deciduous species such as Gambel oak and quaking aspen entered into decay class 2 (fig. 4). This suggests a fundamental difference between coniferous and deciduous trees in residence time within decay class 1. This difference may be related to differences in retention time of needles versus leaves. Low recruitment of deciduous species into decay class 1, coupled with the apparently short residence time of recruited snags in decay class 1 (see above), suggests that snag numbers in decay class 1 were maintained primarily by recruitment of coniferous snags. Snags were recruited at higher rates from coniferous species than from deciduous species in both forest types (fig. 5).

**Modeling Population Dynamics**

Models were parameterized using species-specific data where sample sizes permitted. In mixed-conifer forest, separate models were developed for ponderosa pine (\(n = 461\)), white fir (\(n = 398\)), Douglas-fir (\(n = 212\)), Gambel oak, (\(n = 445\)), and quaking aspen (\(n = 154\)) snags. Collectively, these species comprised 98.2 percent of available snags in this forest type. In ponderosa pine forest, we modeled ponderosa pine separately (\(n = 310\) snags, or approximately 75 percent of total snags) from all other species (\(n = 106\) snags). Gambel oak comprised approximately 80 percent of the other species group in this forest type.

![Figure 4](image)

*Figure 4.* Proportions of snags (by species) recruited into five decay classes within mixed-conifer (\(n = 513\) snags) and ponderosa pine (\(n = 134\) snags) forest, north-central Arizona. Decay classes are described in the text and range from new snags (class 1) to highly decayed snags (class 5). Species acronyms are: ABCO = *Abies concolor* (white fir), OTHER = various species not modeled individually, PIPO = *Pinus ponderosa* (ponderosa pine), POTR = *Populus tremuloides* (quaking aspen), PSME = *Pseudotsuga menziesii* (Douglas-fir), and QUGA = *Quercus gambelii* (Gambel oak). Most snags recruited from coniferous tree species entered into decay class 1, whereas most snags recruited from deciduous tree species (Gambel oak and quaking aspen) entered into decay class 2.
The Leslie matrix models for all snags predicted that snag populations would continue to increase in both forest types through 2032, given constant transition and recruitment rates (fig. 6a). Resulting snag densities in 2032 were predicted to be 32 and 20 percent greater than 2002 densities in mixed-conifer and ponderosa pine forest.

The matrix model for large snags predicted that density of large snags would increase by approximately 32 and 59 percent in mixed-conifer and ponderosa pine forest, respectively (fig. 6b). Despite these increases, model predictions indicated that density of large snags would remain below target levels in both forest types through 2032.

