



Snag densities in relation to human access and associated management factors in forests of Northeastern Oregon, USA

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Abstract

A key element of forest management is the maintenance of sufficient densities of snags (standing dead trees) to support associated wildlife. Management factors that influence snag densities, however, are numerous and complex. Consequently, accurate methods to estimate and model snag densities are needed. Using data collected in 2002 and Current Vegetation Survey (CVS) data collected in 1993–1996, we built models to explain variation in snag densities in northeast Oregon forests in relation to human access and associated management factors. Models that best explained snag densities differed between data sets. Top-ranking models built from 2002 data included intensity of timber harvest, distance to nearest town, and juxtaposition with roads. By contrast, models built from CVS data consistently included slope and dominant tree species. Although sample size with CVS data was 50% larger than that with 2002 data, precision of CVS models was consistently lower. Methods used to collect CVS data did not employ a stratified-random design to maximize precision and minimize bias. By contrast, stratified-random sampling used to collect 2002 data clearly demonstrated the importance of human access in explaining snag densities. We discuss implications for snag sampling, modeling, and management on national forests.

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1. Introduction

Large snags (standing dead trees) provide essential habitat for many terrestrial vertebrates (Thomas, 1979), including a number of species at high risk of extirpation in forests of the interior northwestern United States (Raphael et al., 2001). The presence of roads, however, can negatively affect the maintenance of snags. Snag densities are immediately reduced when forests are cleared during road building (Hann et al., 1997; Reed et al., 1996; Trombulak and Frissell, 2000). Roads also facilitate snag removal as part of timber harvest, safety management, and fuelwood gathering that follow establishment of road access (Hann et al., 1997). In addition, roads modify snag microclimate, which can increase rates of decay and fall, most obviously through increased exposure to wind. Consequently, understanding how snag densities vary in relation to

human access and associated management factors is essential to effective management of wildlife species that depend on snag habitat.

Historically, large-diameter western larch (*Larix occidentalis*) and ponderosa pine (*Pinus ponderosa*) (hereafter referred to as larch and pine) have been harvested because of their high timber and fuelwood values (Hann et al., 1997). These tree species also are among the most valuable for many wildlife species of conservation concern (Wisdom et al., 2000). Large-diameter larch and pine snags are strongly selected by many species of cavity-using wildlife because these snags provide some of the most suitable nest and roost sites, owing to the characteristics of the wood and its decay patterns (Bull et al., 1997).

In the past, firewood cutting of snags was constrained to areas close to roads. Now, however, many commercial firewood cutters use cable systems to harvest snags at long distances from access points. Harvest of snags at increasingly greater distances from roads raises the question: how far into forest stands do these effects extend? In addition, do we observe the same relationships when considering larch and pine snags, considered most

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important to many wildlife species, that we observe when considering all snag species? Distance from a road is likely a major factor, but other management factors may affect snag densities, such as history of timber harvest, seral stage, insect-caused mortality, and topographic constraints to access (Hann et al., 1997).

Although most resource specialists recognize that roads and related management factors can substantially reduce snag densities, no formal studies have quantified these relations. Findings from such research could be used to build landscape models to explain variation in snag densities based on distance to roads or other indices of human access in watersheds or other large areas used for management planning. These models would be useful for managing snags to meet multiple use goals related to fire, recreation, firewood gathering, timber harvest, and wildlife.

In response to this need, we collected data during summer 2002 to examine the relation of snag density to indices of human access and associated management factors in forests of northeastern Oregon. We also analyzed Current Vegetation Survey (CVS) data collected in 1993–1996 for the same area. CVS data are routinely collected by the USDA Forest Service on national forests to estimate and monitor forest characteristics of interest to management, including snag density (Johnson, 2002). We wanted to assess whether we could use the CVS data to strengthen the inference space of our field data and to compare and contrast our results with those from CVS data. Our objectives were to: (1) evaluate the relation between density of all snag species (>23 cm diameter breast height [dbh]; 1.8 m tall) and distance to roads and other indices of human access; (2) evaluate the relation between density of larch/pine snags and distance to roads and other indices of human access; (3) summarize results in a manner that facilitates the construction of models at landscape scales to reliably explain variation in density of snags in relation to roads and other indices of human access, given background topography, seral stage, forest type, timber management, and adjacent land ownership; and (4) examine similarities and differences in models developed from the 2002 data set and data collected by CVS crews in the 1990s.

Our study was designed to provide empirical and modeling support for the Inland Northwest Landscape Analysis System (INLAS). Key goals of INLAS are to develop science-based tools for landscape assessment of forest resources, and to demonstrate the application of those tools in forests of northeast Oregon, USA (Hayes et al., 2004). Our study supported these goals by: (1) evaluating the effectiveness of CVS data, collected on national forests across the northwest region of the United States, as a basis for landscape assessment of snags; (2) identifying the management factors that have most influence on snag densities; and (3) incorporating the most influential management factors in models to assess snag conditions under current and future management.

2. Methods

Our study took place in the upper Grande Ronde River basin (Fig. 1) and adjacent areas of the Wallowa-Whitman National Forest, northeast Oregon (Barbour et al., 2004). The 178,000 ha

area is dominated by dry- and mixed-conifer forests typical of the interior northwestern United States. See Barbour et al. (2004) for details of the study area.

2.1. Field sampling methods for 2002

Boundaries of more than 17,000 stands that composed the study area were delineated by using information on plant association and structural stage from the Forest Service stand exam database. Stands ranged from 1.3 to 44 ha. Mean stand size was 10.1 ha. No accuracy assessment was provided with stand exam data, and thus we corrected attributes of stands as needed during initial fieldwork.

Stands were linked to spatial data available from the Wallowa-Whitman National Forest to obtain information on roads, distance to nearest town, topography, and other spatial characteristics in relation to stand locations. These spatial data were subsequently incorporated into the INLAS database, which served as a common data source for INLAS research (Aitken and Hayes, 2006; Hayes et al., 2004) (Table 1). All spatial data were mapped at 1:24,000 and comply with National Map Accuracy Standards (precision and accuracy ± 12.2 m). We used Arc analysis software, ESRI Inc. (Version 9), for all spatial analysis.

We used stand exam and spatial data to select 102 stands for sampling in 2002. We limited sampling to stands containing a dominant component of larch or pine. These stands were targeted because they contained snags most important to both humans and wildlife. Larch and pine stands were selected by using a stratified-random design 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 (<30, 30–60, and >60 km) and slope (<15, 15–35, >35%). We stratified by seral stage because snag densities can vary strongly with succession (Hann et al., 1997). We stratified by juxtaposition to different road types, by distance to nearest town, and by slope because of the presumed strong influence of these factors on snag densities. Specifically, we anticipated that snag densities would decline closer to roads, closer to towns, and on gentle slopes. These stratifications thus allowed us to maximize precision of snag estimates in relation to these factors. In addition, only five stands with no history of timber harvest (unharvested stands) were available for sampling, and thus all five were selected to obtain baseline estimates of snag densities in the absence of timber harvest.

We used each stand as our sample unit (n). Within each stand, we randomly established transects perpendicular to the closest road, with each transect constituting a subsample. Transects within each stand were >50 m apart, parallel to each other, and the same length. Transects were one of four lengths depending on the size of the stand: 50 m ($n=16$ stands); 100 m ($n=19$); 150 m ($n=24$); or 200 m ($n=44$). For stands adjacent to a primary or secondary road, the starting point of each transect began at the edge of the road. For stands not adjacent to a road (>5 m away), transects were oriented away from the nearest road.

