RESEARCH ARTICLE

J. For. 115(2):103–111
http://dx.doi.org/10.5849/jof.2016-062

forest ecology

Changes in Snag Populations on National Forest System Lands in Arizona, 1990s to 2000s

Joseph L. Ganey and Chris Witt

Snags receive special management attention as important components of forest systems. We used data from the US Department of Agriculture (USDA) Forest Service Forest Inventory and Analysis Program, collected during two recent time periods (1995 to 1999 and 2001 to 2010), to evaluate trends in snag populations in two forest types in Arizona. Densities of snags ≥4 in. dbh increased by 21 and 72% between these time periods in mixed conifer and ponderosa pine (*Pinus ponderosa*) forest, respectively. Proportions of plots meeting USDA Forest Service guidelines for density of large snags (defined as snags ≥18 in. dbh and ≥30 ft tall) increased between time periods in both forest types (from 19 to 45% in mixed conifer and from 5 to 17% in ponderosa pine forest), but large snags remained relatively sparse, especially in less productive ponderosa pine forests. More than 50 and 75% of sampled plots lacked large snags entirely in mixed conifer and ponderosa pine forest, respectively.

Keywords: Arizona, climate change, drought, Forest Inventory and Analysis, large snags, management guidelines, monitoring, snags, tree mortality

Snags (standing dead trees) are important forest components that provide resources for numerous species of wildlife and contribute to decay dynamics and other ecological processes (Bull et al. 1997, Laudenslayer et al. 2002). Because of their demonstrated importance as wildlife habitat, managers have focused special attention on snag populations (Bull et al. 1997, Laudenslayer et al. 2002). Much of this attention is focused on larger snags because of their use as nesting and roosting substrates by many species of cavity-nesting birds and bats (Reynolds et al. 1992, Bull et al. 1997, Chambers and Mast 2014). In the southwestern United States, Reynolds et al. (1992) recommended retaining ≥2 snags ac^{-1} in ponderosa pine (*Pinus ponderosa*) and ≥3 snags ac^{-1} in mixed conifer forest, with retained snags ≥18 in. dbh and ≥30 ft in height (hereafter referred to as large snags). These recommendations were formally adopted for use in 11 national forests in the Southwestern Region, US Department of Agriculture (USDA) Forest Service, through a regionwide amendment to forest plans (USDA Forest Service 1996). These guidelines are being supplanted as individual national forests revise their land management plans, but in the interim they guided snag management within the Region for almost two decades.

Southwestern mixed conifer and ponderosa pine forests have experienced considerable climate-mediated mortality in recent years (Negron et al. 2009, Ganey and Vojta 2011, Kane et al. 2014). Previous work in two national forests in northern Arizona demonstrated that this mortality was increasing overall snag numbers and altering species composition of snag populations in these areas (Ganey and Vojta 2014). Numbers of large snags targeted in management guidelines (USDA Forest Service 1996) also increased, but densities of large snags remained below recommended levels in much of the landscape, especially in ponderosa pine forest (Ganey et al. 2015a). Results also suggested that abundance of large snags was influenced by past management history and factors related to ease of human access such as slope and distance to road (Ganey et al. 2015a), and studies of snags in other regions also found strong relationships between snag numbers and variables related to human access (Bate et al. 2007, Wisdom and Bate 2008, Hollenbeck et al. 2013).

Data on snag populations, trends in those populations, or factors influencing numbers of large snags in those populations were lacking elsewhere within Ari-

Received September 8, 2016; accepted September 16, 2016; published online December 15, 2016.

Affiliations: *Joseph L. Ganey (jganey@fs.fed.us), USDA Forest Service, Rocky Mountain Research Station, Flagstaff, AZ. Chris Witt (chriswitt@fs.fed.us), USDA Forest Service, Rockey Mountain Research Station, Boise, ID.*

Acknowledgments: *We thank all of the FIA field crews and data management and support personnel who collected, entered, summarized, and made available the data used here. We also thank D. Bragg, D. Tinker, and three anonymous reviewers for their thoughtful reviews of earlier versions of this article.*

