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Density of Large Snags and Logs in Northern Arizona Mixed-Conifer and Ponderosa Pine Forests

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Large snags and logs provide important biological legacies and resources for native wildlife, yet data on populations of large snags and logs and factors influencing those populations are sparse. We monitored populations of large snags and logs in mixed-conifer and ponderosa pine (*Pinus ponderosa*) forests in northern Arizona from 1997 through 2012. We modeled density of large snags and logs as a function of forest type, time period, and environmental characteristics of sampled plots. Our objective was to build models that best explained current densities of these structures using these available covariates. The best model for density of large snags indicated that snag density was greater in mixed-conifer than in ponderosa pine forests, lower in plots with evidence of past timber or fuelwood harvest than in plots lacking such evidence, and covaried positively with mean slope and distance to road. The best model for density of large logs indicated that log density was greater in mixed-conifer than in ponderosa pine forests and covaried positively with solar insolation and surface ratio (an index of topographic roughness). The best snag model predicted that current US Department of Agriculture (USDA) Forest Service guidelines for retention of large snags were met only in mixed-conifer forests lacking evidence of past harvest activity. In contrast, the USDA Forest Service guidelines for retention of large logs were met in both forest types. Our results suggest that ease of human access and management history influence density of large snags, that current snag guidelines are unlikely to be met without considering these impacts, and that those guidelines may not be readily attainable in much of the landscape.

Keywords: human access, logs, management guidelines, ponderosa pine forest, snags

Large snags (standing dead trees) and fallen logs provide important biological legacies, contribute to decay dynamics and other ecological processes in forested ecosystems, and provide important resources for native wildlife (e.g., Davis et al. 1983, Maser and Trappe 1984, Harmon et al. 1986, Bull et al. 1997, McComb and Lindenmayer 1999, Laudenslayer et al. 2002). Because of their importance, land managers and researchers have paid special attention to snags and logs in recent decades, and many public land agencies have established specific guidelines for retention of snags and logs. For example, a 1996 amendment to the land management plans for 11 national forests in the Southwestern Region, US Department of Agriculture (USDA) Forest Service, established guidelines for retention of large snags and logs based on snag or log size, abundance, and forest type (USDA Forest Service 1996, p. 92–93). These guidelines defined large snags as snags ≥45.7 cm dbh and ≥9.2 m tall and large logs as ≥30.5 cm midpoint diameter and ≥2.44 m in length, following Reynolds et al. (1992). The guidelines specified that minimum densities of 7.4 and 4.9 large snags ha^{-1} and 12.4 and 7.4 large logs ha^{-1} should be retained in mixed-conifer and ponderosa pine (*Pinus ponderosa*) forests, respectively. Although the intent to protect woody debris in sufficient amounts and appropriate size classes was clear in both USDA Forest Service (1996) and Reynolds et al. (1992), it was not clear how the specific parameters for size and density of snags and logs were derived or at what spatial scale the guidelines should be applied.

Despite these guidelines, data on current densities of large snags and logs on public lands frequently are unavailable (Morrison et al. 1986). We also generally lack information on the environmental factors that influence the abundance of large snags and logs or on trends in populations of large snags and logs (Ffolliott 1983, Hall et al. 1997). Consequently, managers and planners typically do not know how the numbers of large snags and logs are changing over time, which environmental factors most strongly influence the numbers of large snags and logs, whether or not guidelines for snag

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; kilometers (km): 1 km = 0.6 mi; hectares (ha): 1 ha = 2.47 ac.

and log retention are being met currently, or even whether those guidelines are attainable in the context of sustainable management.

We used data from an ongoing study of snag and log populations in mixed-conifer and ponderosa pine forests in northern Arizona to address some of these knowledge gaps. This study monitored snag populations from 1997 through 2012 and log populations from 2004 to 2009 (Ganey and Vojta 2012, 2014). Using data from this study, we modeled numbers of large snags and logs as a function of time period and available site characteristics, used the best resulting models to estimate current mean densities of large snags and logs and associated 95% confidence intervals (CIs) by forest type, and compared these predicted densities and associated 95% CIs to USDA Forest Service guidelines for retention of large snags or logs.

Our three primary objectives in this study were to build models that best explained current densities of large snags and logs, determine which of several available environmental characteristics were most useful in those models, and assess current densities of large snags and logs relative to USDA Forest Service guidelines for retention of those structures. Thus, our focus was on explaining and assessing current densities of these structures. We did not intend the resulting models to be used to predict snag densities in areas not sampled or in future years. We also built models using available environmental covariates. These covariates did not represent all factors that might influence densities of large snags or logs, and we make no claim that our models are comprehensive. Rather, our study provides data on current density of large snags and logs in the study area and on whether those densities are changing over time, quantifies the relative influence of several available environmental characteristics on densities of large snags and logs, and evaluates current density of these structures relative to USDA Forest Service guidelines for retention of large snags and logs. This information should benefit managers charged with retaining adequate numbers of large snags and logs, often using sparse data, in an era of changing management paradigms (e.g., Allen et al. 2002, Stephens and Moghaddas 2005, Reynolds et al. 2013) and altered disturbance regimes (McKenzie et al. 2004, Parker et al. 2006, Williams et al. 2010, Metz et al. 2013).

