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Snag density varies with intensity of timber harvest and human access

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Abstract

Many species of vertebrates depend on snags (standing dead trees) for persistence, and limited research suggests that snag density is lower in areas of intensive timber harvest and increased human access. While intensive timber harvest is one source of potential snag loss, ease of human access to forest stands may also facilitate loss via firewood cutting of snags. Accordingly, we hypothesized that density of snags (number of snags/ha) would decline in forest stands with increasing intensity of timber harvest and increasing ease of human access. We tested our hypothesis by sampling stands under varying levels of timber harvest and access on National Forest land in the northwestern United States. Stands with no history of timber harvest had 3 times the density of snags as stands selectively harvested, and 19 times the density as stands having undergone complete harvest. Stands not adjacent to roads had almost 3 times the density of snags as stands adjacent to roads. Unharvested stands adjacent to non-federal lands and closer to towns had lower snag density, as did stands with flat terrain in relation to nearest road. Our findings demonstrate that timber harvest and human access can have substantial effects on snag density. Meeting snag objectives for wildlife will require careful planning and effective mitigations as part of management of timber harvest and human access.

Keywords: Access; Forest management; Roads; Snags; Snag density; Timber harvest; Wildlife

1. Introduction

Snags (standing dead trees) provide essential habitat for many terrestrial vertebrates in western North America (Thomas, 1979), including many species at high risk of extirpation (Raphael et al., 2001). Intensive timber harvest and increased human access, however, can substantially reduce snag density (number of snags/ha) (Bate et al., 2007). Timber harvest may result in snag loss because some snags are felled for their commercial value, while others are felled to mitigate safety hazards or to reduce perceived fire or disease risk (Hann et al., 1997; Wilhere, 2001; DeLong et al., 2004). Road construction, often associated with timber harvest, further reduces snag density as part of the conversion of forest to roadway (Trombulak and Frissell, 2000; DeLong et al., 2004). In turn, increased access provided by roads may facilitate firewood cutting of snags, further reducing density (Hann et al., 1997; Bate et al., 2007).

Throughout western North American, ponderosa pine (*Pinus ponderosa*) and western larch (*Larix occidentalis*) have been intensively harvested because of their high value as wood products and firewood (Hann et al., 1997). These tree species also are two of the most widespread and valuable species for a suite of vertebrates of conservation concern (Wisdom et al., 1999; Wisdom et al., 2000). Many species of cavity-using wildlife rely on ponderosa pine and western larch (hereafter referred to as pine and larch) snags because they provide some of the most suitable nest and roost sites, owing to characteristics of the wood and its decay patterns (Bull et al., 1997). Consequently, understanding how timber harvest and human access affect pine and larch snags is critical to effective management of snag-dependent wildlife across large areas of western North American (Wisdom et al., 1999).

Further complicating the management of snags is their use for firewood. Cutting of snags for firewood was limited in the past by the distance that wood (log rounds) could be physically carried to a truck. Now, however, many firewood cutters use cable systems to harvest and transport snags, similar to systems used for yarding logs during commercial timber harvest. Snags can now be cut and moved at substantially longer distances from roads because of this improved technology. This begs the

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question: how does human access affect snag density? Distance from a road is a factor, but other factors of human access, such as distance to nearest town and adjacent land ownership, also could influence snag density. In northeast Oregon, Bate et al. (2007) found that snag density was lowest in pine and larch stands adjacent to roads, adjacent to private or other non-federal lands, and closest to towns. Whether these patterns are common to pine and larch forests across a broader area of western North American, however, has not been investigated.

Consequently, we evaluated snag density in relation to intensity of timber harvest and human access in pine and larch forests in northwestern Montana, USA. Our objective was to document if similar relations between snag density, timber harvest, and factors of human access, as observed by Bate et al. (2007) in Oregon, also occurred in a distinctly different geographic area, thus expanding the inference space of results across a broad area of western North America.

2. Study area

Our study took place on the Flathead National Forest, MT, USA (Fig. 1). The Forest covers 9300 km^2 in the northern Rocky Mountains, with elevations of 1400–2600 m. Mixed-conifer forests are common, with pine and larch forests dominating the warmer environments at lower to middle elevations.

Timber harvest and firewood cutting are common activities in the lower to middle elevation forests, and these activities are served by a large network of roads. At the time of our field work in 2001, the Forest contained 5730 km of mapped roads. Of these, 1944 km were open year-round, 663 km open seasonally, and the remainder closed. Extensive road closures were initiated during the late 1980s and early 1990s to meet security objectives for grizzly bear (*Ursus arctos*), but most of these roads were open during earlier decades. Thus, closed roads also were important to include in our analysis of human access, considering that under past management, many of these roads were open to motorized access and originally built as haul routes for timber harvest.

Because timber harvest and firewood cutting are common activities that could reduce snag density, the Flathead National Forest originally adopted snag retention standards in the 1980s. Current snag retention standards, adopted in the late 1990s, specify that 7–20 snags/ha >30 cm dbh will be maintained in forest types like those we studied. The specific retention standard varies with land use allocation and vegetation community.