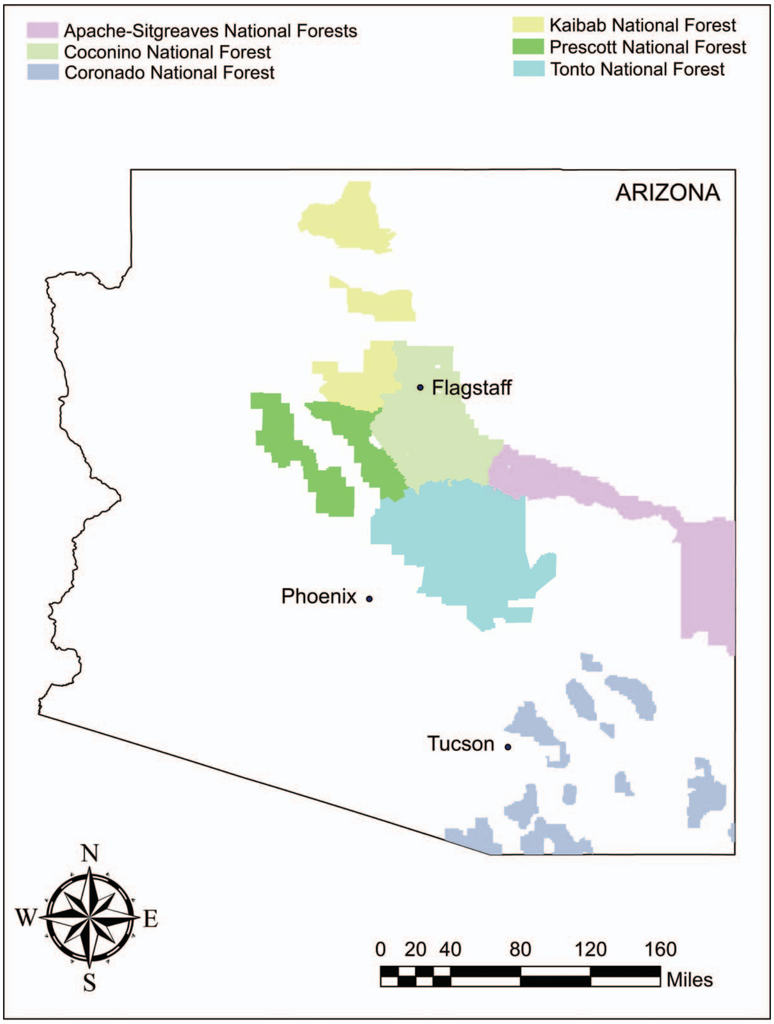

Figure 1. Map showing locations of six national forests within Arizona where USDA Forest Service FIA plots were sampled.

zona. The USDA Forest Service Forest Inventory and Analysis (FIA) program sampled plots across six National Forests in Arizona in two recent time periods (1995–1997 and 2001–2010), and the resulting data provided an opportunity to assess trends in snag populations at broader spatial scales than earlier studies. We used these data to summarize changes in snag density between these time periods, summarize changes in density of large snags and proportions of sampled plots that met USDA Forest Service guidelines for density of large snags (USDA Forest Service 1996) between time periods, model the effects of selected site characteristics on the probability that plots met current snag guidelines, and evaluate change in abundance of individual snag species relative to drought tolerance of those species. This study thus extends the spatial scope of previous studies to provide information on snag populations, trends in those populations, and factors influencing densities of snags across broad spatial scales.

Management and Policy Implications

Snags are important components of forest systems, providing resources for numerous wildlife species and contributing to decay dynamics and other ecological processes. Overall, snag numbers are increasing and species composition of snag populations is changing within mixed conifer and ponderosa pine forests in Arizona due to drought-mediated mortality. Despite increases in overall snag numbers, the large snags most important to native wildlife remained relatively sparse, especially in ponderosa pine forest, and large snags generally were most abundant in areas of reduced human access. Managers and interested public groups should recognize that not all areas can or should support high densities of large snags. In other areas, managers should emphasize retention of large snags and recruitment of the large trees that provide a source for large snags, ensure that large snags remain well (but not uniformly) distributed across heterogeneous landscapes, explicitly consider human disturbance in snag management plans, limit salvage logging of larger snags after disturbance events, and incorporate climate-mediated changes in forest composition and structure and adaptive strategies to address those changes in management plans.

Study Area

Lands included within this study fell within the Apache-Sitgreaves, Coconino, Coronado, Kaibab, Prescott, and Tonto National Forests, Arizona (Figure 1). These forests encompassed a wide range of ecological conditions and topography, ranging from arid deserts to alpine tundra and from valley plains to montane slopes and steep canyons incised into high plateaus.

We focused on two major forest types within these national forests. Mixed conifer forests typically were dominated by Douglas-fir (*Pseudotsuga menziesii*) and white fir (*Abies concolor*). Other relatively common species in this forest type included ponderosa pine, quaking aspen (*Populus tremuloides*), Gambel oak (*Quercus gambelii*), Engelmann (*Picea engelmannii*) and blue (*Picea pungens*) spruce, subalpine (*Abies lasiocarpa*) and corkbark (*Abies lasiocarpa* var. *arizonica*) fir, and southwestern white (*Pinus strobiformis*) and limber (*Pinus flexilis*) pine. Ponderosa pine forest was dominated by ponderosa pine, with other relatively common species including Gambel and gray (*Quercus grisea*) oak, Douglas-fir, white fir, two needle pinyon pine (*Pinus edulis*), alligator juniper (*Juniperus deppeana*), and various other junipers (*Juniperus* spp.). These forest types encompassed >2,000,000 ac of national forest lands in Arizona (Supplemental Figure S1[S]).

Methods

FIA Data

The FIA program conducts inventory on all forested lands within the United States using a standardized plot design with plots distributed on a grid to avoid geo-

[S] Supplementary data are available with this article at http://dx.doi.org/10.5849/jof.15-144.

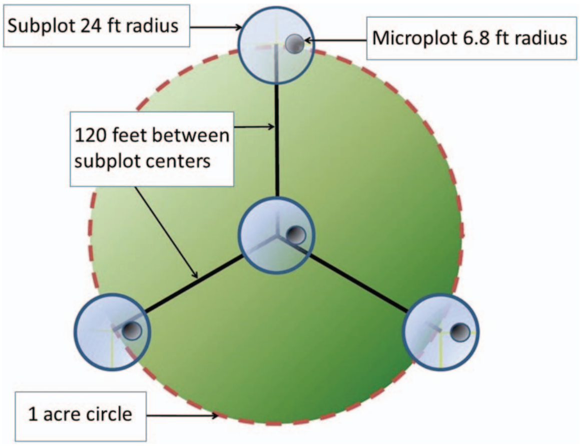

Figure 2. Diagram of plot layout used by field crews in the USDA Forest Service FIA Program. Snags were sampled on four circular plots, a central plot, and three surrounding plots. Snags ≥5 in. dbh (or drc) were sampled in 24-ft radius subplots, whereas snags from 1 to 4.9 in. dbh (or drc) were sampled in 6.8-ft radius microplots. (Based on Bechtold and Patterson 2005).