When visibility in a stand was impeded, we sampled snags along the transects with strip plots 20 m wide (Bate et al., 1999,

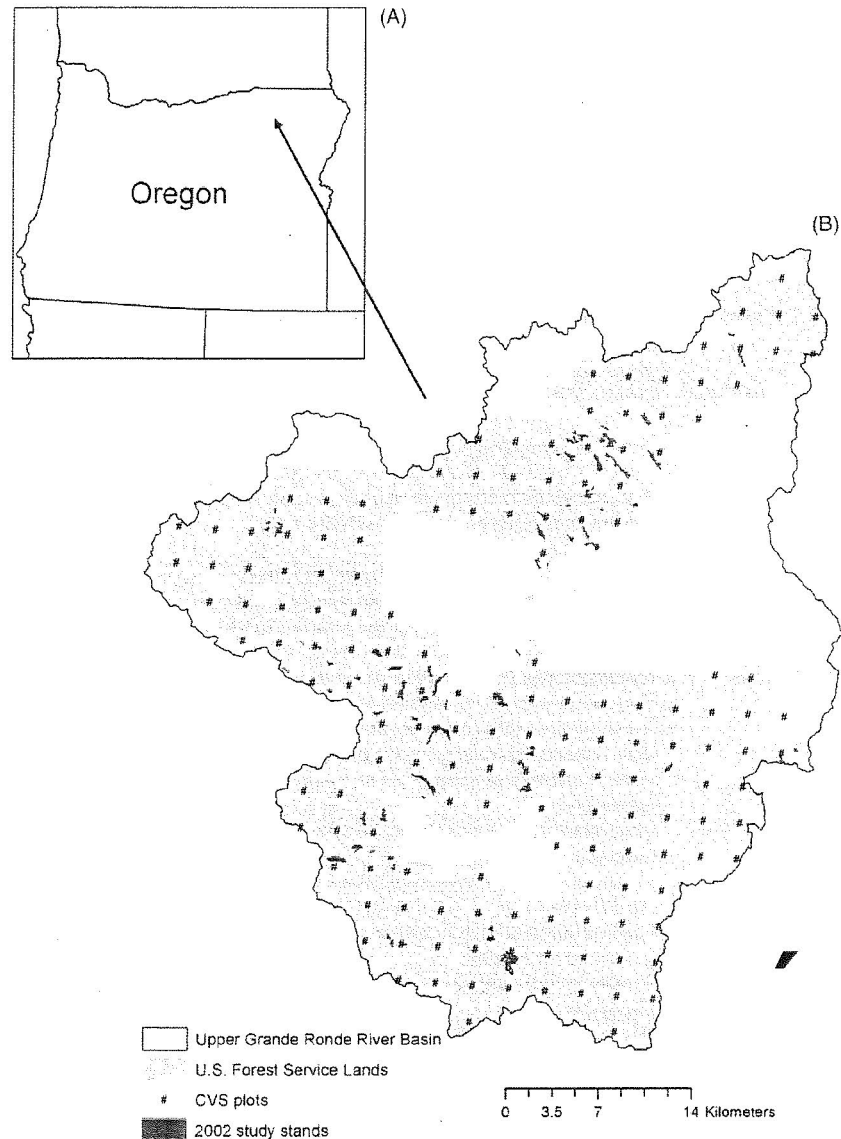


Fig. 1. Study area showing CVS plot locations, stands sampled in 2002, and Forest Service land. Land ownerships other than Forest Service (state, private, tribal, and USDI Bureau of Land Management) are shown in white.

2002). In open stands, we sampled along the transects with strip plots 40 m wide. All snags 2.23 cm dbh and >1.8 m tall were counted in each strip plot by using methods and sampling protocols of Bate et al. (1999). For each snag encountered we measured dbh, species, height, and distance from the nearest road.

2.2. Field sampling methods for CVS data, 1993–1996

We used CVS data collected from 1993 to 1996 at 152 plots in the study area for our second data set. All sample plots were systematically established on a grid pattern with plots 2.7 km apart (Johnson, 2002), as opposed to a random or stratified-random sampling design. Data collected at CVS plots followed sampling protocols outlined in Johnson (2002), which used a

nested design with five smaller subplots contained in one larger (1.2 ha) plot. All plots were circular. Subplot sizes were 0.02, 0.076, or 0.2 ha.

We converted numbers of snags in the CVS database to density (stems/ha), based on the area of the plot in which they occurred. We averaged the densities among all subplots to obtain a value for each CVS plot because subplots were not statistically independent. We then used the mean snag density as our dependent variable. The stands associated with each CVS plot were treated as our sample unit for analysis. Each stand was linked to the same databases used for analysis of 2002 data to obtain information on CVS stands in relation to forest type, seral stage, history of timber harvest, juxtaposition to different road types, topography, and other management factors of interest, described as follows.

Table 1

Vegetation, topographic, and road variables considered for inclusion in global models to explain snag density in relation to human access and other management factors

Database where used	Variable	Type	Definition	Derivation
Both	Adj_Land	Categorical	Ownership of land surrounding stand: (1) exclusively Forest Service (FS) and (2) non-Forest Service lands adjacent to stand on at least one side (other)	INLAS ^a database and GIS coverages ^b
	Comboroad	Categorical	Road category for stand: (1) adjacent to open road; (2) adjacent to closed road; (3) not adjacent to (>5 m from) any road	INLAS database and GIS coverages
	Combo_2	Categorical	Road category for stand: (1) adjacent to any kind of mapped road and (2) not adjacent to (>5 m from) any road	INLAS database and GIS coverages
	ForestCode	Categorical	Stand cover type: (1) larch; (2) pine; (3) mixed conifer ^b	2002: Forest Service stand exam database; CVS ^c : FVS ^d , basal area, or photo interpretation
	Seral	Categorical	Structural stage: (1) early; (2) mid; (3) late seral	2002: Forest Service stand exam database; CVS: FVS, basal area, or photo interpretation
	Town	Continuous	Distance (km) from edge of stand where entered for 2002 data or polygon center to nearest town along roads for CVS data	INLAS database and GIS coverages
	Treatment	Categorical	Harvest history: (1) intensive—stands that had been intensively harvested with procedures such as clearcut harvests, or a seedtree or shelterwood harvest followed by overstory removal; (2) moderate—stands that had undergone a seedtree or shelterwood harvest with no subsequent overstory removal, or stands that had been partially harvested for disease or insect control; (3) light—stands unharvested or only lightly harvested, such as commercial thinning, for the purpose of timber production ^a	2002: Forest Service stand exam database; CVS: Oregon/Washington dead wood database ^e
	Closeddirt	Continuous	Straight air distance (km) from edge of stand to nearest mapped road	Field survey or INLAS database and GIS coverages
	Cuttrees	Categorical	Evidence along each transect of cut stumps or logs: (0) no and (1) yes	Field survey
	Direction	Categorical	General direction of road in relation to stand: (1) flat; (2) uphill; (3) downhill	Field survey
2002	Maproad	Continuous	Distance (m) from edge of 50 m section to nearest mapped road	Field survey or INLAS database and GIS coverages
	Opendirt	Continuous	Straight air distance (m) from edge of stand to nearest open road	Field survey or INLAS database and GIS coverages
	Toposlope	Continuous	% Slope of ground where sampled along transect	Field survey
	Translope	Continuous	% Slope of steepest pitch of ground beside transect if different than along transect	Field survey
	Unmaproad	Continuous	Distance (m) from edge of 50 m section to nearest mapped or unmapped road	Field survey or INLAS database and GIS coverages
	Anyroad	Continuous	Straight air distance (m) from CVS plot center to nearest mapped road	INLAS database and GIS coverages
	Nearestroad	Continuous	Straight air distance (m) from center of stand in which CVS plot was contained to nearest mapped road	INLAS database and GIS coverages
	Opendistance	Continuous	Straight air distance (m) from CVS plot center to open road	INLAS database and GIS coverages
	Slope	Continuous	Mean % slope of stand where CVS plot was located	INLAS 30 m digital elevation model
CVS				

^a INLAS: Inland Northwest Landscape Analysis System (Aitken and Hayes, 2006; Hayes et al., 2004).