Meeting such snag objectives has become increasingly important in recent years, as rural cities near the Flathead National Forest are growing rapidly, and with this growth has come a substantial increase in use of roads for consumptive activities such as firewood cutting. Population growth in Flathead County, which encompasses much of the Flathead National Forest, has increased 15% during the short period from 2000 to 2006. Characteristics of the Forest, its human uses, and its snag objectives are typical of many National Forests, making it a suitable area to study relations of timber harvest and human access with snag density.

3. Methods

3.1. Stand selection

We used a stratified random method to select stands for sampling. We selected these stands from the Timber Stand Management Record System of the Flathead National Forest. Stands with a dominant overstory of pine or larch were first identified from this database. For smaller-diameter stands with a mean tree diameter-at-breast height (dbh) of ≤12.7 cm, the dominant overstory was identified as the tree species of highest density. For larger stands with a mean tree dbh >12.7 cm, dominance was based on the tree species of highest basal area.

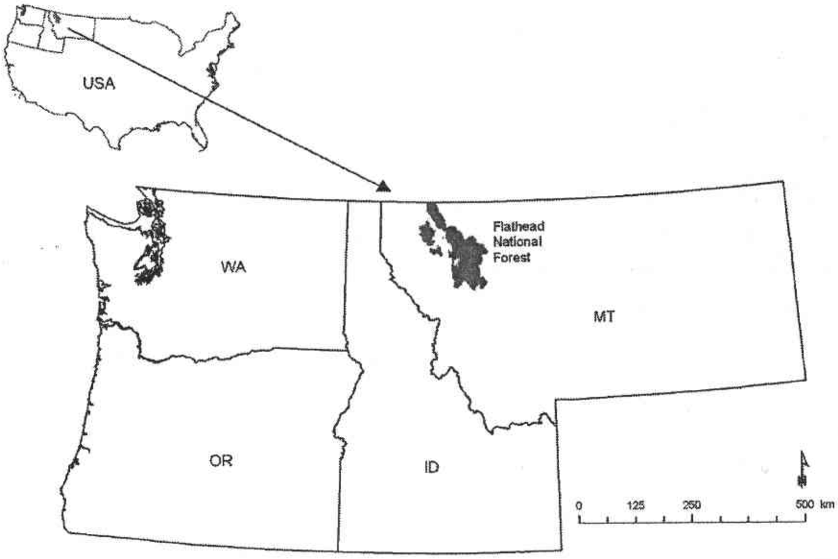

Fig. 1. Location of study area, Flathead National Forest, northwestern Montana, USA.

Table 1
Number of stands sampled within each stratification category based on road type, distance from town, topographic slope, and seral stage

Road type[a]	Distance from town[b]	Topographic slope (%)	Seral stage[c]		
			Early	Mid	Late
Adjacent, Open	Close	<15	1		1
Adjacent, Open	Close	15 to <35		1	2
Adjacent, Open	Close	≥35	1	1	1
Adjacent. Open	Far	<15	1	1	1
Adjacent, Open	Far	15 to <35	1		
Adjacent, Open	Far	≥35	0.5[d]	1	1
Adjacent, Closed	Close	<15	1	1	
Adjacent, Closed	Close	15 to <35		2	2
Adjacent, Closed	Close	≥35	1		1
Adjacent, Closed	Far	<15	1		2
Adjacent, Closed	Far	15 to <35	1	2	
Adjacent, Closed	Far	≥35	1		2
Not adjacent	Close	<15	1	1	
Not adjacent	Close	15 to <35	1	1	1
Not adjacent	Close	≥35		1	2
Not adjacent	Far	<15	1	1	2
Not adjacent	Far	15 to <35			2
Not adjacent	Far	≥35	0.5[d]		2

[a] Adjacent Road variable, Table 2. Adjacent was defined as any road within 5 m of the stand's boundary. Open roads were those open at least seasonally to public use. Closed roads were those closed to public use with a permanent gate, rock or dirt berm, or dense vegetation. Not adjacent refers to stands without any adjacent roads.

[b] Stands ≤40 km from the nearest town were defined as close; those >40 km were defined as far.

[c] Seral Stage variable, Table 2. Definitions of stages described in text.

[d] One transect in the stand was adjacent to a road and one was >200 m from nearest road.

Pine and larch stands then were stratified based on seral stage (early, mid, late), juxtaposition to different road types (adjacent to an open road, adjacent to a closed road, not adjacent to a road), distance to nearest town (≤40 km or >40 km), and slope (<15%, 15–35%, >35%) (Table 1). We stratified by seral stage because snag density can vary strongly with succession and may be correlated or confounded with effects of timber harvest (Hann et al., 1997). Consequently, stratification by seral stage allowed us to explicitly account for this factor when examining the potential effects of timber harvest on snag density. We stratified by juxtaposition to road types, by distance to nearest town, and by slope because of the presumed strong influence of these factors on snag density (Bate et al., 2007).