Study Area

The study area encompassed approximately 73,000 ha within the Coconino and Kaibab National Forests in northcentral Arizona (Figure 1), and we focused on mixed-conifer and ponderosa pine forests within this area. Mixed-conifer forests were dominated numerically by ponderosa pine, white fir (*Abies concolor*), and Douglas-fir (*Pseudotsuga menziesii*), which together accounted for approximately 90% of the total trees in this forest type (Ganey and Vojta 2011). Other species included Gambel oak (*Quercus gambelii*), quaking aspen (*Populus tremuloides*), and limber pine (*Pinus flexilis*), in that order of frequency. Ponderosa pine accounted for >90% of trees in ponderosa pine forests (Ganey and Vojta 2011). Gambel oak also was relatively common (approximately 8% of total trees), and alligator juniper (*Juniperus deppeana*), Douglas-fir, quaking aspen, limber pine, pinyon pine (*Pinus edulis*), and other species of juniper were present in small numbers in some stands.

Our study plots were randomly located within the study area (see below). As a result, they were distributed across a wide range of topographic conditions and soil types, covered the entire elevational range of these forest types within this area, included both commercial forestlands and administratively reserved lands such as wilderness and other roadless areas, and incorporated all of the major disturbance factors operating in southwestern forests, including wildfire, insect infestations, and dwarf mistletoe (*Arceuthobium* spp.) infection. Consequently, our study plots presumably represented the full range of disturbance histories and forest structural conditions present in these forest types.

Methods

Data Collection

We sampled snags on a set of 1-ha plots (100 × 100 m) originally established in 1997 using a stratified random sampling design with mixed-conifer and ponderosa pine forests representing the two strata recognized (for details on establishing plots, see Ganey 1999). Within each plot ($n = 53$ plots in mixed-conifer and 60 plots in ponderosa pine forests), we sampled all snags ≥2 m in height and ≥20 cm in dbh in 1997, 2002, 2007, and 2012. The 20-cm minimum diameter was selected because smaller snags were suspected to be relatively unimportant to native wildlife (e.g., Bunnell et al. 2002, Saab et al. 2004), and our initial study objectives focused on wildlife habitat. For all snags, we recorded dbh to the nearest cm using a dbh tape and estimated snag height to the nearest m using a clinometer. All plots were sampled from May through September in all years.

We sampled logs in 2004 and 2009 in a 0.09-ha subplot (30 × 30 m) within each of the larger snag plots. We reduced plot size because logs were more abundant than snags, and time constraints precluded sampling these features on the entire plot. Subplots were established starting at the first corner of the larger plot and following the same compass bearings used to establish the larger plot. Because both plot locations and compass bearings originally were selected randomly (Ganey 1999), subplots were located randomly with respect to forest structure.

Within each subplot, we sampled all logs ≥20 cm in large-end diameter and ≥2 m in length. Measurements for length (recorded to nearest 0.1 m) and diameter (nearest cm) of logs referred to the portion of the log contained within plot boundaries, and only that portion of the log was sampled. The 20-cm minimum large-end diameter was used for consistency with the snag sampling.

Environmental Characteristics of Plots

We also recorded several plot-level characteristics that might influence abundance of large snags or logs for use in modeling snag and log density. These included forest type (mixed-conifer or ponderosa pine), year sampled (1997, 2002, 2007, or 2012 for snags and 2004 or 2009 for logs), timber status (harvested or unharvested), mean elevation, mean slope, surface ratio, and mean annual solar insolation (described below).

Previous work clearly documented that mixed-conifer forest contained greater numbers of both snags and logs than ponderosa pine forest in this area (Ganey 1999, Ganey and Vojta 2012, 2014). Consequently, we expected densities of these structures to be greater in mixed-conifer forest. We modeled both forest types simultaneously, however, because we hoped to build a single model useful for identifying which of several available environmental covariates most strongly influenced the density of large snags and logs across forest types.

We also expected a time trend in the density of large snags, because previous work indicated that the numbers of snags and logs were increasing during the study due to drought-mediated tree mortality (Ganey and Vojta 2011, 2012, 2014). These earlier analyses