graphic bias and sampled at an intensity of approximately one field plot per 6,000 ac (Bechtold and Patterson 2005). We restricted our analyses to mixed conifer and ponderosa pine forests for comparison with previous studies in these forest types (Chambers and Mast 2014, Ganey and Vojta 2014, Ganey et al. 2015a) and with plots on National Forest System lands. Plots were classified to forest type using the live tree stocking data collected on each plot (see below). We used the standard FIA definition to classify ponderosa pine forest but defined mixed conifer forest using criteria from the US Department of Interior Fish and Wildlife Service (2012) for consistency with previous studies (Ganey and Vojta 2014, Ganey et al. 2015a) and because the Interior West FIA program does not have a working definition for mixed conifer forest. Mixed conifer forest as defined here included plots from the following FIA-defined forest types: Douglas-fir (60.0% of total mixed conifer plots), white fir (25.5%), Engelmann spruce (5.5%), blue spruce (4.5%) ponderosa pine (1.8%), and Engelmann spruce/subalpine fir, limber pine, aspen, and deciduous oak woodland (<1% each).

FIA crews sampled 53 and 64 plots in mixed conifer forest on National Forest System lands during the 1990s and 2000s, respectively, and 396 and 367 plots in ponderosa pine forest during these time periods. Most plots sampled during the 1990s were sampled in 1995 and 1996, whereas plots were distributed approximately equally across years during the 2000s (Supplemental Table S1). Elevation ranged from 5,600 to 10,512 ft above sea level (ASL) (mean = 8,200 ft) at plots sampled in mixed conifer forest and from 5,200 to 9,205 ft (mean = 7,244 ft) in ponderosa pine forest.

The FIA plot design consisted of four circular plots configured as a central plot and three peripheral plots (Figure 2) (Bechtold and Patterson 2005). All standing trees (live or dead) with dbh (for timber trees) or diameter at rootcollar (drc) (for woodland trees) ≥5 in. were measured on the four 24-ft radius subplots, and trees 1–4.9 in. dbh or drc were measured on 6.8-ft radius microplots located within each subplot (Figure 2) (Bechtold and Patterson 2005). FIA field crews recorded a number of snag attributes, of which species, height, and dbh were used in our analyses. FIA crews also recorded a number of plot attributes. We selected three of these for use in modeling the probability that a plot met USDA Forest Service guidelines for density of large snags (details and rationale below). These included percent slope, stand age (years), and an index of site productivity based on annual growth in cubic feet of wood volume per acre. This index was a factor variable with seven categories. We collapsed the index into two categories representing sites with productivity <50 and ≥ 50 ft^3 ac^{-1} $year^{-1}$, (coded as classes 1 and 2, respectively) to avoid modeling with small sample sizes in some categories.

FIA sampling schemes and field methods have changed through time (Bechtold and Patterson 2005). Past inventories of Arizona were periodic inventories where all plots in a state were sampled over a period of 2–4 years; the last periodic inventory was completed in 1999. FIA implemented an annual inventory cycle in Arizona in 2001, in which approximately 10% of plots from the full sample set in a state were measured each year (Supplemental Table S1). The first inventory under this annual cycle was completed in 2010.

We used data from the periodic inventory of 1995–1999 and the annual inventory cycle completed in 2010 to assess changes in snag populations. Both inventories used included National Forest System lands, used the same mapped-plot design protocols described above, and used the same field methods and definitions. We did not include data from earlier inventories because of changes in definitions and methodology between these earlier inventories and the recent inventories. There were changes in plots sampled even for these two recent inventories, with some plots sampled during both periods and others in only one of the inventory periods.

Changes between FIA inventories in plots sampled can complicate assessment of change. For example, Goeking (2015) evaluated apparent trends in live and dead tree volume, growth, and mortality using plots from recent periodic and annual inventories in eight western states. Trends estimated using all plots from these inventories often differed in magnitude and sometimes in direction from trends estimated using only plots sampled during both inventories. However, Goeking (2015) estimated parameters across all forest types combined, the periodic and annual inventories compared did not sample different forest types equally, and much of the observed difference in trends derived from the differential sampling of forest types by periodic versus annual inventories. In contrast, we focused all analyses within forest type and numbers of plots sampled by forest type were comparable in both inventories used here (Supplemental Table S1), making valid comparisons between inventories possible. Because not all plots were sampled in both inventories, however, we focused on changes over all plots between time periods and made no attempt to assess change within individual plots.

Data Analysis

We calculated snag densities within plots based on plot area, summarized snag density by forest type and time period, and compared snag density between time periods. Although we estimated variability in snag density among plots, we were not able to explicitly model spatial variability or autocorrelation in our analyses, because FIA does not release plot coordinates. We do not expect spatial autocorrelation to be a significant problem in this data set, because FIA plots are separated by a minimum distance of >3.1 miles. We also did not use national forest as a surrogate for plot coordinates in analysis because sample sizes were too small for many combinations of national forest and time period to allow for reliable estimates (Supplemental Table S1). We graphically summarized snag density by forest, forest type, and time period, however, to allow for visual inspection of potential spatial structuring.