We then randomly selected 49 stands across the above strata to obtain a relatively even and representative distribution among strata for field sampling (Table 1). Additional stands could have been selected, but available resources limited sampling to the 49 stands.

Stands <6 ha in size were excluded from the selection process. This minimum size limit on stands was required to minimize the confounding edge effects from human activities in areas adjacent to smaller stands, and to ensure that selected stands could accommodate two 200-m sampling transects (see Section 3.3).

3.2. *Explanatory variables*

We identified 10 variables as having high potential to explain variation in snag density, based on rationale and results of Bate et al. (2007) (Table 2). The 10 variables included those of human access, timber harvest, topography, and adjacent land ownership. The 10 variables also included those used to stratify stands for sampling (Table 1). Importantly, these variables were not correlated (correlation coefficients [*r* values] of <0.3 for the 49 stands selected for sampling), and thus could explain variation in snag density independent of one another (see methods regarding separation of human access effects from those of timber harvest under Section 3.4). Finally, the variables were readily available or derivable from existing spatial databases of National Forests or could be efficiently collected with limited field sampling.

Information on the 10 explanatory variables was obtained or derived from a spatial database available from the Flathead National Forest for the 49 stands, or was collected as part of field sampling in the 49 stands (Table 2). All spatial data were mapped at 1:24,000 and comply with National Map Accuracy

Table 2
Name, type, definition, and data source of 10 explanatory variables evaluated in relation to snag density on the Flathead National Forest, northwestern Montana, USA

Explanatory variable	Type	Definition (data source)
Adjacent Ownership[a]	Categorical	Ownership of land adjacent to stand: (1) exclusively National Forest, (2) not National Forest on at least one boundary (spatial database[b]).
Adjacent Road[a]	Categorical	Road category for stand: (1) adjacent to open road, (2) adjacent to closed road, (3) not adjacent to a road (spatial database[b]). Adjacent was defined as any road within 5 m of the stand's boundary.
Adjacent Road II	Categorical	Road category for stand: (1) adjacent to any kind of road, (2) not adjacent to a road (spatial database[b]). Adjacent was defined as any road within 5 m of the stand's boundary.
Nearest Open Road	Continuous	Straight air distance (km) from edge of stand to nearest open road (spatial database[b]).
Nearest Road[a]	Continuous	Straight air distance (km) from edge of stand to nearest closed or open road (spatial database[b]).
Nearest Town[a]	Continuous	Distance (km) from edge of stand to nearest town following travelable roads (field sampling).
Seral Stage[a]	Categorical	Stage of forest development within the stand: (1) early, (2) mid-, (3) late (spatial database[b]).
Slope Direction[a]	Categorical	Orientation of stand from nearest road: (1) uphill, (2) downhill, or (3) flat (field sampling).
Timber Harvest[a]	Categorical	Intensity of timber harvest: (1) complete harvest, (2) partial harvest, (3) no harvest (spatial database[b]).
Slope	Continuous	Percent slope of stand as measured along 200-m sampling transects (field sampling).

[a] One of seven variables selected during AIC analyses as best fitting the data on snag density, and that were the focus of all subsequent analyses.

[b] Derived from spatial database of the Flathead National Forest.

Standards (precision and accuracy ±12.2 m). We used Arc analysis software, ESRI Inc. (version 9), for all spatial analysis.

3.2.1. *Seral stage*

We obtained information on the designated seral stage of each stand from the spatial database of the Flathead National Forest (Seral Stage, Table 2). Definitions of the three seral stages were based on those used by National Forests in the United States (USDA Forest Service, 1996):

(1) Early-seral: stands at least 10% stocked with trees of all sizes but dominated by seedlings or saplings. Seedlings are <2.5 cm dbh. Saplings are 2.5 to <12.7 cm dbh.
(2) Mid-seral: stands at least 10% stocked with trees ≥12.7 cm dbh, in which dominance of trees 12.7 to <23 cm dbh exceeds that of trees ≥23 cm dbh.
(3) Late-seral: stands at least 10% stocked with trees ≥12.7 cm dbh, in which dominance of trees ≥23 cm dbh exceeds that of trees 12.7 to <23 cm dbh.

3.2.2. *Timber harvest*

We placed each stand in one of three categories of timber harvest (Timber Harvest, Table 2): (1) stands that had undergone a clearcut harvest, or a seedtree or shelterwood harvest followed by overstory removal, referred to as complete harvest ($\bar{x}$ stand size = 24 ha); (2) stands that had undergone a seedtree or shelterwood harvest with no subsequent overstory removal, or stands that had been partially harvested (salvage logged) for disease or insect control, or had undergone single-tree selection, defined as partial harvest ($\bar{x}$ stand size = 18 ha); and (3) stands that had not been harvested for commercial wood products, referred to as not harvested or unharvested ($\bar{x}$ stand size = 34 ha). Structural conditions in unharvested stands were diverse, reflecting multiple age classes and stages of development created by natural disturbances of wildfire, insect outbreaks, disease, and drought.