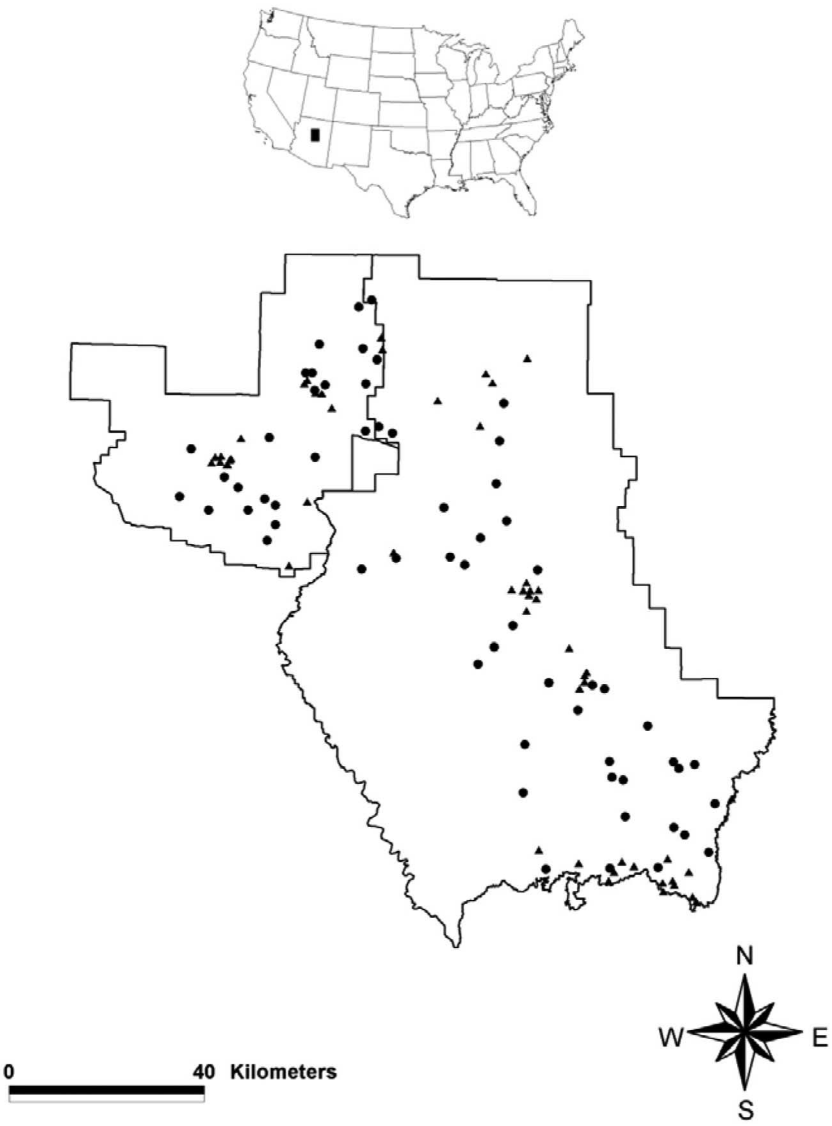

Figure 1. Location of the study area (black box, top) in northern Arizona, and locations of sampled plots within the study area (bottom). Plots were located in the Kaibab (left) and Coconino (right) National Forests. Plots in ponderosa pine forest ($n = 60$) are indicated by circles and plots in mixed-conifer forest ($n = 53$) are indicated by triangles.

included snags and logs of all sizes; however, this study focused only on large snags and logs as defined in USDA Forest Service (1996).

We recorded timber status on all plots as harvested if there was evidence of past tree cutting such as cut stumps and as unharvested where such evidence was lacking. Therefore, plots classified as harvested included plots subject to fuelwood harvesting as well as commercial timber harvest and/or precommercial thinning. The intensity and timing of past management clearly differed among plots, but detailed management histories were not available for our study plots. We expected that densities of large snags, but not necessarily large logs, would be greater in unharvested than in harvested plots, because past timber management or fuelwood cutting can influence the densities of snags (Bate et al. 2007, Wisdom and Bate 2008, Hollenbeck et al. 2013).

Given that past timber management and/or fuelwood harvest can affect densities of large snags and logs (Bate et al. 2007, Wisdom and Bate 2008, Hollenbeck et al. 2013) and that human activity probably is related to ease of access, we also hypothesized that covariates related to relative ease of human access might help explain current densities of large snags and logs. Specifically, we predicted that human access and activity would decrease and densities of large snags and logs would consequently increase with increasing distance to road, slope steepness, and topographic roughness. We estimated distance (km) from the plot centroid to the nearest road using ArcGIS, version 10 (Environmental Systems Research Institute 2011) and spatial layers depicting road locations within the Coconino and Kaibab national forests.[1] We estimated mean slope (degrees) within each plot using the National Elevation Dataset.[2] We calculated mean slope using the ArcGIS extension from Jenness (2013). All plots contained between 9 and 16 grid cells, depending on where plot boundaries fell relative to the orientation of the data grid, and values used in analysis represented plot means estimated using all cells within each plot. We used the methods outlined in Jenness (2004) to calculate total surface area for each plot and then divided the surface area by the planimetric area to estimate the surface ratio (an index of topographic roughness).

Our plots and the overall study area experienced considerable drought-mediated tree mortality during the study (Ganey and Vojta

2011), with much of that mortality due to insects, including a complex of bark beetles (primarily *Ips* spp.) in ponderosa pine and pinyon pine (Negron et al. 2009, USDA Forest Service 2009, Hoffman et al. 2012), Douglas-fir beetle (*Dendroctonus pseudotsugae*) and fir engraver (*Scolytus ventralis*) in Douglas-fir and white fir (USDA Forest Service 2009), and western tent caterpillar (*Malacosoma californicum*) in aspen (Fairweather et al. 2007, USDA Forest Service 2009). This mortality directly influenced the abundance of snags and possibly logs, but we lacked data directly measuring relevant factors such as moisture stress, abundance and activity of forest insects, and/or levels of dwarf mistletoe. Consequently, we used available data that we hypothesized might serve as surrogates for some of these factors. For example, we included mean elevation and mean annual solar insolation in hopes that these variables might crudely index relative moisture stress, which in turn could influence susceptibility of trees to insect-driven mortality and/or dwarf mistletoe infection. We hypothesized that moisture stress and insect activity would decrease with increasing elevation, because of the reduction in ambient temperature and increase with increasing solar radiation. We estimated mean elevation (m) within each plot using the National Elevation Dataset (described above), and calculated mean annual solar insolation (kWh m^{-2}) using the solar radiation module under the default parameters in ArcGIS10 (Environmental Systems Research Institute 2011).

In summary, the suite of variables available for modeling the density of large snags and logs included environmental characteristics of the sampled plots as well as several variables hypothesized to relate to either ease of human access or moisture stress. We lacked data directly indexing several environmental characteristics known to influence snag densities or fuel loads, such as levels of dwarf mistletoe or bark beetle infestation (Hoffman et al. 2007, 2012) or direct estimates of moisture stress but hoped that some of the variables used would serve as surrogates for these parameters. We recognize that these surrogate variables may serve as fairly crude indicators of the real parameters of interest. Because few of our plots experienced wildfire during the study (see below), we also had insufficient data on fire history to explicitly include fire effects (Passovoy and Fulé 2006) in our models, although fire certainly influenced density of snags and logs on our plots.