We also did not explicitly incorporate temporal variability within FIA sampling period in analyses. The FIA inventories were designed to provide a valid sample over the entire sampling period rather than by individual year within sampling periods.

As in previous studies (Ganey and Vojta 2014, Ganey et al. 2015a), distributions of snag density were highly asymmetric and frequently featured high concentrations of values around the median as well as numerous outliers and extreme values much larger than the median. Consequently, neither mean nor median values adequately described central location in these distributions. Where possible, we based location estimates on Huber's M-estimator, a generalized maximum likelihood estimator that yields robust location estimates in distributions containing outliers (Huber and Ronchetti 2009). We also graphically summarized results for snag density using boxplots, which portrayed the entire distribution.

We estimated percent change in snag density between time periods as [(2000s density − 1990s density)/1990s density]. We estimated percent change separately for all snags ≥4 in dbh or drc and for large snags. We used Huber's M-estimator in calculations for all snags ≥4 in dbh or drc but used median values for calculations involving large snags because distributions of large snags were so highly concentrated around the median that we could not compute Huber's M-estimator. We computed all estimates and associated 95% bias-corrected confidence intervals (CIs) using 10,000 bootstrap iterations (Efron and Tibshirani 1993) in version 23 of IBM SPSS Statistics.[1]

We estimated proportions of plots that met USDA Forest Service guidelines for density of large snags (≥2 and ≥3 snags ac^{-1} in ponderosa pine and mixed conifer forest, respectively) (USDA Forest Service 1996) and compared these proportions between time periods using Z-tests for proportions (Zar 1984, p. 395–397). We modeled the probability that sampled plots met USDA Forest Service snag guidelines as a function of selected habitat covariates using generalized linear models with a binary logistic response variable coded as 0 for plots that did not meet the guidelines or 1 for plots that met the guidelines. Covariates used in models included percent slope, stand age, and site productivity class. We used percent slope to index topographic roughness, stand age to index tree age and potential decadence, and site productivity class to index the relative ability of a site to grow large trees. We predicted that all covariates would positively influence the probability of a plot meeting the snag guidelines, assuming that increasing slope would reduce the extent and intensity of past timber and/or fuelwood harvest (Bate et al. 2007, Wisdom and Bate 2008, Hollenbeck et al. 2013), increasing stand age would increase tree age, size, and probability of tree mortality, and higher site productivity would indicate greater potential to grow the larger trees that produce large snags. Because some individual plots were sampled during both time periods, we included only plots from the most recent inventory period in models.

We evaluated eight models for each forest type, representing all possible combinations of the above covariates, using the *glmulti* package (Calcagno 2013) in the R computing environment (R Core Team 2013). We ranked models using Akaike's information criterion corrected for small sample size (AICc) and considered any models with ΔAICc ≤2 to be competing models (Burnham and Anderson 2002). We computed model weights after Burnham and Anderson (2002) and estimated relative covariate importance by summing model weights across all models containing that covariate. Because model covariates differed in scale, we standardized all covariates to unit variance and mean zero to facilitate interpretation of parameter estimates (Legendre and Legendre 1998). We calculated model-averaged parameter estimates and 95% CIs for standardized covariates using unconditional variance (Burnham and Anderson 2002).

We pooled snags within forest type and time period to estimate percent change in abundance of major snag species present (with percent change estimated as described previously). Only snag species that comprised ≥10% of 1990s snag populations were included in these estimates. We qualitatively evaluated species-specific changes in snag abundance relative to drought tolerance, using a drought tolerance index based on physiological tolerance to water stress, morphological and life cycle strategies to cope with scant water, and water availability estimated on the sites where the species frequently occur (Niinemets and Vallardes 2006).

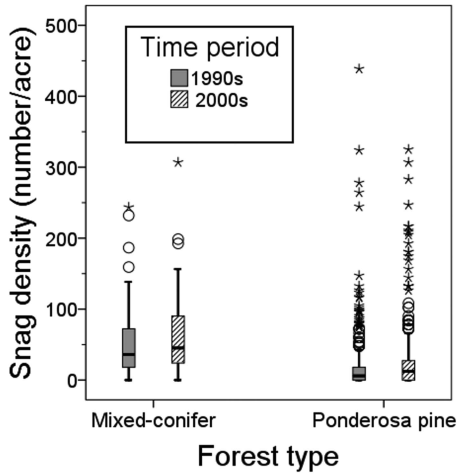

Figure 3. Density of snags ≥4 in. dbh or drc in mixed conifer and ponderosa pine forest in national forest lands in Arizona by time period. Estimates are based on plots sampled by the USDA Forest Service FIA Program (n = 53 and 64 plots in mixed conifer during the 1990s and 2000s, respectively, and 396 and 367 plots in ponderosa pine during those time periods). The box indicates the interquartile range, the line within the box indicates the median, and the exterior lines indicate the range in the data excluding outliers (circles) and extremes (asterisks), defined as observations >1.5 and 3 times the box length outside the box, respectively.