3.2.3. *Human access*

We characterized the 49 stands based on 5 distance variables of human access (Table 2). One such variable was distance (km) from each stand to the nearest town (Nearest Town). This variable was measured with the odometer of the vehicle when traveling from each stand. A town was defined as any human population center of 1000 inhabitants or more. We also estimated the direct distance, by air, from each stand (Table 2) to the nearest road (Nearest Road) and nearest open road (Nearest Open Road).

Each stand also was characterized by its adjacency to roads and road type with two variables. The first variable, Adjacent Road, contained three categories of adjacency to roads for a given stand (Table 2): (1) adjacent to an open road, (2) adjacent to a closed road, and (3) not adjacent to a road. Adjacent was defined as any stand with a road within 5 m of the stand's boundary. Open roads were those open seasonally or year-round to public use. Closed roads were those where vehicle travel was impeded because of a permanent gate, dirt berm, boulders, or dense, impenetrable vegetation. The second variable (Adjacent Road II) was composed of two categories: (1) adjacent to any kind of road, and (2) not adjacent to any road.

We also documented short segments of road inside some stands that had not been recorded on inventories or maps. These were primitive, two-track roads that appeared to be used infrequently in the past and often were not drivable. We initially considered these unmapped roads for analysis (see Unmapped Roads, Bate et al., 2007), but the low number of stands (insufficient sample size) in which this road type was present ultimately precluded analysis.

3.2.4. *Slope direction*

Topography within each stand was characterized by measuring percent slope along each 12.5-m subsegment of each 50-m sampling transect, as described under methods of field sampling (Slope, Table 2). We averaged these slope measurements among transects to obtain a slope estimate for each stand. During field sampling, we also characterized each stand as (1) flat, (2) uphill from nearest road, or (3) downhill from nearest road (Slope Direction, Table 2).

3.2.5. *Adjacent land ownership*

Each stand was classified as to whether it was surrounded exclusively by National Forest land or was adjacent to lands other than National Forest on at least one boundary (Adjacent Ownership, Table 2). When adjacent lands were not National Forest, ownership was either private (timber corporations or individuals) or state lands administered by Montana.

3.3. *Field sampling*

We randomly established two transects, each 200 m long, for sampling snags within each stand. One stand was limited to one transect, however, owing to the combination of extremely steep topography and small stand size. Random establishment of the two transects was constrained so that transects were ≥50 m apart and parallel to one another. This minimum distance and layout was designed to eliminate the possibility of overlap between transects and to assure adequate spatial coverage of sampling. Random establishment also was constrained so that transects were perpendicular to the nearest road and to the associated stand edge adjacent to or closest to the nearest road. This constraint allowed us to sample the gradient of potential snag conditions from stand areas close to, versus far from, the nearest road. Starting and ending points of each 200-m transect were recorded using a Global Positioning System (GPS).

Each transect served as the centerline for strip plots that we used to count snags (Bate et al., 1999, 2002, 2008). The width of each strip plot ranged from 20 to 40 m (10–20 m outward from each side of the transect centerline). A complete count of all snags ≥23 cm dbh was made within each strip plot, using the appropriate width that provided adequate visibility to accurately detect and tally snags and other structures of interest (e.g., cut stumps, logs, or trees) along the centerline (Bate et al., 1999, 2002, 2008). This sampling process does not include a specified time search, but instead limits the sampling width to the distance from the centerline in which snags and other structures of interest can be accurately and efficiently detected and counted (see Bate et al., 1999, 2002, 2008).

In clearcut stands, we used strip plots 40-m wide because of high sampling visibility and low snag density (Bate et al., 1999, 2002, 2008). Strip plots of 20-m width were used to sample most other stands where visibility was impeded (Bate et al., 1999, 2002, 2008). For each snag counted in the strip plot, we recorded dbh, species, and height.

To assess whether timber harvest or firewood cutting may have modified within-stand patterns of snag density, we also recorded the presence of cut stumps or sawed logs within each strip plot. To understand whether snag density varied with slope, which often affects potential ease of firewood cutting and transport, we used a clinometer to measure percent slope at the centerline of each 12.5-m subsegment of transect.

3.4. Data analysis

We used Akaike's Information Criterion (AIC) (Akaike, 1973) in a model selection process to identify which combination of the 10 explanatory variables (Table 2) best fit the snag density data with the fewest parameters used (Burnham and Anderson, 1998). With this approach, the model that best fits the data while limiting the number of parameters is considered the most parsimonious (Burnham and Anderson, 1998). Burnham and Anderson further suggest that all models with Δ AIC scores ≤ 2 should be considered in making inferences. Consequently, we identified the top-ranked models as those with Δ AIC scores ≤ 2, and conducted multiple regression analysis to calculate variation in snag density explained by the combination of explanatory variables in each of these models. We conducted the above analyses for all snag species and for pine and larch snags only.