Analysis and Modeling

We estimated the numbers of large snags and logs within plots based on size requirements in USDA Forest Service (1996, p. 92–93). We modeled the abundance of large snags and logs as a function of time and site characteristics using the generalized estimating equation routines in SAS PROC GENMOD (SAS Institute, Inc. 2011). This procedure allowed us to accommodate the discrete nature of the data with an appropriate distribution and account for the repeated measures on each plot with a suitable error structure. We included a first-order autoregressive error structure [AR(1)] because plots were sampled repeatedly at regular time intervals and errors therefore were correlated across the time intervals within plots. We ran initial models using a Poisson distribution, but results indicated that data were overdispersed. Values for Pearson χ^2 square and *df* were 3.3369 and 2.6579 for the best models for snags and logs, respectively. Consequently, we used a negative binomial distribution with a log link function in subsequent modeling. Confidence intervals around dispersion parameter estimates for the best resulting negative binomial models for snags and logs were 0.4435–0.6835 and 0.6700–1.3836, respectively, indicating that the negative binomial provided a significantly better fit over the Poisson distribution. We modeled density (numbers ha^{-1}) of large snags directly, because they were sampled on 1-ha plots. In contrast, logs were sampled on smaller subplots (0.09-ha). Consequently, we modeled large log abundance and estimated parameters based on counts in the subplot data and then converted the results to density estimates (number ha^{-1}) when we compared the results to the USDA Forest Service guidelines.

We parameterized models using forest type, time period, timber status, and the GIS-derived plot covariates (mean elevation, mean slope, distance to road, surface ratio, and solar insolation). In the model selection and multimodel inference framework of Burnham and Anderson (2002), we developed a suite of 33 candidate models incorporating single factors or covariates or combinations of variables that previous studies suggested may influence densities of snags and logs (Tables 1 and 2). For example, we hypothesized that densities of large snags and logs would be greater in mixed-conifer than in ponderosa pine forests, that densities of large snags would be greater in unharvested plots than in harvested plots (Ganey 1999), and that densities of both large snags and logs would increase during the study (Ganey and Vojta 2012, 2014). We further hypothesized that densities of large snags and logs would increase with decreasing ease of human access and thus would be related positively to mean slope, surface roughness, and distance to road (Bate et al. 2007, Wisdom and Bate 2008, Hollenbeck et al. 2013). Because forests in our study area were experiencing drought-related tree mortality (Ganey and Vojta 2011), we also hypothesized that densities of large snags and logs might be influenced by plot covariates related to potential moisture stress and thus would be positively related to elevation and negatively related to solar insolation.

We evaluated candidate models in a model selection framework using the quasi-likelihood under the independence model criterion (QIC) (Pan 2001, Hardin and Hilbe 2003). QIC is analogous to the more widely used Akaike information criterion (AIC) and can be used similarly in model selection. We used QIC rather than AIC because the generalized estimating equation method is quasi-likelihood-based, so a modified AIC technique is required. Specifically, we used QICu, which incorporates a penalty for including additional parameters in the model and is therefore similar to AICc (Akaike information criterion corrected for small sample size) (Hurvich and Tsai 1989).We considered the model with the lowest QICu value to represent the best model and considered any models with ΔQICu <2 to be competing models (after Burnham and Anderson 2002, see also Barnett et al. 2010). We calculated Akaike model weights using ΔQICu in place of ΔAICc, following Burnham and Anderson (2002). These weights can be interpreted as the relative probability that the indicated model represents the best model in the suite of models evaluated. We report model selection results for all models evaluated, but report parameter estimates only for competing models as defined above. Standard errors and associated 95% CIs around parameter estimates were estimated using sandwich estimators, which are robust to misspecification of the correlation structure (White 1982, Royall 1986, Zeger et al. 1988).

We used the best model for snags or logs to estimate means and associated 95% CIs for current density of snags or logs in each factor level included in those models. We fixed any continuous covariates included in that model at their group mean for that factor level in this process. We used only the top model here rather than model averaging, because each competing model contained all previous

Table 1. Model results for 33 candidate models relating density of large snags to environmental characteristics of sampled plots in mixed-conifer and ponderosa pine forests in northern Arizona (n = 53 and 60 plots in mixed-conifer and ponderosa pine forests, respectively).

Model[1]	QICu[2]	ΔQICu[3]	Model weight[4]
Forest + timber + slope + road	−3,305.22	0.00	0.994
Global	−3,295.01	10.21	0.006
Forest + timber + surface + road	−3,223.81	81.41	0.000
Forest + timber + slope	−3,221.99	83.23	0.000
Forest + timber + slope + insolation + surface	−3,210.04	95.18	0.000
Forest + timber + slope + insolation + road	−3,202.91	102.31	0.000
Forest + timber + slope + insolation	−3,170.99	134.23	0.000
Forest + slope + road	−3,163.92	141.30	0.000
Forest + timber + insolation + surface + road	−3,119.13	186.09	0.000
Forest + timber + insolation + surface + road + surface × road	−3,099.43	205.79	0.000
Forest + timber + surface	−3,091.29	213.93	0.000
Forest + surface + road	−3,088.63	216.59	0.000
Forest + timber + insolation + surface	−3,062.56	242.66	0.000
Forest + timber + road	−3,043.21	262.01	0.000
Forest + timber + insolation + road	−3,003.36	301.86	0.000
Forest + surface + road + surface × road	−2,943.11	362.11	0.000
Forest + slope + insolation	−2,928.51	376.71	0.000
Year	−2,920.7	384.52	0.000
Forest + insolation + surface	−2,853.74	451.48	0.000
Forest + timber	−2,841.85	463.37	0.000
Forest + timber + insolation	−2,841.77	463.45	0.000
Forest + elevation + insolation + elevation × insolation	−2,824.09	481.13	0.000
Elevation	−2,744.1	561.12	0.000
Forest + insolation + road	−2,728.52	576.70	0.000
Forest + elevation + insolation	−2,726.5	578.72	0.000
Slope	−2,630.96	674.26	0.000
Null	−2,457.44	847.78	0.000
Timber	−2,402.59	902.63	0.000
Surface	−2,365.75	939.47	0.000
Road	−2,282.13	1,023.09	0.000
Insolation	−2,205.94	1,099.28	0.000
Forest	−2,031.96	1,273.26	0.000
Forest + year	−2,010.65	1,294.57	0.000

Models are presented in order based on QICu values.