^b For our 2002 data we only used pine and larch stands.

^c CVS: Current Vegetation Survey (Johnson, 2002).

^d FVSL: Forest Vegetation Simulator (Ager, 2004).

^e Ohmann and Waddell (2002) and Rose et al. (2001).

2.3. Timber harvest and vegetation variables

We derived several variables to assess management factors that may influence snag densities (Table 1). For 2002 data we used the Forest Service stand exam database to obtain infor-

mation on history of timber harvest, referred to as Treatment variable. We used three categories of the Treatment variable for regression modeling: light, moderate, or intensively harvested (Table 1). Unharvested stands ($n = 5$) were included in the lightly harvested treatment category and were used as a background ref-

erence for snag densities in stands that showed no signs of timber harvest, human access, or other management activity.

We corrected the Treatment variable after field assessments indicated several inaccuracies in 2002 data. We estimated that about 40% of the stands were incorrectly classified using data on harvest history provided by the stand exam database. Information on harvest history was not included in the CVS database and ground truthing was not possible given budget and time constraints. Therefore, we linked each plot to the Oregon/Washington dead wood database (Ohmann and Waddell, 2002; Rose et al., 2001) to categorize harvest treatments for each CVS plot within our stands.

We also assigned each stand to a ForestCode, or dominant tree cover type (Table 1). For 2002 field work, only stands that contained a dominant cover of larch or pine were considered. Stands with at least 20% basal area in larch or pine were classified as one of these two forest types based on Forest Service stand exams. For analysis of CVS data, stands were classified as larch, pine, or mixed conifer. For the majority of CVS plots, we obtained dominant cover type information by using the Forest Vegetation Simulator (FVS) (Ager, 2004). For the remaining plots, the dominant cover type was classified as larch or pine if these trees had at least 20% basal area, and mixed conifer otherwise. Stands classified as mixed conifer were dominated by Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), or subalpine fir (*Abies lasiocarpa*).

Each stand was identified as one of three seral stages (Seral, Table 1) based on the size class of dominant trees. Decision rules for seral stage followed the Timber Management Control Handbook of the Forest Service (USDA Forest Service, 1996) for size classes:

1. Early seral (seedling or sapling): Stands at least 10% stocked with trees of any size, in which the stand size class is neither pole timber nor saw timber (neither of next two classes). Seedlings are generally <2.5 cm dbh and saplings generally 2.5 to <12.7 cm dbh.
2. Mid-seral (pole timber): Stands at least 10% stocked with trees 12.7 cm dbh and larger, in which the stocking of trees 12.7 to <23 cm dbh exceeds the stocking of trees 23 cm dbh and larger.
3. Late-seral (saw timber): Stands at least 10% stocked with trees 12.7 cm dbh and larger, in which the stocking of trees 23 cm and larger is at least equal to the stocking of trees 12.7 to <23 cm.

For 2002 data, we obtained seral class information from Hemstrom et al. (2007), who classified each stand into a structural stage based on photo interpretation. Structural stages were then combined into one of the three seral classes. For CVS data, we obtained seral class information in one of three ways, as no single data set provided information for all stands containing CVS plots. The first method was based on a classification produced by the Forest Vegetation Simulator (Ager, 2004). The majority of stands associated with CVS plots were classified by using this approach. The second method was the same used with

2002 data (Hemstrom et al., 2007). The third approach relied on CVS tree data. With this approach we calculated tree densities and mean diameters in the three size classes listed above.

To help assess whether snag densities were influenced by timber harvest or firewood collection, we also recorded the presence of cut stumps or sawed logs for each transect sampled during 2002 fieldwork (Cuttrees). Recording this information allowed us to compare snag densities between harvested and non-harvested stands.

2.4. Human access variables

Spatial data on roads and access were obtained from the Wallowa-Whitman National Forest database described earlier. Road coverage included all primary and secondary roads in the study area, as well as most primitive roads, per road definitions used by the Forest Service (Aitken and Hayes, 2006; Rowland et al., 2004). Also included were highways and major roads on private lands in the study area.

To evaluate the influence of human population centers and roads on snag densities, we used the database and field data to derive several distance variables of human access. First, we calculated the distance from each stand sampled during 2002 fieldwork, or stand containing a CVS plot, to the nearest town (Town, Table 1). A town was defined as any human population center of at least 1000 inhabitants. This variable was expressed as the driving distance on travelable roads from nearest town to the stand.

For both the 2002 field data and CVS plots, each stand was assigned to one of three road categories (Comboroad): (1) adjacent to an open road; (2) adjacent to a closed road; or (3) not adjacent to any road (Table 1). An open road was defined as any road that was open seasonally or year-round. A closed road was defined as any road where vehicle travel was impeded because of a permanent gate, dirt berm, large rocks, or was overgrown with vegetation. To test whether there was a difference between open and closed roads, we also aggregated stands into one of two categories based on their juxtaposition to a road (Combo 2): (1) adjacent to any kind of road and (2) not adjacent to any road. A stand was considered adjacent to a road if the distance between the stand and the road was <5 m.

For 2002 data, we derived four continuous variables that measured the distance of each stand to road types: (1) nearest closed dirt road (Closeddirt); (2) nearest open dirt road (Opendirt); (3) nearest mapped road (Maproad); and (4) nearest unmapped road (Unmaproad) (Table 1). These distances were measured in the field when the nearest road to each stand could be identified. When we were uncertain about distance to nearest road type, we measured the distance by using INLAS spatial data.

For CVS data, we derived three variables of distance to roads (Table 1). The first variable measured the distance from the center of the stand to the nearest road regardless of where the CVS plot was positioned within that stand (Nearestroad). The second variable measured the distance from the CVS plot center to the nearest road (open or closed) (Anyroad). The third variable measured the distance from the CVS plot center to the nearest open road (Opendistance).

2.5. Topographic variables

Topographic slopes in 2002 fieldwork were measured along each transect and averaged for each stand (Translope, Table 1). We also derived a slope variable by using measurements taken along the steepest part of the transect (Toposlope, Table 1). We calculated slopes for CVS stands by using a 10 m digital elevation model (DEM). Slope values from the DEM were averaged across each stand (Slope).

We also analyzed 2002 data as to whether snag density changed with direction that a stand sloped away from the nearest road (Direction). This variable was examined because the orientation of slope (up or down) from the road may affect the ease with which cable yarding of snags could be achieved.