Explanatory variables included in one or more of the top-ranked AIC models also were evaluated individually in relation to snag density. For explanatory variables that were categorical, we calculated the mean and standard error of snag density for each class of the variable. For explanatory variables that were continuous, we regressed snag density on the variable, using ordinary least squares regression (Kirk, 1982). For regression analysis and calculation of means and standard errors, we summarized results for all snag species and pine and larch snags only.

We also evaluated how snag density varied in relation to human access in the absence of timber harvest. For this analysis, we were interested in removing the potential interaction of timber harvest with human access as they might jointly affect snag density, and instead wanted to understand how snag density might vary with human access in the absence of such interaction. Consequently, we restricted this analysis to unharvested stands and examined variables of human access in relation to snag density in one of the two ways: (1) if the variable was categorical and occurred in any of the top-ranked AIC models, we calculated the mean and standard error of snag density for each class of the variable, or (2) if the variable was continuous and occurred in any of the top-ranked AIC models, we regressed snag density on the variable. We conducted this analysis for all snag species and for pine and larch snags only.

We used the stand as our sample unit for all analyses ($n = 49$). We also used a 'log $y + 1$' transformation of snag data to obtain a normal distribution for all analyses. Statistical analyses were conducted with SYSTAT (version 10.2.05, 2002). All results refer to snags ≥ 23 cm dbh and >1.8 m tall.

4. Results

4.1. Model selection and multiple regression

Based on AIC values, the best model (Δ AIC $= 0$, representing the lowest AIC value and most parsimonious model) for predicting snag density among stands included six variables: (1) Timber Harvest, (2) Seral Stage, (3) Adjacent Road, (4) Slope Direction, (5) Nearest Town, and (6) Nearest Road. This model also accounted for most variation in density of all snag species under multiple regression analysis ($r^2 = 0.82$; $P < 0.001$; $n = 49$).

The second model also had a low Δ AIC value of 1.2, indicating a good fit and high parsimony. This model included all the variables listed above except Nearest Road and also accounted for most variation in density of all snag species ($r^2 = 0.81$; $P < 0.001$; $n = 49$).

The third ranking model (Δ AIC $= 2$) included all variables in the first model plus Adjacent Ownership. Like the first two models, the third-ranked model accounted for the large majority of variation in density of all snag species ($r^2 = 0.82$; $P < 0.001$; $n = 49$).

When only larch and pine snags were considered, two models had Δ AIC scores ≤ 2. The first model contained three explanatory variables: (1) Timber Harvest, (2) Adjacent Road, and (3) Slope Direction ($r^2 = 0.75$; $P < 0.01$; $n = 49$). The second model contained two variables: (1) Timber Harvest, and (2) Adjacent Road ($r^2 = 0.73$; $P < 0.01$; $n = 49$).

4.2. Seral stage

Late-seral stands supported the highest density of snags when all species were considered. Mean density was >3 times higher in late-seral than in mid-seral stands, and >9 times

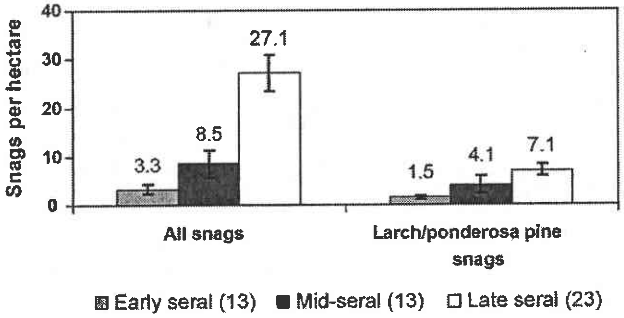

Fig. 2. Mean density of all snag species ≥ 23 cm dbh, and only ponderosa pine and western larch snags ≥ 23 cm dbh (±S.E.), in early-, mid-, and late-seral stands (Seral Stage variable, Table 2). Sample sizes are in parentheses.

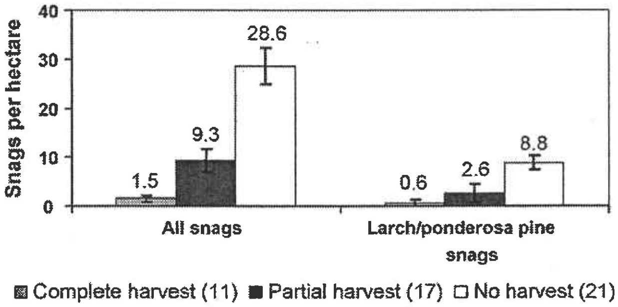

Fig. 3. Mean density of all snag species ≥23 cm dbh, and only ponderosa pine and western larch snags ≥23 cm dbh (±S.E.), in stands that had undergone complete harvest, partial harvest, or no harvest (Timber Harvest variable, Table 2). Sample sizes are in parentheses.

higher than in early-seral stands (Fig. 2). The same pattern occurred when considering pine and larch snags: mean density was almost 2 times higher in late-seral than in mid-seral stands, and >5 times higher than in early-seral stands (Fig. 2).