Results

Snag density varied widely among sampled FIA plots in both forest types and time periods, and distributions were highly asymmetric for both forest types and time periods (Figure 3). Based on Huber's M-estimator, density of snags >4 in. dbh increased by 21 and 72% between time periods in mixed conifer and ponderosa pine forests, respectively (Table 1). Because of the pronounced variability among plots, however, CIs around this estimator overlapped between time periods for both forest types (Table 1). Sample sizes within many combinations of national forest, forest type, and time period were too small to permit formal analysis (Supplemental Table S1). Distributions of snag density overlapped broadly among for-

Table 1. Density of snags in mixed conifer and ponderosa pine forest on national forest lands in Arizona by two time periods.

	Density of snags			
	1995–1997		2001–2011	
Forest type	Estimate[1]	95% CI	Estimate[1]	95% CI
	(snags ac^{-1})			
Mixed conifer				
All snags	40.6	28.5–53.4	49.1	37.5–65.5
Large snags	0.0	0.0–0.0	0.0	0.0–6.0
Ponderosa pine				
All snags	7.2	6.2–9.2	12.4	7.9–14.0
Large snags	0.0	0.0–0.0	0.0	0.0–0.0

Estimated densities (estimate and 95% bias-corrected CI) are shown separately for all snags ≥4 in. dbh (referred to as all snags) and for "large" snags, defined as snags ≥18 in. dbh (or drc) and ≥30 ft tall (USDA Forest Service 1996). Estimates were based on plots sampled as part of the USDA Forest Service FIA program. n = 53 and 396 plots in mixed conifer and ponderosa pine forest, respectively, in the 1990s and 64 and 367 plots in mixed conifer and ponderosa pine forest, respectively, in the 2000s.

[1] Estimates shown are Huber's M-estimator for all snags and medians for large snags. Huber's M-estimator is a generalized maximum-likelihood estimator that yields robust location estimates in distributions containing outliers (Huber and Ronchetti 2009). This estimator could not be computed for large snags because the distribution was highly centered around the median. All estimates were computed using 10,000 bootstrap iterations.

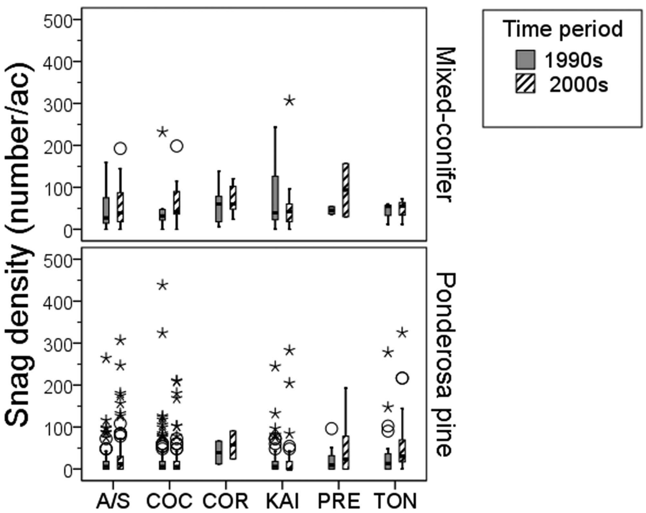

Figure 4. Density of snags ≥4 in. dbh or drc in mixed conifer and ponderosa pine forest in national forest lands in Arizona by national forest and time period. Estimates are based on plots sampled by the USDA Forest Service FIA Program. The box indicates the interquartile range, the line within the box indicates the median, and the exterior lines indicate the range in the data excluding outliers (circles) and extremes (asterisks), defined as observations >1.5 and 3 times the box length outside the box, respectively. A/S, Apache-Sitgreaves; COC, Coconino; COR, Coronado; KAI, Kaibab; PRE, Prescott; TON, Tonto. Numbers of plots sampled by forest and time period are shown in Supplemental Table S2.

ests in both forest types and time periods, however, suggesting that snags were widespread and providing no evidence for spatial structuring in snag density among individual forests (Figure 4).

Variability among plots also was pronounced for density of large snags. Large snag distribution among plots was highly concentrated around the median (Figure 5). Median density of large snags was zero in both forest types for both time periods (Table 1), with >50 and >75% of mixed conifer and ponderosa pine plots, respectively, containing no large snags in either time period (Figure 5). Proportions of plots that met USDA Forest Service guidelines for density of large snags increased significantly in both forest types between the 1990s and the 2000s, however (Table 2).

Two competing models, which contributed 85% of model weight, distinguished mixed conifer plots that met USDA Forest Service guidelines for density of large snags from plots that did not meet those guidelines (Table 3). The top model included percent slope and site productivity class, and the competing model included these covariates plus stand age. All covariates were positively associated with plots that met USDA Forest Service guidelines (Table 4). Percent slope was the strongest predictor of whether or not a mixed conifer plot met USDA Forest Service snag guidelines, as indicated by high relative importance and a confidence interval that did not include zero. Site productivity had relatively high estimated importance, but a confidence interval that included zero, and proportions of mixed conifer plots that met USDA Forest Service guidelines did not differ significantly between productivity classes (χ^2_1 = 0.017, P = 1.000). Stand age had both low estimated importance and a CI that included zero. Slope averaged 28.5% (CI = 23.3–33.7%) at mixed conifer plots that did not meet snag guidelines and 50.2% (CI = 39.3–61.0%) at plots that met snag guidelines.