[1] Plot factors and covariates included in models are the following: forest represents forest type (mixed-conifer or ponderosa pine); year represents year sampled (1997, 2002, 2007, or 2012); timber represents timber status (harvested or unharvested); slope represents mean slope (degrees); elevation represents mean elevation (m); insolation represents mean annual solar insolation (kWh m^{-2}); surface represents surface ratio (the ratio of calculated surface area to planimetric map area, an index of topographic roughness [Jenness 2004]); and road represents the distance to nearest road (km). The null model contained none of these plot covariates, and the global model contained all of them.

[2] QICu is the quasilikelihood under the independence model criterion (Pan 2001, Hardin and Hilbe 2003) adjusted for number of parameters in the model.

[3] ΔQICu is the change in QICu from the top model.

[4] w_i are the Akaike model weights calculated after Burnham and Anderson (2002) using ΔQICu in place of ΔAICc (Hurvich and Tsai 1989).

predictors (see Results), suggesting that the additional predictors were not adding a significant amount of predictive power over the previous suite of predictors. We assessed congruence between current densities of large snags and logs and guidelines for retention of these structures using these predicted means and associated confidence intervals.

Table 2. Model results for 33 candidate models relating density of large logs to environmental characteristics of sampled plots in mixed-conifer and ponderosa pine forests, northern Arizona, 1997–2012.

Model[1]	QICu[2]	ΔQICu[3]	Model weight[4]
Forest + insolation + surface	−49.86	0.00	0.346
Forest + timber + insolation + surface	−49.53	0.33	0.294
Forest + timber + insolation + surface + road	−48.14	1.72	0.147
Forest + timber + slope + insolation + surface	−46.23	3.63	0.056
Forest + slope + insolation	−46.12	3.74	0.053
Forest + timber + insolation + surface + road + surface × road	−45.45	4.41	0.038
Forest + timber + slope + insolation	−44.90	4.96	0.029
Forest + timber + slope + insolation + road	−44.77	5.09	0.027
Forest + slope + road	−40.23	9.63	0.003
Forest + timber + slope	−39.38	10.48	0.002
Forest + timber + slope + road	−38.21	11.65	0.001
Forest + surface + road	−38.09	11.77	0.001
Forest + timber + surface	−38.06	11.80	0.001
Global	−37.76	12.10	0.001
Forest + timber + surface + road	−36.19	13.67	0.000
Forest + surface + road + surface × road	−35.73	14.13	0.000
Forest + elevation + insolation	−32.08	17.78	0.000
Forest + elevation + insolation + elevation × insolation	−29.43	20.43	0.000
Forest + timber + insolation	−28.34	21.52	0.000
Forest	−27.86	22.00	0.000
Forest + timber	−27.11	22.75	0.000
Slope	−27.05	22.81	0.000
Forest + timber + insolation + road	−26.49	23.37	0.000
Forest + insolation + road	−26.23	23.63	0.000
Forest + year	−25.54	24.32	0.000
Forest + timber + road	−25.14	24.72	0.000
Surface	−23.44	26.42	0.000
Elevation	−17.53	32.33	0.000
Timber	−5.28	44.58	0.000
Insolation	2.11	51.97	0.000
Null	4.87	54.73	0.000
Road	6.04	55.90	0.000
Year	6.72	56.58	0.000

n = 53 and 60 plots in mixed-conifer and ponderosa pine forest, respectively. Models are presented in order based on QICu values.

[1] Plot factors and covariates included in models are as the following: forest represents forest type (mixed-conifer or ponderosa pine); year represents year sampled (1997, 2002, 2007, or 2012); timber represents timber status (harvested or unharvested); slope represents mean slope (degrees); elevation represents mean elevation (m); insolation represents mean annual solar insolation (kWh m^{-2}); surface represents surface ratio (the ratio of the calculated surface area to the planimetric map area, an index of topographic roughness [Jenness 2004]); and road represents distance to nearest road (km). The null model contained none of these plot covariates, and the global model contained all of them.

[2] QICu is the quasilikelihood under the independence model criterion (Pan 2001, Hardin and Hilbe 2003) adjusted for number of parameters in the model.

[3] ΔQICu is the change in QICu from the top model.

[4] w_i are the Akaike model weights calculated after Burnham and Anderson (2002) using ΔQICu in place of AICc (Hurvich and Tsai 1989).

Results

None of our sampled plots underwent commercial timber harvest between 1997 and 2012. Three plots in the ponderosa pine forests underwent thinning of smaller trees during this period. Ten plots experienced prescribed fire or low-severity wildfire during this period (one in mixed-conifer and nine in ponderosa pine forests), and seven plots burned with high severity (four in mixed-conifer and

Table 3. Parameter estimates (and 95% CIs) for models relating density of large snags or logs to environmental characteristics of sampled plots in mixed-conifer and ponderosa pine forests, northern Arizona, 1997–2012 (n = 53 and 60 plots in mixed-conifer and ponderosa pine forests, respectively).