4.3. *Timber harvest*

Mean snag density, considering all species, was 19 times higher in unharvested stands compared to stands that had undergone a complete harvest, and 3 times higher than stands that had undergone partial harvest (Fig. 3). Density of pine and larch snags had similar patterns in relation to intensity of timber harvest (Fig. 3). Mean density of pine and larch snags in unharvested stands was 15 times higher than that in stands that had undergone complete harvest, and 3 times higher than in stands partially harvested (Fig. 3).

4.4. *Roads*

Stands without a road adjacent to them had 3 times the mean density of snags of all species in contrast to stands adjacent to an open road, and twice that of stands adjacent to a closed road (Adjacent Road, Fig. 4). Mean snag density in stands adjacent to closed versus open roads, however, had overlapping standard errors (Fig. 4).

A similar pattern existed for pine and larch snags. Mean density was 4–6 times higher in stands without an adjacent road compared to stands adjacent to a road (Fig. 4). Moreover, we found no difference (overlapping standard errors) in mean density of stands adjacent to an open versus a closed road (Fig. 4).

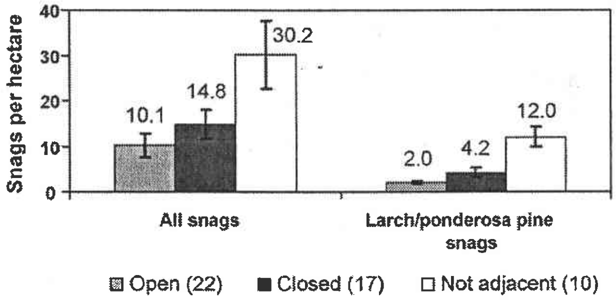

Fig. 4. Mean density of all snag species ≥23 cm dbh, and only ponderosa pine and western larch snags ≥23 cm dbh (±S.E.), in stands adjacent to open roads, adjacent to closed roads, and not adjacent to roads (Adjacent Road variable, Table 2). Sample sizes are in parentheses.

Mean density of pine and larch snags was nearly 5 times higher in unharvested stands without an adjacent road ($\bar{x} = 14.7$ snags/ha, S.E. = 4.4) versus unharvested stands with an adjacent, open road ($\bar{x} = 3.0$ snags/ha, S.E. = 0.8). Moreover, mean density was nearly twice as high in unharvested stands without an adjacent road in contrast to unharvested stands with an adjacent, closed road ($\bar{x} = 7.7$ snags/ha, S.E. = 1.8).

Distance from the stand to nearest road (Nearest Road, Table 2) was one of two continuous variables in the top-ranked AIC models but accounted for little variation in density of all snag species ($r^2 = 0.04$, $P = 0.18$). However, when only pine or larch snags were considered, distance to nearest road accounted for statistically significant variation in snag density ($r^2 = 0.19$, $P = 0.002$).

4.5. *Nearest town*

Distance to nearest town explained little variation in mean density of all snag species (Nearest Town, $r^2 = 0.02$, $P = 0.315$), even though the variable was included in the top-ranked AIC models for all snag species. However, when the potential effect of timber harvest was removed by analyzing only unharvested stands, distance to nearest town accounted for substantial variation in mean density ($r^2 = 0.35$, $P = 0.004$).

4.6. *Slope direction*

Stands that were oriented downhill from the nearest road contained the highest mean density of snags of all species, followed by stands that were uphill (Slope Direction, Fig. 5). Stands on flat terrain contained the lowest mean density of snags.

Snag density of pine and larch also varied in the same manner in relation to slope direction from the nearest road (Fig. 5). Mean density was almost twice as high in stands oriented downhill from the nearest road compared to uphill stands, and >3 times higher than in flat stands (Fig. 5).

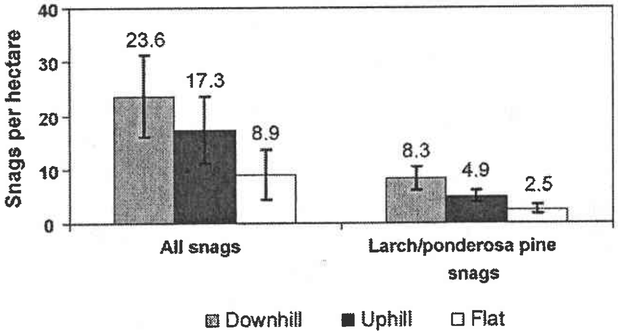

Fig. 5. Mean density of all snag species ≥23 cm dbh, and only ponderosa pine and western larch snags ≥23 cm dbh (±S.E.), in stands downhill from the nearest road, uphill from nearest road, or flat in relation to nearest road (Slope Direction variable, Table 2). Sample sizes are in parentheses.

4.7. *Adjacent ownership*

We found no difference in mean density of all snag species in stands surrounded by National Forest land ($\bar{x} = 15.9$ snags/ha, S.E. = 3.1) versus those adjacent to state-administered or private land ($\bar{x} = 15.6$ snags/ha, S.E. = 3.4). However, mean density was 50% higher in unharvested stands surrounded by National Forest ($\bar{x} = 31.4$ snags/ha, S.E. = 4.9) compared to those adjacent to other ownerships ($\bar{x} = 21.7$ snags/ha, S.E. = 3.9).