2.6. Adjacent land ownership

One additional variable was developed for both data sets, Adj.Land. This variable identified whether: (1) the stand was completely surrounded by other Forest Service land or (2) the stand had non-Forest Service land adjacent on at least one side. For stands adjacent to non-Forest Service land, the adjacent ownership was private, tribal, or administered by the state of Oregon or USDI Bureau of Land Management (Table 1). In nearly all cases, the adjacent, non-Forest Service ownership consisted of private land.

2.7. Analysis offield samples

We used general linear models (GLM), correlation matrices, means, and standard errors to evaluate the relation between mean snag density and the management factors (variables) listed above. All statistical analyses were conducted with SYSTAT (Version 10.2.05, 2002). We estimated snag density for each stand and used the stand as our sampling unit ($n = 102$ for 2002 data; $n = 152$ for CVS data). All results refer to snags >23 cm dbh and > 1.8 m tall. Density was expressed as the number of snags/ha for each stand, with mean density calculated among stands.

We used the data sets to first develop global regression models to evaluate comprehensive sets of variables to explain variation in snag density. Global models contained variables identified by Hann et al. (1997) and Wisdom et al. (2000) as affecting snag density. For each data set, one global model was based on snags of all species because most Forest Service plans set snag guidelines for all species combined. A second global model included larch and pine snags only, as these two species are most important in the northwestern United States for fuelwood and merchantable lumber and for wildlife as snag habitat (Bull et al., 1997).

We controlled for multicollinearity among continuous variables by first examining Bonferroni adjusted P-values. When two or three explanatory variables were highly correlated, we conducted multiple tests to determine which had the most explanatory power for the given data set and only included this variable in our global model.

We used the GLM procedure to evaluate all possible models containing subsets of the explanatory variables in the global

model. The number of models (M) evaluated for each subset of variables was based on the following equation:

$$M = 2^n - 1$$

where n is the number of explanatory variables in the global model.

To further ensure that explanatory variables within models were not correlated, we evaluated tolerance values, which measure the correlation of the candidate variable with all other variables. Tolerance ranges from 0 to 1. Low tolerance (<0.1) indicates that a variable is nearly predicted by other variables and should be excluded. In these instances the variable with lowest tolerance was removed. The model that had the highest coefficient of determination (R^2), while minimizing the mean-square error (MSE), maximizing the tolerance values, and containing the fewest variables, was considered the best or top-ranking model.

In addition to our evaluation of top-ranked models, we hypothesized that snag density would vary strongly by type of forest stand, history of timber harvest, seral stage, distance to road type, and the land ownership adjacent to stands. We specifically hypothesized that snag density would be lower in pine versus larch or mixed-conifer stands, with increasing intensity of timber harvest, at younger stages of seral development, when roads were adjacent to stands, especially open roads, and when stands were adjacent to non-Forest Service lands. Consequently, we calculated means and standard errors to evaluate class differences for each of these variables. We also conducted one set of a posteriori t -tests to understand differences in slope direction in relation to results for originally derived classes of this variable.

Forests in northeastern Oregon experienced high snag recruitment during the past 15–20 years because of an outbreak of spruce bud worm (*Choristoneura occidentalis* Free.) in the late 1980s and early 1990s (Sheehan, 1996). Densities of grand fir and Douglas-fir snags were high in some stands, creating high variance in our mean snag densities. Therefore, all snag densities were " $\log y + 1$ " transformed, which normalized the variance and residuals.

3. Results

3.1. Top-ranking models

The top-ranking regression model built from 2002 data explained more variation ($R^2 = 0.440$) in snag density of all species than top-ranking models built from either the full CVS data set (larch, pine, and mixed-conifer stands, $R^2 = 0.353$) or the subset of CVS data for stands classified as pine or larch ($R^2 = 0.383$) (Table 2). The top-ranking model built from 2002 data also had a lower mean-squared error than the full and subset CVS data sets, and retained the smallest percentage of explanatory variables initially considered in global models (Table 2). The top-ranking regression models from 2002 data and full CVS data sets for all snag species had four explanatory variables in common: Adj.Land, Comboroad, ForestCode, and Treatment. ForestCode and Treatment were the only explanatory variables

Table 2

Variables included in global regression models and those selected for top-ranked models to explain variation in density of all snag species in upper Grande Ronde River basin when using 2002 data and CVS data (n = number of stands sampled)

Data set	Variables evaluated in global model	Variables included in top model	Partial F statistic	Tolerance	Number of models evaluated	R^2 (mean-squared error)
Field data, 2002 ^a ($n = 102$)	Adj_Land	Adj_Land	2.2	0.93	255	0.440 (1.398)
	Comboroad	Comboroad	1.3	0.68		
	Direction	ForestCode	12	0.91		
	ForestCode	Treatment	6.7	0.67		
	Maproad	Town	15.9	0.85		
	Seral					
	Town					
CVS data, 1993–1996 ($n = 152$)	Adj_Land	Adj_Land	1.9	0.94	127	0.353 (1.902)
	Anyroad	Anyroad	3.8	0.5		
	Comboroad	Comboroad	2.6	0.54		
	ForestCode	ForestCode	9.1	0.61		
	Seral	Seral	3.7	0.54		
	Slope	Slope	8.7	0.79		
	Treatment	Treatment	3.3	0.4		
CVS data, 1993–1996 ($n = 106$) ^a	Adj_Land	ForestCode	19.7	0.8	63	0.383 (1.812)
	Anyroad	Seral	5.1	0.57		
	ForestCode	Slope	5.8	0.9		
	Seral	Treatment	2.6	0.38		
	Slope					
	Treatment					

^a Only includes stands containing a dominant component of larch or pine trees.

shared by the top-ranking regression models for the 2002 and subset CVS data sets (Table 2).

More variation in density of larch and pine snags also was explained by the top-ranking model from 2002 field data

($R^2 = 0.351$) than from the full ($R^2 = 0.263$) or subset CVS data ($R^2 = 0.210$) (Table 3). The best model developed from the three data sets explained less variation in density of larch and pine snags than did corresponding models for all snag species

Table 3

Variables included in global regression models and those selected for top-ranked models to explain variation in density of larch and pine snags in upper Grande Ronde River basin when using 2002 data and CVS data (n = number of stands sampled)

Data set	Variables evaluated in global model	Variables included in top model	Partial F statistic	Tolerance	Number of models evaluated	R^2 (mean-squared error)
Field data, 2002 ^a ($n = 102$)	Adj_Land	Adj_Land	4.9	0.93	127	0.351 (0.895)
	Comboroad	Comboroad	2.3	0.66		
	ForestCode	Town	5.2	0.87		
	Seral	Treatment	6	0.66		
	Town	Unmaproad	2.5	0.79		
	Treatment					
	Unmaproad					
CVS data, 1993–1996 ($n = 152$)	Adj_Land	ForestCode	10.7	0.66	127	0.263 (1.287)
	Anyroad	Seral	9.4	0.62		
	Comboroad	Slope	4	0.98		
	ForestCode					
	Seral					
	Slope					
	Treatment					
CVS data, 1993–1996 ($n = 106$) ^a	Adj_Land	ForestCode	2.4	0.9	127	0.210 (1.481)
	Anyroad	Seral	9	0.62		
	Comboroad					
	ForestCode					
	Seral					
	Slope					
	Treatment					

^a Only includes stands containing a dominant component of larch or pine trees.