Model and parameter[1]	Estimate	95% CI	P[2]
Snags			
Intercept	0.444	−0.009–0.898	0.055
Mixed-conifer	0.875	0.481–1.270	<0.001
Harvested	−0.691	−1.046–−0.337	<0.001
Mean slope (°)	0.045	0.021–0.070	<0.001
Distance to road (km)	0.536	−0.075–1.147	0.085
Logs			
1			
Intercept	−17.833	−30.022–−5.644	0.004
Mixed-conifer	1.189	0.615–1.763	<0.001
Solar insolation[3]	0.003	0.001–0.005	0.033
Surface ratio	13.180	4.535–21.825	0.003
2			
Intercept	−19.495	−32.973–−6.017	0.005
Mixed-conifer	1.208	0.637–1.780	<0.001
Solar insolation[3]	0.003	0.001–0.005	0.029
Surface ratio	14.606	4.393–24.819	0.005
Harvested	0.178	−0.416–0.772	0.557
3			
Intercept	−19.544	−33.105–−5.982	0.005
Mixed-conifer	1.200	0.619–1.782	<0.001
Solar insolation[3]	0.003	0.001–0.005	0.032
Surface ratio	14.748	4.446–25.051	0.005
Harvested	0.118	−0.473–0.708	0.696
Distance to road (km)	−0.001	−0.001–0.001	0.577

Results are shown for all competing models, defined as models with ΔQICu < 2 (QICu is quasilikelihood under the independence model criterion [Pan 2001, Hardin and Hilbe 2003]).

[1] Parameter estimates for factor variables are relative to reference categories, which include forest type (ponderosa pine) and timber status (unharvested).

[2] P values shown are from Z tests.

[3] Solar insolation represents mean annual solar insolation (kWh m^{-2}).

Table 4. Predicted values for number of large snags in northern Arizona mixed-conifer and ponderosa pine forests, 1997–2012.

		Large snags		Covariate means	
Forest type/timber status	n[1]	Mean	95% CI	Slope (°)	Distance to road (km)
		. . . . . (ha^{-1})			
Mixed-conifer					
Harvested	30	3.27	2.50–4.28	10.16	0.18
Unharvested	23	11.31	9.03–14.15	19.71	0.39
Ponderosa pine					
Harvested	53	1.08	0.87–1.34	5.29	0.16
Unharvested	7	3.10	2.14–4.48	8.98	0.52

Predicted values were estimated for factor levels from the top model for density of large snags, holding continuous covariates constant at within-factor-level means (also shown).

[1] N, number of plots sampled by factor level.

three in ponderosa pine forests). We included all plots in our analyses, because our objective was to evaluate trends in populations of large snags and logs across the landscape, including recently disturbed areas, but we were unable to explicitly model the effects of fire or thinning on snag and log density because of the low numbers of plots affected by these disturbances.

The top model relating density of large snags to plot characteristics included forest type, timber status, mean slope, and distance to road (Table 1). This model carried 99.4% of collective model weight, and there were no competing models. The AR(1) term for this model was 0.5847, indicating a moderate amount of correlation between sequential time points. Parameter estimates indicated that densities of large snags were greater in mixed-conifer forests than in ponderosa pine forests, lower in harvested plots than in unharvested plots, and covaried positively with mean slope and distance to road (Table 3). Confidence intervals around parameter estimates did not overlap zero for forest type, timber status, and mean slope, suggesting a strong influence for these variables. In contrast, the confidence interval for distance to road overlapped zero, and the associated P value also suggested a weak influence for this variable (Table 3). Model-predicted means and confidence intervals suggested that USDA Forest Service guidelines for density of large snags were met only in unharvested plots in mixed-conifer forests (Table 4). The upper bounds of the confidence intervals were below the recommended guideline in harvested plots in both forest types and in the unharvested plots in ponderosa pine forests.

Plots exploring the effect of continuous covariates on predicted snag density suggested that the USDA Forest Service guidelines for snag retention were likely to be met for unharvested plots in mixed-conifer forests where the slope exceeded approximately 15° (Figure 2) or where distance to road exceeded approximately 0.2 km; both values were below the group means for unharvested mixed-conifer forests (Table 4). In contrast, plots suggested that harvested plots in mixed-conifer forests were likely to meet USDA Forest Service guidelines for snag retention only on very steep slopes or in areas distant from roads. Similar plots for ponderosa pine forests suggested that harvested plots were unlikely to meet USDA Forest Service guidelines for snag retention for any level of slope or distance to road and that unharvested plots with slope similar to the group mean were unlikely to meet USDA Forest Service guidelines anywhere within the range sampled for distance to road. In contrast, mean predicted values for large snag density in unharvested ponderosa pine plots exceeded the minimum guideline for slopes of greater than approximately 20° (although the lower bound of the 95% CE remained below the recommended minimum value) (Figure 2).

There were three competing models for density of large logs (Table 2). These three models collectively carried 78.7% of the overall model weight. The top model included forest type, solar insolation, and surface ratio. The AR(1) term for this model was 0.9635, indicating a high amount of correlation between sequential time points. The next most likely model included these three variables plus timber status, and the third model added distance to road (Table 2). Confidence intervals around parameter estimates did not overlap zero for any variables in the top model, suggesting that all three included variables had a strong influence (Table 3). This was also true for these three variables in both competing models. In contrast, confidence intervals for variables added in the competing models (timber status and distance to road) overlapped zero, suggesting weaker influence for these variables. Because the competing models included all predictors in the top model and because all additional variables appeared to have only weak model effects (Table 3), we did not view these models as strongly competitive.