5. Discussion

5.1. *Inferring effects of explanatory variables*

Our results showed a remarkably strong relation between snag density and seral stage, timber harvest, and human access in pine and larch forests. Our results mirror those of Bate et al. (2007) in Oregon, where snag density declined with retrogression of seral stage, with intensive timber harvest, and with higher levels of human access. Variables that accounted for substantial variation in snag density in both study areas included seral stage; timber harvest; adjacent road; nearest town; adjacent ownership and slope direction. Moreover, because correlation among these explanatory variables was low, our results suggest that the variables operated independently of one another in their relations with snag density.

Notably, stands in both study areas with highest snag density had one or more of the following characteristics: (1) late-seral, (2) unharvested, (3) not adjacent to a road, (4) far from towns (all stands in Oregon and unharvested stands in Montana), (5) surrounded by National Forest land (all stands in Oregon and unharvested stands in Montana), and (6) downhill orientation from nearest road. By contrast, stands in both study areas with lowest snag density were (1) early-seral, (2) clearcut harvested, (3) adjacent to an open road, (4) close to towns (all stands in Oregon and unharvested stands in Montana), (5) adjacent to land ownership different than National Forest (all stands in Oregon and unharvested stands in Montana), and (6) on flat terrain in relation to nearest road.

These results, although correlative, were supported by additional findings from our study that suggested that these explanatory variables were operating in a cause-effect manner on snag density. For example, we found that mean snag density was 40% lower along the portion of transects within 50 m of an adjacent road ($\bar{x} = 6.9$ snags/ha, S.E. = 1.5) compared to the portion of transects >50 m from adjacent roads ($\bar{x} = 12.9$ snags/ha, S.E. = 2.3). We also found that 88% of unharvested stands that were adjacent to a road showed signs of cutting along the first 50-m portion of sampling transect from the road (using the same line transects and strip plots to record evidence of cutting that were used to count snags, as outlined in Methods). In the second sampling transect 50–100 m from the road, 48% of the unharvested stands had snags, trees or logs removed by cutting. This dropped to 22% along the third and fourth sampling transects that were >100 m from the nearest road.

By contrast, we found no signs of cutting in unharvested stands that had no adjacent road. Moreover, these stands, which had no direct road access and no signs of human entry, had an average of 37.3 snags/ha (S.E. = 8.8), the highest mean density that we documented for any analyses. Accordingly, the combination of reduced snag density and high frequency of non-commercial cutting along the edges of unharvested stands, when adjacent to a road, provides compelling evidence of cause-effect relations between increased human access and reduced snag density. Moreover, the strong relation observed between decreasing snag density and increasing intensity of timber harvest also suggests a cause-effect relationship, given the commercial value of some snags and strict regulations to remove snags deemed as safety hazards during logging operations (Wilhere, 2001).

Additional factors related to access, such as the stand's slope direction from nearest road, also provided evidence of cause-effect relations on snag density. Specifically, density was highest in stands located downhill from the nearest road, a condition that provides the greatest challenge to yarding of felled snags to roads, in contrast to stands of flat topography or uphill from a road.

One additional variable related to access—adjacent land ownership—provided intriguing results. Snag density was substantially lower in unharvested stands adjacent to private or other non-National Forest land versus unharvested stands surrounded by National Forest. This pattern could be attributed to state and federal safety regulations, which require that snags be felled in areas adjacent to stands undergoing timber harvest, even if the adjacent areas are of different land ownership. These regulations likely were relevant to private and state lands in our study area, because most of these non-federal lands underwent some form of timber harvest in the past. In addition, illegal harvest of snags for timber and firewood on National Forest land by adjacent landowners, given the facilitation of access to public land afforded by adjacent, private ownership, could also explain the reduced snag density in stands adjacent to non-federal lands.

5.2. *Background conditions and disturbances*

Our highest snag density ($\bar{x} = 37.3$ snags/ha, S.E. = 8.8) occurred in unharvested stands that had no adjacent roads. These stands reflect snag conditions for pine and larch forests in the absence of direct human disturbances. Consequently, this estimate of snag density may serve as useful background context for snag management in pine and larch forests like those we studied.

Harris (1999) also documented highest snag density in uncut pine and larch forests in western Montana, reporting a mean density of >25 snags/ha. Ganey (1999) documented a median snag density of 30 snags/ha in ponderosa pine forests in Arizona that were reserved from logging and unroaded, and a higher median snag density for unlogged versus logged areas. Although estimates from these studies are not directly comparable with our results, owing to different sampling methods and different methods and classes used to stratify data for analysis, the patterns indicate that snag density is substantially higher in the absence of direct human disturbances.