(Tables 2 and 3). Top-ranking models for larch and pine snags contained many of the same variables as the top-ranking model for all snag species. For example, using the full CVS data set, the model for larch and pine snags contained ForestCode, Seral, and Slope, whereas the model for all snag species also contained Anyroad, Comboroad, and Treatment. Models developed for larch and pine snags from 2002 data and the full CVS data shared no variables.

3.2. Explanatory variables

3.2.1. Forest type

Whether a stand was classified with a dominant cover type of larch or pine (ForestCode) was the most important categorical variable in explaining variation in density of all snag species using 2002 data (Table 2). Mean snag density in larch stands was twice as high as that found in pine stands (Fig. 2A). The variable ForestCode was not included in the top model for larch/pine snags (Table 3) using 2002 data, likely because mean larch/pine snag densities were similar between forest types (Fig. 2A).

The variable ForestCode was most important in explaining snag density with CVS data (Table 2). Compared to pine stands, snag density was about three times greater in mixed-conifer forests and about four times greater in larch stands (Fig. 2B). When considering only larch or pine snags, the variable ForestCode again was the most important categorical variable for CVS data (Table 3). Mean snag density in larch stands was about three times that found in pine stands and six times that observed in mixed-conifer stands (Fig. 2B).

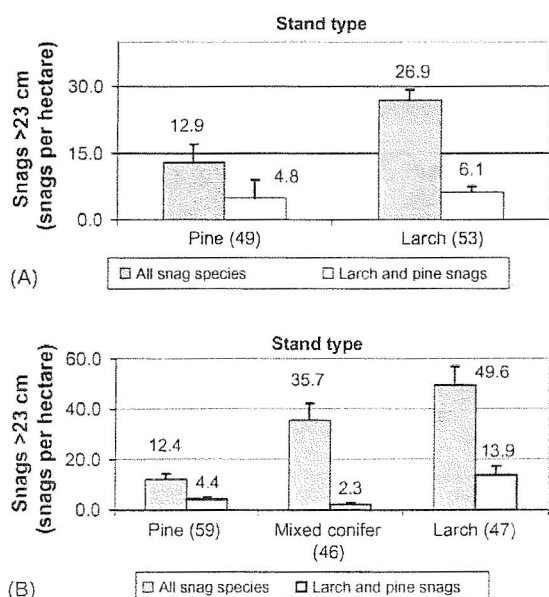


Fig. 2. Mean number of snags per hectare (+S.E.) for all snag species vs. larch and pine snags only, as estimated in three types of stands: (1) pine; (2) larch; and (3) mixed conifer. Data were collected on the upper Grande Ronde River basin in 2002 (A) or following CVS protocol in 1993–1996 (B). Sample sizes are in parentheses.

3.2.2. Timber harvest

The intensity of timber harvest (Treatment) was the second-most important categorical variable for explaining density of all snag species with 2002 data (Table 2). In lightly harvested stands, mean snag density was approximately four times greater than in stands that had undergone intensive harvest. Stands classified as moderately harvested supported about one-third the density found in lightly harvested stands (Fig. 3A).

The variable Treatment also was included in the top-ranking model for all snags with CVS data (Table 2). Stands that had undergone intensive timber harvest had one-third the snag density of moderately harvested stands and about one-fifth that of lightly harvested stands (Fig. 3B). Only 12 of 152 (8%) stands, however, were classified as intensively harvested with the Oregon/Washington dead wood database (Ohmann and Waddell, 2002; Rose et al., 2001).

When considering only larch/pine snags using 2002 data, Treatment variable was most important in explaining density (Table 3). Difference in mean density between lightly and intensively harvested stands was greater with larch and pine snags compared to all snag species. Lightly harvested stands supported about six times as many larch/pine snags compared to intensively harvested stands (Fig. 3A).

The variable Treatment was not selected in the top model to explain density of larch or pine snags using CVS data (Table 3). Intensively harvested stands had a mean density of 3.4 snags/ha. Moderately harvested stands contained 5.6 snags/ha, and lightly harvested stands had 9.7 snags/ha (Fig. 3B).

3.2.3. Seral stage

Mean snag density differed among seral stages with 2002 data (Fig. 4A). Seral stage, however, was correlated with Treat-

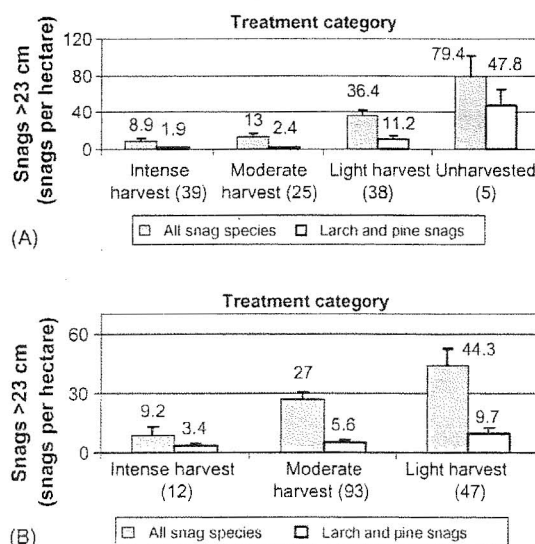


Fig. 3. Mean number of snags per hectare (+S.E.) for all snag species vs. larch and pine snags only in stands that had undergone different levels of timber harvest. Data were collected on the upper Grande Ronde River basin in 2002 (A) or following CVS protocol in 1993–1996 (B). Sample sizes are in parentheses.

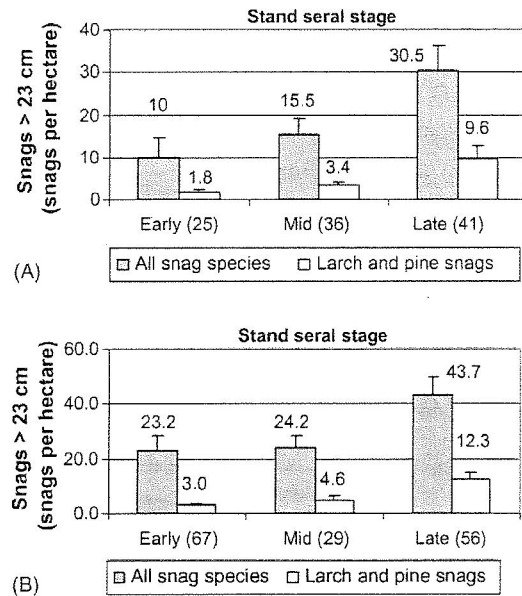


Fig. 4. Mean number of snags per hectare (+S.E.) for all snag species vs. larch and pine snags in early-, mid-, and late-seral stands. Data were collected on the upper Grande Ronde River basin in 2002 (A) or following CVS protocol in 1993–1996 (B). Sample sizes are in parentheses.

ment (Spearman's rank order correlation coefficient: $r_s = 0.65$), and Treatment was the better variable in explaining snag density.

By contrast, Seral stage was not correlated with Treatment with CVS data (Spearman's rank order correlation $r_s = 0.075$) and was selected in the top model with six other variables (Table 2). Early and mid-seral stands had similar snag densities (Fig. 4B). Late seral stands averaged about twice the density of snags as that in early or mid-seral stands (Fig. 4B).