The matrix models predicted only modest changes in species composition from 2002 to 2032 (fig. 7). In mixed-conifer forest, the proportion of ponderosa pine and white fir snags decreased by approximately 5 and 3 percent, respectively, whereas the proportion of Gambel oak and quaking aspen snags increased by approximately 4 and 5 percent, respectively (fig. 7a). In ponderosa pine forest, the proportion of ponderosa pine snags decreased by approximately 2.5 percent, whereas the proportion of other snags increased by the same amount (fig. 7b). Most of that increase was due to predicted increases in abundance of Gambel oak snags. Species composition changed across the modeling horizon in both forest types and did not appear to have stabilized in either forest type by 2032 (fig. 7).
Figure 6. Simulated trends in density of (A) all snags and (B) large snags in mixed-conifer and ponderosa pine forests, northern Arizona. Shown are empirical data from 2002 and projections for five-year intervals from 2007 to 2032. Projections were derived from a Leslie matrix model of population growth, parameterized using data collected in 1997 and 2002. Overall snag density was predicted to increase over this interval in both forest types, with greater change predicted in mixed-conifer forest than in ponderosa pine forest. Density of large snags also was predicted to increase over this interval, with a greater proportional increase in ponderosa pine forest. Targets for retention of large snags are shown by horizontal reference lines (purple for mixed-conifer target, blue for ponderosa pine target). Density of large snags was predicted to remain below target values (7.4 and 4.9 snags/ha in mixed-conifer and ponderosa pine forest, respectively) in both forest types throughout the interval modeled.
Figure 7. Simulated trends in species composition of snags in northern Arizona mixed-conifer (A) and ponderosa pine (B) forest. Shown are empirical data from 2002 and projections for five-year intervals from 2007 to 2032. Projections were derived from a Leslie matrix model of population growth, parameterized using data collected in 1997 and 2002. Snags were modeled for individual species where sample sizes allowed. Species acronyms are: ABCO = *Abies concolor* (white fir), OTHER = various species not modeled individually, PIPO = *Pinus ponderosa* (ponderosa pine), POTR = *Populus tremuloides* (quaking aspen), PSME = *Pseudotsuga menziesii* (Douglas-fir), and QUGA = *Quercus gambelii* (Gambel oak). Proportions of quaking aspen and Gambel oak were predicted to increase in mixed-conifer, with concomitant decreases in white fir and ponderosa pine. In ponderosa pine forest, proportions of ponderosa pine snags were predicted to decrease and proportions of OTHER snags were predicted to increase, with most of that increase in the Gambel oak component.
Figure 8. Simulated trends in decay-class distributions of snags in northern Arizona mixed-conifer (A) and ponderosa pine (B) forest. Shown are empirical data from 2002 and projections for five-year intervals from 2007 to 2032. Projections were derived from a Leslie matrix model of population growth, parameterized using data collected in 1997 and 2002. Decay classes (after Raphael and White 1984) are described in the text and range from new snags (class 1) to highly decayed snags (class 5). Decay-class composition did not change greatly in either forest type, but there was a slight trend toward increases in class 5 snags in both types.
The matrix models also predicted only modest changes in decay-class distributions from 2002 to 2032 (fig. 8). In both forest types, proportions of snags changed by only 2 to 5 percent for various decay classes. Decay-class distribution appeared to be relatively stable by 2032 in mixed-conifer forest, but continued to change across the modeling horizon in ponderosa pine forest. Proportions of older snags continued to increase, and newer snags to decrease, in this forest type. We did not model species or decay-class composition of large snags due to low sample sizes in most combinations of species and decay class.

Conclusions

The matrix models used here are simplistic. These models do not incorporate data on stand structure and composition, so they are unsuited for modeling snag dynamics at the scale of individual forest stands. Rather, these models were parameterized using data averaged over a wide range of stand conditions across a large landscape. Consequently, these data are useful primarily in a coarse-filter modeling framework, involving modeling trends across large landscapes.

These models also require the assumption of constant recruitment and transition rates. This assumption is unlikely to be met. Snag recruitment depends partly on predictable factors such as stand structure (e.g., Fiedler and Morgan 2002) and partly on unpredictable events such as fire, wind events, and disease and/or insect outbreaks (e.g., Keen 1995, Morrison and Raphael 1993, Mitchell and Preisler 1998, McHugh and others 2003), and thus can be highly episodic. Transition rates also may vary through time depending on factors such as cause of death and disturbance events (e.g., fire, large wind events; Morrison and Raphael 1993, Bull and others 1997). The assumption of constant rates also becomes more untenable with increasing time frames. As a result, we restricted model projections to a fairly short (30 years) modeling horizon.

The current model also used rate estimates derived from short-term data. As future inventories (planned for five-year intervals) are completed on these plots, we will be able to base estimates of recruitment and transition rates on longer time frames, which will incorporate wider ranges of environmental conditions, and on larger samples of snags. Future inventories thus should improve model accuracy and will provide empirical data with which to test model predictions.

Another important shortcoming of these models is the inability to incorporate data on snag dynamics in severely burned plots due to tag loss and resulting uncertainty regarding fates of individual snags. Wildfire is both prevalent and increasing in frequency and extent in southwestern forests (e.g., McKenzie and others 2004) and can affect snag numbers and types, sometimes greatly (e.g., Chambers and Mast 2005, Ganey and Vojta 2005). Therefore, it would be desirable to incorporate the ability to model dynamics of individual snags in burned areas. This likely could be accomplished simply by substituting steel tags for aluminum tags (perhaps depending on fire intensity).
Despite these shortcomings, however, matrix models provide a useful tool for modeling snag dynamics at the landscape scale. Model projections suggest that, at least in the short term, snag numbers will continue to increase, snags will continue to be relatively abundant in these forests, and densities of large snags will increase in both forest types but remain below target levels.

Data on populations of live trees in these forests would help in modeling snag dynamics. Obviously, abundance and composition of snag populations depends heavily on the abundance and composition of source populations (live trees). Therefore, future modeling efforts will attempt to incorporate data on stand conditions in estimates of transition and recruitment rates.

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Literature Cited


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