There also were two competing models, contributing >99% of model weight, distinguishing ponderosa pine plots that met USDA Forest Service guidelines from those that did not (Table 3). The top model again included percent slope and site productivity class, and the competing model included those covariates plus stand age. Plots that met the guidelines were positively associated with all covariates (Table 4). Both site productivity class and percent slope had high importance values and confidence intervals that did not include zero in ponderosa pine forest. In contrast, stand age had low importance and a CI that included zero. Slope averaged 13.6% (CI = 12.1–15.2%) at ponderosa pine plots that did not meet snag guidelines and 20.7% (CI = 15.6–25.8%) at plots that met snag guidelines. Almost twice as many ponderosa pine plots that met snag guidelines (26.3%) had productivity ≥50 ft^3 ac^{-1} year^{-1} than plots that did not meet those guidelines (13.7%; χ^2_1 = 5.619, P = 0.027).

Species-specific changes in snag abundance between time periods generally tracked drought tolerance within forest type. In mixed conifer forest, quaking aspen, white fir, and Douglas-fir snags all increased in abundance, whereas abundance of the more drought-tolerant ponderosa pine and Gambel oak decreased or remained the same (Figure 6). Similarly, in ponderosa pine forest, ponderosa pine snags increased in abundance, whereas the more drought-tolerant Gambel oak showed a slight decline in snag abundance. Note that ponderosa pine behaved oppositely in the two forest types, however, showing an approximately 40%

decline in snag abundance in mixed conifer forest and an increase of approximately 80% in ponderosa pine forest (Figure 6).

Discussion

Direct comparisons between this study and previous studies of snag populations in these forest types in northern Arizona (Chambers and Mast 2005, 2014, Ganey and Vojta 2014, Ganey et al. 2015) are complicated by differences in spatial scale and sampling and analysis methods. For example, median densities of large snags in FIA plots were zero in both forest types in both time periods, whereas median densities of large snags in the study area in Ganey et al. (2015a) were >0 for both forest types and four sampling occasions (1997, 2002, 2007, and 2012). These differences could reflect ecological differences between that study area and the larger area sampled by FIA crews, with some of that larger area perhaps lower in productivity and numbers of large snags. They also could reflect differences in the spatial scale of plots sampled. Ganey et al. (2015a) sampled snags within 2.47-ac plots, whereas FIA crews sampled snags within plots of approximately 1 ac in area. Given that large snags were relatively sparse, they probably were absent from many more FIA plots relative to the larger plots sampled by Ganey et al. (2015a). At present, we cannot distinguish between these hypotheses, which are not mutually exclusive. Regardless of the underlying reason, the large number of plots lacking large snags resulted in a high concentration of values for large snag density around the median (Figure 5) and complicated assessment of change in the densities of these large snags.

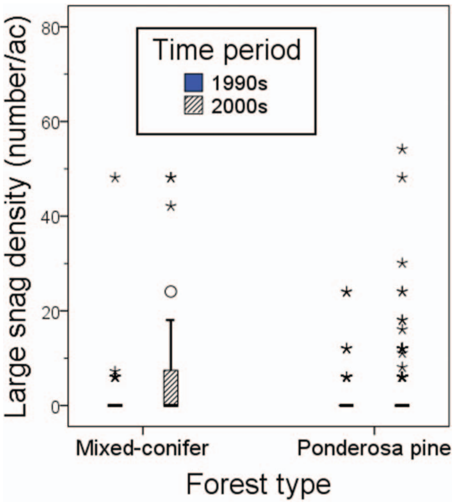

Figure 5. Density of large snags (defined as snags ≥18 in. dbh or drc and ≥30 ft in height) (USDA Forest Service 1996) in mixed conifer and ponderosa pine forest in national forest lands in Arizona by time period. Note that the scale here differs from that in Figures 3 and 4. Estimates based on plots sampled by the USDA Forest Service Forest Inventory and Analysis Program (*n* = 53 and 64 plots in mixed conifer during the 1990s and 2000s, respectively, and 396 and 367 plots in ponderosa pine during those time periods). The box indicates the interquartile range, the line within the box indicates the median, and the exterior lines indicate the range in the data excluding outliers (circles) and extremes (asterisks), defined as observations >1.5 and 3 times the box length outside the box, respectively.

Despite differences in sampling methods and spatial scale, however, many of our results were consistent with results from previous studies in these forest types, thus extending the spatial scope of inference of those studies. As in previous studies, increases in overall snag numbers were widespread in these forest types in Arizona, and variation in snag density among plots was pronounced (Figures 3–5). That variation, coupled with the large number of small plots lacking large snags (see above), reinforces previous recommendations that snag densities should be assessed over large areas and allowed to vary across the landscape (Balda 1975, Stephens 2004, Hutto 2006, Ganey 2016).

The observed increase in snag density also was consistent with the increased tree mortality observed by Goeking (2015) between the recent periodic and annual inventories in Arizona. Mortality increased by approximately 9 or 15% between these inventories, depending on whether the analysis focused on all sampled plots or only on plots sampled in both inventories, respectively (Goeking 2015) (Table 2). The conclusion that mortality increased between inventories thus was robust with respect to samples used, despite differences between those samples in estimated magnitude of this trend.

Previous studies documented that USDA Forest Service guidelines for retention of large snags were not met in large portions of the landscape, especially in ponderosa pine forest (Ganey et al. 2015a). Although proportions of plots meeting those guidelines increased significantly in both forest types between time periods, median densities of large snags remained below those guidelines in both forest types during the 2000s, and <50% of sampled plots met USFS guidelines in both forest types, consistent with previous results.