Seral stage was not included in the top model to explain density of larch/pine snags with 2002 data (Table 2). Mean density of larch/pine snags, however, increased with age of stands (Fig. 4A). With CVS data, Seral stage was one of three selected variables to explain density of larch/pine snags (Table 3). Late seral stands averaged about three times as many larch/pine snags as mid-seral stands and four times as many as early seral stands (Fig. 4B).

3.2.4. Distance to nearest town

Distance to nearest town (>1000 inhabitants) was the most important variable in explaining density of all snag species when using 2002 data, with snag density increasing with distance to nearest town (Table 2). By contrast, we observed no relation between snag density and distance to nearest town with CVS data ($R^2=0.0$; $F_{1,150}=0.0$; $P=0.985$).

Distance to nearest town also was the most important variable in explaining density of larch/pine snags with 2002 data (Table 3). As with the model for all snag species, density of larch/pine snags increased with increasing distance to nearest town. By contrast, we observed no relation between larch/pine snag density with distance to nearest town with CVS data ($R^2=0.001$; $F_{1,150}=0.18$; $P=0.671$).

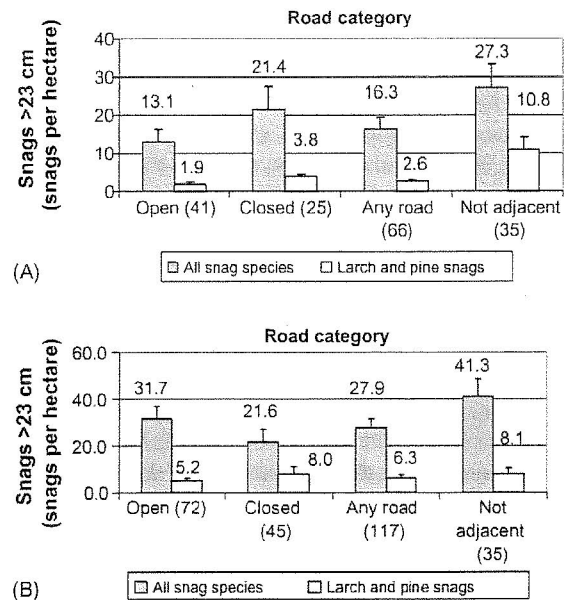


Fig. 5. Mean number of snags per hectare (+S.E.) for all snag species vs. larch and pine snags only in stands adjacent to open roads, adjacent to closed roads, adjacent any road (open or closed), or not adjacent to a road. Data were collected on the upper Grande Ronde River basin in 2002 (A) or following CVS protocol in 1993–1996 (B). Sample sizes are in parentheses.

3.2.5. Juxtaposition to different road types

Although Comboroad was selected in the top-ranking model with 2002 data, it contributed less to explaining variation in snag density than any of the other four retained variables (Table 2). When we evaluated stands adjacent to different road types, we found that stands adjacent to any road type averaged 11 fewer snags/ha than stands not adjacent to a road. Similarly, stands adjacent to open roads had less than half the snags found in stands not adjacent to roads (Fig. 5A). The trend was the same in stands adjacent to closed roads, where snag density averaged about 8 snags/ha less in stands adjacent to open roads compared to stands adjacent to closed roads.

The variable Comboroad also was included in the top model with CVS data (Table 2). Unlike results from 2002 data, however, stands adjacent to closed roads had the lowest snag density (Fig. 5B). Mean density between open and closed roads, however, was not significantly different. Snag density in stands adjacent to any kind of road had fewer snags compared to densities in stands not adjacent to a road (Fig. 5B).

When considering only larch and pine snags with 2002 data, Comboroad was again selected as a variable in the top model but contributed the least among retained variables (Table 3). Larch and pine snags were twice as abundant in stands adjacent to closed roads compared to stands adjacent to open roads (Fig. 5A). In stands not adjacent to any road, snag density was about four times greater than in stands positioned alongside a road.

The variable Comboroad was not selected in the model to explain density of larch/pine snags using CVS data (Table 3). Stands along closed roads and stands not adjacent to a road supported the same number of larch/pine snags (Fig. 5B). Larch/pine snag density in stands adjacent to any type of road

was not significantly different from that in stands not adjacent to a road.

3.2.6. Continuous road variables

The four continuous road variables (Opendirt, Closeddirt, Maproad, Unmaproad) were correlated in the analysis of 2002 data (r values ranged from 0.308 to 0.999; $P < 0.1$). Initial analysis showed that Maproad explained the most variation in snag density ($r = 0.188$; $P = 0.058$) among the four variables and so was included in our global model (Table 2). It was not, however, included in the top-ranking model.

In the global model for larch/pine snags using 2002 data, initial analysis showed that Unmaproad explained the most variation in snag density among the four continuous road variables, and thus was included in the global model (Table 3). Unmaproad also was retained in the top-ranking model for larch/pine snags ($r = 0.302$; $P = 0.002$).

The three continuous road variables available for the CVS data (Table 1) were also correlated (r values ranged from 0.392 to 0.887; $P < 0.001$). Of these three variables, initial analysis showed that Anyroad explained the most variation ($r = 0.254$; $P = 0.009$). Consequently, Anyroad was included in global models to explain density of all snags and larch/pine snags, and also was included in the top model for all snag species (Table 2). Mean snag density increased with increasing distance from any road. By contrast, we observed no relation between larch/pine snags and the distance to any road ($r = 0.083$; $P = 0.932$).

3.2.7. Topographic variables

Among the three topographic variables evaluated with 2002 data, Toposlope explained the most variation in density of all snags, but the relationship was weak ($R^2 = 0.049$; $F_{1,100} = 5.1$; $P = 0.026$). Considering only larch/pine snags, we observed no significant ($P > 0.10$) relationships between topographic variables and density of larch/pine snags with 2002 data. By contrast, the variable Slope was the second strongest variable in explaining density of all snags when using CVS data, with snag density increasing with slope (Table 2). Slope also was included in the top model for larch/pine snags with CVS data (Table 3).

Mean snag density also did not differ between flat versus stands upslope from the nearest road with 2002 data (Direction variable) (t -test, mean difference = 2.2 snags/ha; $t_{77} = 0.43$; $P = 0.67$). Consequently, we combined these data and found that stands oriented downhill from the nearest road had more snags/ha (37.8 snags/ha) than stands on flat ground or oriented uphill from the nearest road (15 snags/ha) (z -test, mean difference = 22.8 snags/ha; $two = 2.4$; $P = 0.023$).

3.2.8. Land ownership

Ownership of land surrounding a stand (Adj.Land) ranked fourth among variables in explaining density of all snags with 2002 data (Table 2). Although only eight of our stands were located adjacent to private or other non-Forest Service lands, snag density in these stands was about one-seventh the density found in stands completely surrounded by other Forest Service stands (Fig. 6A). Stands adjacent to non-Forest Service lands were a mixture of treatment categories and seral stages.