Parameter estimates indicated that density of large logs was greater in mixed-conifer forests than in ponderosa pine forests and covaried positively with solar insolation and surface ratio. Model-predicted means and confidence intervals suggested that USDA Forest Service guidelines for density of large logs were met in both forest types (Table 5). The predicted means were greater than the recommended minimums in both forest types, and even the lower bound

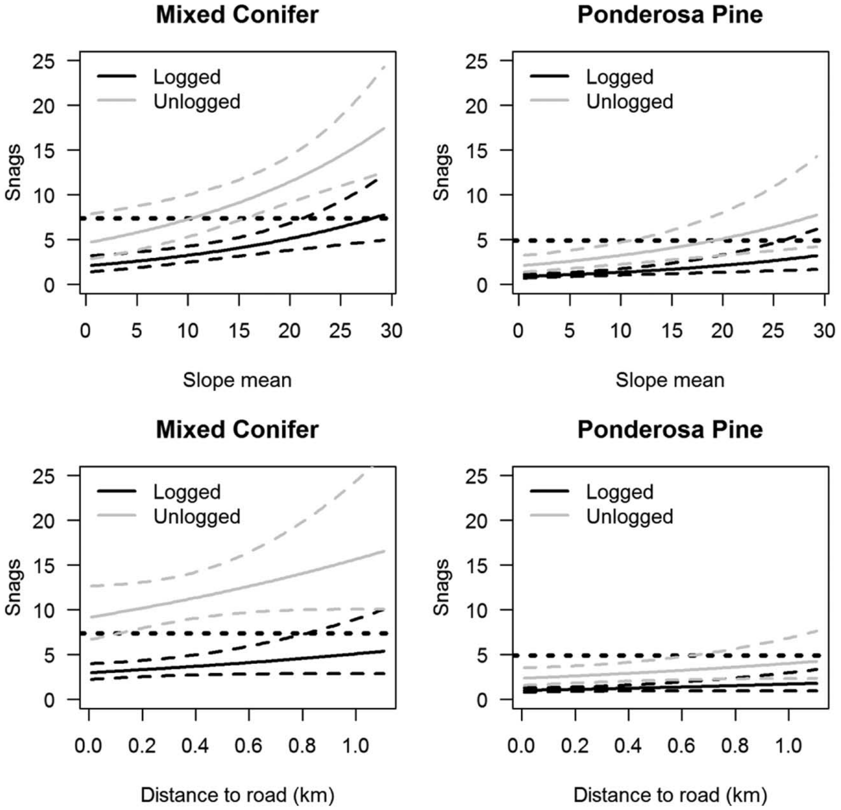

Figure 2. Plots showing predicted numbers of large snags ha^{-1} as a function of forest type, timber status, mean slope, and distance to road. Solid lines indicate the predicted mean, and dotted lines show upper and lower boundaries of 95% CIs. Predicted values were generated using the top model for density of large snags and holding continuous covariates constant at the group mean (see Table 4) for groups shown. The top plots show the effects of varying mean slope while holding distance to road constant, the bottom plots show the effect of varying distance to road while holding mean slope constant. The horizontal reference line shows guidelines for large snags from USDA Forest Service (1996): 7.4 and 4.9 large snags ha^{-1} in mixed-conifer and ponderosa pine forests, respectively.

Table 5. Predicted values for number of large logs in northern Arizona mixed-conifer and ponderosa pine forests, 1997–2012.

	Large logs		Covariate means	
Forest type	Mean	95% CI	Solar insolation ($kWh\ m^{-2}\ yr^{-1}$)	Surface ratio[1]
	. . . . . .(ha^{-1}).			
Mixed-conifer	35.37	28.38–44.09	1,562.72	1.05
Ponderosa pine	8.64	5.42 –13.77	1,666.34	1.01

Predicted values were estimated from the top model for density of large logs, holding continuous covariates constant at within forest type means (also shown). Data are based on 53 and 60 plots sampled in mixed-conifer and ponderosa pine forests, respectively.

[1] Surface ratio is the ratio of surface area for each plot divided by the planimetric area.

of the 95% CI was greater than the recommended minimum in mixed-conifer forests.

Discussion

This study used existing data to increase knowledge regarding current densities of large snags and logs and some of the environmental factors influencing those densities. We were limited by the types of data available and were not able to explicitly model the effects of several major forest disturbance agents, including forest insects, dwarf mistletoe, and fire (Passovoy and Fulé 2006, Hoffman et al. 2007, 2012), on densities of large snags and logs. All of these (and other) disturbance factors were represented in our study plots, however. Consequently, although we were not able to model the effects of those disturbances, our inference extends to landscapes in which they operate.

Given issues with data availability, our study focused on a subset of environmental factors hypothesized to relate to either ease of human access or moisture stress. In this context, our results supported some but not all of our a priori hypotheses regarding environmental factors influencing densities of large snags and logs. For example, density of large snags was greater in mixed-conifer forests and in unharvested plots, as expected and as documented in previous work (Ganey 1999, Bate et al. 2007, Wisdom and Bate 2008, Hollenbeck et al. 2013). Density of large snags also covaried positively with mean slope and distance to road, as predicted. Density of large logs also was greater in mixed-conifer forests and covaried positively with surface ratio and solar insolation, again as predicted.

Other predictions did not hold, however. For example, time was not a significant predictor for either large snags or logs, despite considerable drought-related mortality in recent years (Ganey and Vojta 2011), which has resulted in overall increases in snag and log density (Ganey and Vojta 2012, 2014). We also found no evidence that factors hypothesized to relate to moisture stress, such as elevation or solar insolation, were significant predictors of large snag density, although solar insolation was a significant predictor for density of large logs. Given that large logs may represent legacy structures from many years ago, these contrasting findings may indicate that relationships between tree mortality and moisture stress play out over time frames longer than our study. For example, the positive effect of solar insolation on the density of large logs may reflect slow decay rates for large logs in dry sites due to moisture limitation or case hardening (Webster and Jenkins 2005).