Higher snag density in the absence of direct human disturbances reflects the positive effects of prevalent background disturbances of wildfire, insects, disease, and drought, all of which serve to recruit snags in coniferous forests of western North America (Bull et al., 1997; Saab and Dudley, 1998; Chambers and Mast, 2005; Holden et al., 2006). Franklin et al. (2002) also noted the substantially higher snag abundance in unmanaged coniferous forests of western North America, using Douglas-fir (*Pseudotsuga menziesii*) forests as an example; they attributed lower snag abundance in managed forests to silvicultural practices that fail to mimic natural disturbance processes that recruit and maintain legacy structures such as snags. Wilhere (2001) explored the effects of current, industrial silvicultural practices on snag dynamics in Douglas-fir forests, and also concluded that such practices largely fail to recruit and maintain snags at densities like those in unmanaged forests. Our findings support the conclusions of Franklin et al. (2002) and Wilhere (2001) as applied to pine and larch forests.

5.3. Limits of inference

Our methods were designed to minimize inadvertent sampling of adjacent stands, and to minimize the edge effect of adjacent stands on our results. We did this by setting a minimum stand size of 6 ha for sampling. Larger stands are more buffered from the effects of roads and harvest activities in adjacent stands, and our results might be different for smaller stands.

Consequently, our results may not be applicable to smaller stands in more fragmented landscapes. For such stands, it may be difficult to define a "stand" or "patch," and a different sampling design may be needed. For example, it may be more desirable to sample smaller, fragmented patches in context with surrounding areas and seral conditions. That is, to sample a stand by seral stage, intensity of timber harvest, road adjacency, etc., but use conditions in adjacent stands as covariates. It is likely that conditions for such smaller stands are influenced substantially by adjacent stands and management, and thus the surrounding environmental context needs to be accounted for more explicitly in sampling design and analysis.

In addition, some of the inaccuracies of spatial data available from National Forests for snag analyses, as documented and described by Bate et al. (2007), posed initial problems for our study as well. Consequently, data on some explanatory variables obtained for stands from the Forest's spatial database had to be re-classified after our initial field visit, resulting in reduced sampling of some strata (Table 1). The coarse nature of existing spatial data for many National Forests points to the need to conduct extensive field checks of such data to minimize inaccuracies.

Finally, our results have obvious geographic limits of inference. Our study was conducted in one geographic area (western Montana), but our results were remarkably similar to those from northeast Oregon (Bate et al., 2007). These two study areas are >600 km apart, yet both studies took place in pine and larch forests on National Forest land. Consequently, our findings, combined with those from Oregon, indicate a geographic area of inference for results that includes pine and larch forests on National Forests throughout the interior northwestern United States (see states outlined in Fig. 1). These forest types encompass millions of ha within this geographic area. Additional studies are needed to understand whether our results also are common to pine and larch forests in other areas of western North America.

5.4. Management implications

In the context of our stated limits of inference, our results have compelling and direct implications for management. First, methods of intensive timber harvest must include more effective mitigations to meet snag objectives for wildlife. Safety regulations, requiring the felling of leaning or decadent snags before timber harvest, can be mitigated by establishing "no harvest" buffers around such snags, which often are the most valuable as wildlife habitat. Such "no harvest" buffers would essentially remove areas of important snag habitat from the timber harvest area, thereby increasing the chance that such snags can be retained. Additional green trees can also be retained during timber harvest, and then treated mechanically or biologically to create suitable snags for nesting and roosting wildlife (Lewis, 1998). This second mitigation, however, is extremely time-consuming and costly, and not an effective alternative to retention of adequate, existing snags (Lewis, 1998).

Second, access for firewood cutting must be managed effectively to mitigate snag loss in areas where snag standards are not met. In most cases, mitigation would involve road closures or obliterations immediately following road construction and use for timber harvest (most roads are built and used as haul routes for timber harvest and then left open). In addition, roads adjacent to unharvested stands would need to be closed or obliterated to prevent additional cutting of snags for firewood, if objectives are not being met in these stands for snag-dependent wildlife. Moreover, prohibition of salvage harvest in late-seral or unharvested stands is an important option to consider in tandem with road closures or obliterations adjacent to these stands.

Third, effects of adjacent, non-National Forest land must be considered when setting landscape objectives for snag-dependent wildlife. It appears unlikely that an optimal or higher snag density can be maintained in unharvested stands on National Forest land adjacent to private or other non-National Forest land. Consequently, recruitment and retention of higher levels of snag density may be required on other National Forest land, farther away from private or other non-federal ownerships, as compensation for snag loss adjacent to non-federal ownerships.

Snag management for wildlife is a complicated and challenging endeavor. Our results point to key factors directly related to, and that appear to affect, the density of snags in pine and larch stands in National Forests of the northwestern United States. Explicit and thoughtful consideration of these factors in snag management is imperative if objectives for snag-dependent wildlife are to be met in pine and larch forests. New forest management plans should outline how snag objectives will be met in relation to timber harvest and human access. Without such considerations and mitigations, it is likely that snag density will decline with additional timber harvest and increased access demanded by forest users.

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