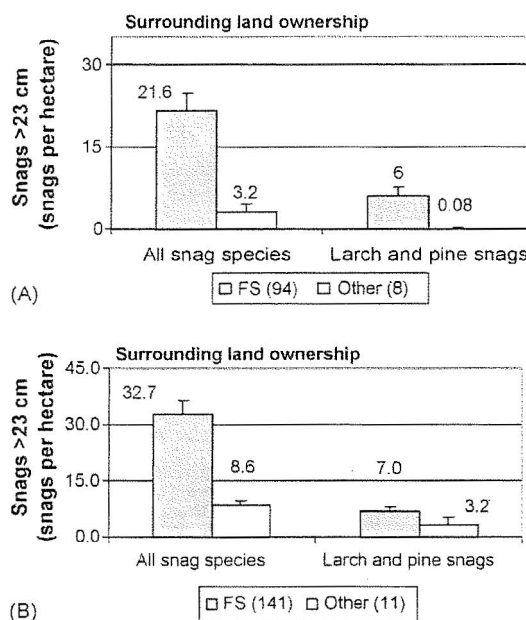


Fig. 6. Mean number of snags per hectare (+S.E.) for all snag species vs. larch and pine snags in stands completely surrounded by USDA Forest Service land (FS) vs. stands adjacent to non-Forest Service lands on at least one boundary (other). Data were collected on the upper Grande Ronde River basin in 2002 (A) or following CVS protocol in 1993–1996 (B). Sample sizes are in parentheses.

With CVS data, density of all snag species also was explained by the Adj.Land variable (Table 2). Stands surrounded by Forest Service land contained about four times the mean density of snags as compared to stands adjacent to non-Forest Service lands (Fig. 6B).

The variable Adj.Land was the third most important variable in explaining density of larch/pine snags with 2002 data (Table 3). Density of larch/pine snags were 75 times higher in stands surrounded only by Forest Service land compared to stands adjacent to private or other non-Forest Service lands (Fig. 6A). With CVS data, landownership was not important in explaining density of larch/pine snags (Table 3 and Fig. 6B).

4. Discussion

4.1. Interpreting results from 2002 data versus CVS data

Our results demonstrate how sampling design and methods used to estimate snag density and associated management factors affect results. Models that best explained snag density differed, both in the explanatory variables and the strength of association, depending on which data set we used.

The 2002 data set was based on stratified-random sampling. Under this design, all (>17,000) stands in the upper Grande Ronde River basin were stratified based on varying levels of seral stage, juxtaposition to roads, distance to nearest town, and slope. We randomly selected stands for sampling from these strata, maintaining relatively equal sample sizes across strata. This process ensured that precision of snag estimates was maximized in relation to the management factors (explanatory variables) of

interest. Random selection of stands within these strata further ensured that resulting estimates were unbiased.

By contrast, CVS plots were selected systematically and non-randomly by using a grid, resulting in uneven sample sizes across the strata of interest. Lack of stratification of CVS samples resulted in low precision (high variance) in estimates of snag density in relation to human access and other management factors. Sample size associated with CVS data was >50% higher than that for the 2002 data, yet precision in snag estimates was substantially lower than with 2002 data. Thus, CVS data apparently had lower statistical power to detect differences in snag density among the management factors of interest. We believe these problems account for the weak relations observed between snag density and most variables of human access with the use of CVS data. In addition, CVS data were analyzed in the form provided by the Forest Service, and possible inaccuracies in these data also may have contributed to low precision of estimates.

The difference that stratification made between the two data sets in relation to human access variables is illustrated by results for distance to nearest town. We observed a positive relationship with both data sets between snag density and distance to towns up to 60 km, but snag density declined beyond 60 km with CVS data whereas snag density continued to increase at longer distances with 2002 data. We observed that nine stands >60 km from town were classified as lightly harvested, late seral, and not adjacent to roads with 2002 data, but only one stand in the CVS data set met these same criteria. Lack of stratification with CVS data thus resulted in large sample sizes within some stratum and small sample sizes in others. We observed similar problems in the location of CVS sample plots in relation to the other road variables. CVS plots were not located along a gradient of distances from roads of different types, thus limiting the degree to which variation in snag density could be evaluated with variation in distance to roads.

An exception to the pattern of more variation explained by variables in snag models built from 2002 data was observed with topographic factors. Slope was a strong explanatory variable for snag density with CVS data, but not with 2002 data. However, in a subsequent analysis with 2002 data, snag density was substantially lower in stands that were flat or uphill in relation to the nearest road. This result was similar to findings with CVS data, where snag density was lowest on flat slopes and increased steadily with increasing slope. If firewood gathering affects snag density, one would expect lower density in stands on flatter slopes or uphill from roads, because yarding or hauling of snags for firewood is easiest when material is on gentle slopes or can be moved downhill. Results from both data sets, considered together, supported this expectation.

Differences in plot shape and size also likely influenced the precision of estimates. The 2002 data were collected on rectangular plots that ranged in length from 50 to 200 m. CVS sampling used circular plots nested within one another that varied in size. In collecting the 2002 data, we encountered 1281 snags >23 cm dbh and >1.8 m tall in 102 stands. In the CVS data, 997 snags of the same size were encountered in 152 stands. With 2002 data, 75% of all snags encountered were in stands

that contained 0.8 ha sample plots. By contrast, 69% of all snags encountered on CVS plots were on plots only 0.076 ha, about 1/10 the plot area sampled during 2002 fieldwork.

Bull et al. (1990) showed that it was difficult to obtain precise and unbiased estimates of snags with small plots unless very large, often prohibitive sample sizes were obtained. Krebs (1989) summarized research findings regarding plot shape, which showed that rectangular or strip plots perform better than circular or square plots for sampling habitat structures with clumped distributions such as snags.

In addition to the problem of imprecise estimates associated with CVS data, the systematic, non-random selection of stands under CVS sampling did not ensure that potential sources of bias were minimized. Non-random sampling may result in stands sampled that are not representative of the larger population of stands of interest. Whether any biases were introduced from the CVS sampling design is unknown. Nonetheless, the imprecise estimates obtained with CVS data, combined with the uncertainty about estimation bias, emphasize the need for a stratified-random system of sampling to ensure accurate modeling of snag densities in relation to management factors of interest.

Importantly, CVS sampling was not specifically designed to model snag density in relation to variables that we analyzed. Rather, CVS data are routinely collected to monitor a large suite of forest characteristics across northwestern USA to meet more general monitoring objectives (Johnson, 2002); such objectives require a generic sampling design that can be implemented consistently across millions of hectares by many field personnel. One of our objectives was to understand how well data collected under such an extensive, generic sampling design could be used to make specific inferences about snag density in relation to human access and associated management factors. Results from our use of CVS data suggest that these data may be of low utility in making inferences related to human access, and provide a cautionary note regarding attempts to adapt such data to meet more specific objectives than those originally specified.

Despite differences in sampling design and field methods, we observed similar results between the two data sets for many variables beyond those of human access. With both data sets, we found that snag density was lower with increasing intensity of timber harvest, with earlier seral stages, on flatter slopes, and adjacent to non-Forest Service lands. These patterns appear robust to differences in sampling design and methods used in our research, and deserve consideration in future management of snags, as described in our conclusions.

4.2. *Effects of human access*

Results from our 2002 fieldwork clearly demonstrated the importance of human access as an influence on larch and pine snag density. Mean snag density in stands not adjacent to roads (10.8 snags/ha) was four times that in stands adjacent to any road (2.6 snags/ha) (Fig. 5A). Mean density of larch and pine snags in stands along closed roads (3.8 snags/ha) was twice that in stands along open roads (0.9 snags/ha), suggesting that management of road access can strongly affect snag density.

Comboroad had the most explanatory value of any road variables with 2002 data (Table 2). When only larch/pine snags were considered, however, the continuous road variable, Unmaproad, was slightly more important than Comboroad. This finding suggests that unmapped roads, presumably less traveled because of their primitive state, may be used by fuel wood gatherers seeking larch and pine snags.