Most of the variables functioning as significant predictors of density of large snags appeared to be related to ease of human access (mean slope and distance to road) or past management history (timber status). This finding is consistent with past studies of snag density. For example, Wisdom and Bate (2008) found that (1) stands in western Montana that underwent selective or complete harvest had lower snag density than stands with no history of timber harvest, (2) stands adjacent to roads had lower snag density than stands not adjacent to roads, (3) unharvested stands adjacent to towns had lower snag density than similar stands farther from towns, (4) stands on flat terrain had lower snag density than stands on slopes, (5) stands oriented uphill from the nearest road had lower snag density than stands downhill from the nearest road, and (6) snag density was 50% greater in unharvested stands surrounded by national forestlands than in similar stands surrounded by other ownerships. Bate et al. (2007) observed similar patterns in forests in northeastern Oregon.

Similarly, Hollenbeck et al. (2013) evaluated the effects of human access on snag densities and diameter class distributions in interior ponderosa pine forests at nine locations across the western United States. Density of small ($<$50 cm dbh) snags in their study sites was not influenced by human access, whereas density of snags of $>$50 cm dbh was best predicted by road density and declined by 0.7 snag ha^{-1} (on average) for every km of road km^{-2}.

These studies (Bate et al. 2007, Wisdom and Bate 2008, Hollenbeck et al. 2013, this study) collectively suggest that ease of human access and resulting human activity levels exert a significant influence on density of large snags across the landscape. Results are less clear with respect to density of large logs. Most previous studies did not include logs, and this study provided weaker evidence for the effects of human access on logs than on snags.

Our results indicate that guidelines for retention of large snags generally were being met in mixed-conifer forest lacking evidence of past timber or fuelwood harvest. In contrast, guidelines were met in mixed-conifer forests with evidence of past harvest only where such forests occurred on very steep slopes or distant from roads. This finding suggests that the guidelines are attainable in the mixed-conifer forest type, but that they are not likely to be met in harvested stands in flat terrain or adjacent to roads (Table 4; Figure 2). In ponderosa pine forests, even areas lacking evidence of past harvest failed to meet current snag guidelines. Given the extensive, and perhaps unsustainable, drought-related tree mortality documented in our study area (Ganey and Vojta 2011), this observation may indicate that current guidelines for this forest type are unrealistic. Our sample of unharvested ponderosa pine plots was very small, however. It would be desirable to sample such areas more extensively before concluding that current snag guidelines are not attainable in ponderosa pine forest. Note also that natural fire regimes have been disrupted in our study area for $>$100 years (Covington and Moore 1994), with resulting pronounced changes in forest structure in ponderosa pine and drier mixed-conifer forest types (Covington and Moore 1994, Smith et al. 2008, Fulé et al. 2009, Margolis et al. 2013). These changes further complicate the assessment of current snag guidelines.

Our results suggest that current guidelines for retention of large logs generally are being met in our study area (Table 4). The apparent disconnect between meeting the guidelines for numbers of large logs versus large snags may be due to several factors. First, the size requirements are more stringent for large snags ($\geq$45.7 cm dbh and 9.2 m tall) than for large logs ($\geq$30.5 cm midpoint diameter and 2.44 m in length). Consequently, many pieces of down wood that qualified as large logs could be too small in diameter, length, or both to qualify as large snags. Second, because of the reduced length requirement for large logs, a single fallen large snag could break into multiple large log pieces. Third, logs decay slowly in southwestern forests, so many logs may represent legacy structures from many years ago. In contrast, snags decay and fall more rapidly. Finally, logs also may result from breakage and falling of live trees, without ever passing through a snag stage. For all of these reasons, the probability of meeting snag versus log guidelines was not tightly coupled on our plots.

Our study was limited by the types of data available for modeling. It would be desirable to develop data sets allowing explicit modeling of the effects of major disturbance factors on densities of large snags and logs, including fire, infestation levels of forest insects, and levels of dwarf mistletoe infection (Passovoy and Fulé 2006, Hoffman et al. 2007, 2012). It also would be desirable to expand the spatial scope of this study. This spatial expansion is beyond the scope of our current study but may be possible using data from the USDA Forest Service Forest Inventory and Analysis program (Bechtold and Patterson 2005).

Management Implications

Our results suggest that snag management in southwestern forests should explicitly incorporate the impacts of human access and that snag guidelines are unlikely to be met without considering these impacts. For example, reducing road densities in areas of flat to moderate terrain could reduce the impact of unmanaged fuelwood harvesting on densities of large snags. Spatial variation in snag numbers is great, however (Ganey and Vojta 2014), and managers need not manage all areas for high snag densities. Given our findings, it may make sense to manage for greater snag densities in areas distant from roads or in steeper terrain and for lower densities in more accessible areas.

Managing populations of snags and logs is a complicated endeavor, and one that is not always well integrated into forest planning and management. Our results illustrate the need to maintain and/or recruit the large trees that provide future sources of large snags and logs. In some cases this may require reducing harvest levels of larger trees, whereas in others it may require increasing harvest levels to reduce tree densities and allow for greater growth of remnant trees. Our results also indicate that current guidelines for snag density may not be readily attainable in all situations, suggesting that these guidelines may need revision. Any revision of snag (or log) guidelines should consider those guidelines in the context of sustainable forest management, particularly given changing management paradigms (Allen et al. 2002, Stephens and Moghaddas 2005, Reynolds et al. 2013), climates (Seager et al. 2007), disturbance regimes (McKenzie et al. 2004, Parker et al. 2006, Williams et al. 2010), and interactions among these factors (e.g., Metz et al. 2013).

Endnotes

1. Road locations within the Coconino and Kaibab national forests were obtained from www.fs.fed.us/r3/gis/coc/Transportation.zip and www.fs.fed.us/r3/gis/kai/Transportation.zip, respectively.
2. The National Elevation Dataset is available at nationalmap.gov/viewer.html.

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