The fact that densities of large snags in this study were positively associated with percent slope in both forest types also was consistent with previous studies in Arizona and elsewhere that documented greater snag densities in areas with reduced ease of human access, including areas featuring rougher topography and/or those that were distant from roads or towns (Bate et al. 2007, Wisdom and Bate 2008, Hollenbeck et al. 2013, Ganey et al. 2015a). Standing rates of snags were negatively related to slope in a study area in northern Arizona (Ganey et al. 2015b), suggesting that the observed greater densities of large snags on steep slopes did not result from greater snag longevity in such areas.

Densities of large snags also were positively associated with site productivity class in both forest types, but this relationship was far stronger in ponderosa pine than in mixed conifer forest. This may be driven at least in part by differences between forest types in relative productivity. Only 17% of ponderosa pine plots had productivity ≥50 ft^3 ac^{-1} $year^{-1}$ versus >61% of mixed conifer plots. Thus, it may be more difficult to produce and/or maintain the recommended number of large snags in pon-

Table 2. Percentage (and associated 95% CI) of FIA plots in Arizona that met USDA Forest Service guidelines for density of large snags, by two time periods.

	Time period				
	1995–1997		2001–2011		
Forest type	% plots	95% CI	% plots	95% CI	*P*
Mixed conifer	18.9	8.4–29.4	45.3	33.1–57.5	<0.003
Ponderosa pine	5.1	2.9–7.3	17.2	13.3–21.1	<0.001

n = 53 and 396 plots in mixed conifer and ponderosa pine forest, respectively, in the 1990s and 64 and 367 plots in mixed conifer and ponderosa pine forest, respectively, in the 2000s. Large snags were defined as snags ≥18 in. dbh (or drc) and ≥30 ft tall (USDA Forest Service 1996).

[1] *P* values from Z-tests comparing proportions of plots meeting guidelines for density of large snags between time periods.

Table 3. Model selection results for generalized linear models distinguishing between plots that did and did not meet USDA Forest Service guidelines for density of large snags in mixed conifer forest and ponderosa pine forest on national forest lands in Arizona, based on plots sampled from 2001 to 2010.

Forest type	Model[1]	ΔAICc[2]	w_i[3]
Mixed conifer[4]	Slope + site productivity	0.000	0.512
	Slope + site productivity + stand age	0.858	0.333
	Slope	3.471	0.090
	Slope + stand age	4.204	0.063
	Site productivity	12.410	0.001
	Site productivity + stand age	13.863	<0.001
	Null	16.403	<0.001
	Stand age	17.610	<0.001
Ponderosa pine[5]	Slope + site productivity	0.000	0.716
	Slope + site productivity + stand age	1.911	0.275
	Site productivity	9.520	0.006
	Site productivity + stand age	11.096	0.003
	Slope	54.308	<0.001
	Slope + stand age	56.350	<0.001
	Null	63.494	<0.001
	Stand age	65.401	<0.001

Guidelines were from USDA Forest Service (1996).
[1] Covariates evaluated: slope (%); site productivity (class 1 = 0–49 $ft^3\ ac^{-1}\ year^{-1}$, class 2 = ≥50 $ft^3\ ac^{-1}\ year^{-1}$); stand age (years).
[2] Change in AICc relative to the model with the lowest AICc.
[3] w_i = model weight for the specified model (Burnham and Anderson 2002).
[4] n = 64 plots, of which 29 met USDA Forest Service guidelines for large snag density.
[5] n = 367 plots, of which 63 met USDA Forest Service guidelines for large snag density.

Table 4. Model-averaged parameter estimates from suites of generalized linear models evaluating the influence of plot covariates on whether or not plots met USDA Forest Service guidelines for density of large snags in mixed conifer or ponderosa pine forest on national forest lands in Arizona, based on plots sampled from 2001 to 2010.

Forest type/parameter	Estimate[1]	95% CI	Importance[2]
Mixed conifer			
Intercept	0.245	0.081–0.410	1.000
Slope (%)	0.213	0.106–0.321	0.998
Site productivity[3]	0.029	−0.174–0.231	0.847
Stand age (yr)	0.027	−0.060–0.113	0.397
Ponderosa pine			
Intercept	0.140	0.098–0.182	1.000
Site productivity[3]	0.110	0.007–0.213	1.000
Slope (%)	0.066	0.027–0.106	0.991
Stand age (yr)	0.002	−0.012–0.016	0.278

Guidelines were from USDA Forest Service (1996). Positive values for parameters are associated with an increased probability of meeting the management guidelines.
[1] All estimates refer to standardized variables to aid in interpretation of coefficients.
[2] Relative importance was computed by summing model weights across all models containing the indicated parameter.
[3] Site productivity for class 2 (≥50 $ft^3\ ac^{-1}\ year^{-1}$) relative to class 1 (0–49 $ft^3\ ac^{-1}\ year^{-1}$).

derosa pine forests than in more productive mixed conifer forests (Ganey 2016). Stand age was not an important predictor in either forest type.

Our results with respect to change in snag abundance by species also were generally consistent with previous studies in these forest types. For example, both Ganey and Vojta (2011) and Kane et al. (2014) observed high mortality in aspen and white fir in mixed conifer forest and hypothesized that the observed mortality was climate mediated. This explanation is consistent with changes in major species observed in this study. In mixed conifer forest, aspen had the lowest drought tolerance among the major species represented and the greatest increase in snag abundance (Figure 6). White fir was the next least drought-tolerant species and also showed a relatively strong increase in snag abundance. In contrast, abundance of snags declined in mixed conifer forest for the more drought-resistant ponderosa pine. In ponderosa pine forest, ponderosa pine was less drought tolerant than Gambel oak, and snag abundance increased for ponderosa pine and decreased for Gambel oak in this forest type (Figure 6).