Distance to nearest town was a better explanatory variable for snag density than distance to roads, and was one of the best explanatory variables in top-ranking models built from 2002 data for all snag species and for larch/pine snags. These results suggest that stands closer to towns are disproportionately used for firewood gathering, even when road access is not ideal. Importantly, roads in our study area classified as closed by the Forest Service were not legally closed to all forms of motorized vehicles. Roads closed to truck and car traffic remained open to all-terrain vehicles (Penninger, personal communication), which often are used to access areas for fuel wood gathering. Whether this type of "road closure" had an effect on snag densities is unknown.

Additional findings from 2002 fieldwork were indirectly related to human access. For example, stands adjacent to non-Forest Service lands ($n = 8$) had substantially lower snag density, presumably because of increased human access from lands that were predominantly private in ownership (Fig. 6). Landownership in many areas of the northwestern United States follows a checkerboard pattern. Where this pattern exists, snag loss may be greater owing to increased human access.

Our field checks of the road layer indicated that maps of primary and secondary roads were accurate but did not include additional, primitive roads that we encountered while sampling. Twenty percent of all stands surveyed in 2002 had at least 1 unmapped road, and a number of these stands contained more than 1 unmapped road. We observed that as the distance to the nearest unmapped road decreased, signs of human access in the form of cut trees or logs increased ($r = -0.449$; $P < 0.001$). Although the variable Unmaproad was not important in our model to explain density of all snags, it was important for larch/pine snags. Again, this suggests that woodcutters use these unmapped roads to gain access to harvest snags most desirable for firewood.

4.3. Effects of other management factors

Separating the effects of timber harvest from roads is difficult because harvest usually takes place after a road has been established, or roads are specifically constructed to facilitate harvest. Consequently, it was not surprising that, as with road variables, the degree of timber harvest was one of the strongest explanatory variables for snag density with 2002 data.

In unharvested stands ($n = 5$), mean density of snags approached 80/ha for all species combined, the highest density we recorded under any conditions sampled during 2002. Density of larch and pine snags within these stands averaged about 48 snags/ha, again the highest density we recorded for any conditions sampled. All unharvested stands were long distances from nearest roads (mean = 330 m) and also far from

town (mean = 71 km), such that effects of harvest could not be separated from effects of human access. We suggest that the independent and combined effects of timber harvest and road management (e.g., open versus closed versus no roads) be carefully considered in future snag sampling to help distinguish separate versus cumulative effects of these factors.

Whereas the dominant tree species (ForestCode) was included in our top-ranking model to explain density of all snag species with 2002 data, this variable was not selected in the model for larch/pine snags. The high density of grand fir snags within the larch stands may be responsible for this pattern, owing to the high defoliation-caused mortality of grand fir from an outbreak of western spruce bud worm during the late 1980s and early 1990s (Scott and Schmitt, 1996). By contrast, grand fir snags in pine stands were absent or present in low density. This likely explained why ForestCode was an important explanatory variable for all snag species (Table 2), but not for larch/pine snags (Table 3).

4.4. Inaccuracies in available databases

Attempts to model snag density may be confounded by inaccuracies within the available databases. For 2002 fieldwork, we sampled stands within each stratum described earlier. Some stands, however, had to be reclassified after our initial field visit, resulting in some stand stratifications being over- or under-sampled. One of the greatest database problems was the lack of accurate information on history of timber harvest. This problem was particularly surprising, given that timber harvest constitutes one of the most common and pervasive land uses on national forests. We spent considerable time to acquire and validate information on history of timber harvest so that we could conduct our study. Accurate information on harvest history is imperative for effective modeling and management of snags, given the strong effect that timber harvest had on snag density.

4.5. Snag modeling and management

Our results have several implications for snag modeling and management. First, a stratified-random sampling design, like that used in 2002 fieldwork, is needed to reliably estimate and model snag densities in relation to human access. Accordingly, the top-ranking models built from 2002 data appear useful as tools for evaluating effects of land management on snag densities in larch and pine forests of the northwestern United States. The explanatory variables in our top-ranking models from 2002 data—adjacent land ownership (Adj.Land), juxtaposition of different road types (Comboroad), distance to nearest town (Town), history of timber harvest (Treatment), and dominant tree species (ForestCode)—are available from Forest Service databases or could easily be acquired or derived for use in these databases. However, it is particularly problematic that many human access variables were not available from Forest Service databases, and had to be derived from other data sources or from field work. A related problem is the need to correct inaccuracies in Forest Service databases regarding history of timber harvest.

Assuming that Forest Service databases can be strengthened with the addition of human access variables and corrections to information on timber harvest, the explanatory variables in our top-ranking models built from 2002 data could be considered in management planning to meet wildlife, fire, timber, firewood, safety, and recreation goals. That is, each stand in a given watershed or planning area could be mapped in relation to each of the explanatory variables included in the 2002 top-ranked models. Stands could then be ranked according to their relative snag density. For example, stands that were unharvested, composed of larch, far from town, and without roads or non-Forest Service lands adjacent to them, would be expected to contain the highest snag density. Stands that were intensively harvested, not dominated by larch, close to town, and with roads and non-Forest Service ownership adjacent to them, would be expected to contain the lowest snag density.

This type of assessment would be particularly useful for evaluating snag density in stands under current conditions versus conditions projected under future management alternatives for these same landscapes. Such assessments are now possible with evaluation tools available from INLAS (Ager et al., 2007; Hayes et al., 2004), the Interior Columbia Basin Ecosystem Management Project (Hemstrom et al., 2001; Raphael et al., 2001), and the Forest Vegetation Simulator (Reinhardt and Crookston, 2003; Wykoff et al., 1982). Our results also support the use of buffering techniques to map areas adjacent to roads that may be negatively affected by loss of snags from increased human access (Gaines et al., 2003). Buffering techniques would be particularly helpful for evaluating relative differences in snag density within large stands (e.g., stands >100 ha) that have substantial variation in distance to an adjacent road.

5. Conclusions

Snag densities are affected by a variety of management factors. Snag densities were lower near roads, closer to town, after intensive timber harvest, in earlier stages of seral development, on flatter slopes, and when adjacent lands were of private or other non-Forest Service ownership. These patterns were evident when evaluating ail snag species as well as larch and pine snags. With the exception of human access variables such as distance to nearest town, the above patterns were common to results from data collected during 2002 as well as from CVS data collected during 1993–1996.

Despite these common patterns, top-ranking regression models built from the two data sets differed in explanatory power and explanatory variables (management factors). Top-ranking models built from 2002 data performed better than those using CVS data, with higher coefficients of determination and lower mean-squared errors. Statistical power to detect differences of interest appeared to be lower with CVS data, presumably because sampling was not stratified in relation to human access and other management factors. Consequently, use of CVS data appears to have low utility in estimating and modeling snag densities in relation to human access, and should be avoided unless CVS data can be stratified in relation to human access variables to achieve adequate sample sizes across desired strata. By con-

trast, the stratified-random sampling design used to collect 2002 data resulted in higher precision of estimates while minimizing estimation bias.

Management of snags in national forests will continue to be a challenging proposition, given the number of variables that affect snag densities and the complexities associated with their management. Models and results from our study provide a basis for improved management of snags in forests of the northwestern United States, and could be used as a template for further studies of snags in other areas of western North America. We urge scientists and managers to consider these opportunities in future research and management of snags.

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