Only two species were abundant enough in both forest types to allow comparison of changes in abundance of those species between forest types. Gambel oak behaved similarly in both forest types, showing little change in snag abundance in either type (Figure 6). In contrast, ponderosa pine snags declined in abundance by approximately 40% in mixed conifer forest, but increased by approximately 80% in ponderosa pine forest (Figure 6). We are not certain what drove this different response. It may be that moisture stress for this species was greater in the drier ponderosa forest than in wetter mixed conifer forests. Alternatively, considerable ponderosa pine mortality in ponderosa pine forests was attributed to bark beetles (primarily *Ips* spp. and *Dendroctonus* spp.) in the 2000s (Negron et al. 2009, Chambers and Mast 2014). These beetles may not have reached the same levels of abundance in the more species-diverse mixed conifer forest, where ponderosa pine was present at lower densities, than in ponderosa pine forests that were heavily dominated by a single species. These hypotheses again are not mutually exclusive, and there also may have been interactions between moisture stress and bark beetle impacts that differed between forest types.

Thus, our results generally supported and extended the results from previous studies of tree and snag populations in southwestern mixed conifer and ponderosa pine forests (Ganey and Vojta 2011, 2014, Ganey et al. 2015a). Although variation in snag densities among plots was pronounced, snag numbers generally were increasing in both forest types. That increase was driven by drought-mediated mortality (Ganey and Vojta 2011, Kane et al. 2014, Goeking 2015), which was altering species composition consistent with drought tolerance of the major species represented (Ganey and Vojta 2011, Kane et al. 2014). The observed changes in species composition and increased mortality (Goeking 2015) are likely to continue, given current climate projections for this region (Seager et al. 2007, Williams et al. 2012), resulting in changes in structure and composition of future forests and suggesting that managers should incorporate climate-mediated changes in forest composition and structure and adaptive strategies to address

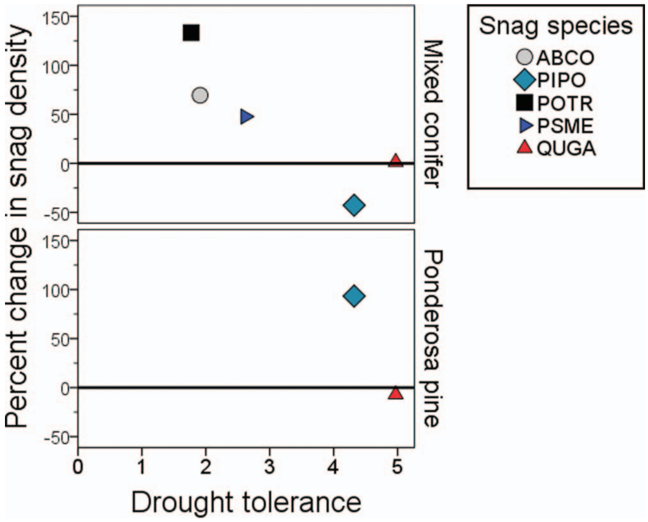

Figure 6. Relative change in numbers of snags by species between two time periods on national forest lands in Arizona mixed conifer and ponderosa pine forest as a function of drought tolerance for those species. Drought tolerance values followed Niinemets and Vallardes (2006) and ranged from 0 (no tolerance) to 5 (maximal tolerance). Relative change was estimated based on plots sampled by the USDA Forest Service FIA Program (*n* = 53 and 64 plots in mixed conifer during the 1990s and 2000s, respectively, and 396 and 367 plots in ponderosa pine during those time periods), computed as [(snag number in 2000s − snag number in 1990s)/ snag number in 1990s] · 100. The horizontal reference line indicates no change between time periods, with values above and below this line indicating increase or decrease in abundance, respectively. ABCO, white fir; PIPO, ponderosa pine; POTR, quaking aspen; PSME, Douglas-fir; QUGA, Gambel oak.

those changes in management plans (Mori et al. 2013).

Despite increases in overall snag numbers, numbers of large snags remained relatively sparse (see also Ganey et al. 2015a, Ganey 2016). Large snags were more abundant on steeper slopes in both forest types, possibly reflecting more limited human access or less intensive past tree harvest in these areas (Bate et al. 2007, Wisdom and Bate 2008, Hollenbeck et al. 2013, Ganey et al. 2015a). This suggests that areas with reduced human access may be best suited for management of large snags and that managers should implicitly consider human disturbance in snag management plans.

Densities of large snags also may be limited by site productivity in many ponderosa pine forests. We have little information on historical snag densities in these forests, and studies documenting ecologically sustainable snag levels (e.g., Harrod et al. 1998) are badly needed, especially in ponderosa pine forest (Ganey 2016). In the meantime, managers should emphasize retention of large snags and recruitment of the large trees that provide a source for large snags, ensure that large snags remain well (but not uniformly) distributed across the landscape, and limit salvage logging of large snags after disturbance events (Chambers and Mast 2005, 2014, Ritchie and Knapp 2014, Ganey 2016). Managers and interested public groups also need to acknowledge that not all areas can or should support high densities of large snags, however.

Endnotes

1. For more information, see www-01.ibm.com/software/analytics/spss/products/statistics/.

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