Synthesis of Regional Wildlife and Vegetation Field Studies to Guide Management of Standing and Down Dead Trees

Bruce G. Marcot, Janet L. Ohmann, Kim Mellen-McLean, and Karen L. Waddell

Abstract: We used novel methods for combining information from wildlife and vegetation field studies to develop guidelines for managing dead wood for wildlife and biodiversity. The DecAID Decayed Wood Advisor presents data on wildlife use of standing and down dead trees (snags and down wood) and summaries of regional vegetation plot data depicting dead wood conditions, for forests across the Pacific Northwest United States. We combined data on wildlife use by snag diameter and density and by down wood diameter and cover, across studies, using parametric techniques of meta-analysis. We calculated tolerance intervals, which represent the percentage of each species' population that uses particular sizes or amounts of snags and down wood, and rank-ordered the species into cumulative species curves. We combined data on snags and down wood from >16,000 field plots from three regional forest inventories and calculated distribution-free tolerance intervals compatible with those compiled for wildlife to facilitate integrated analysis. We illustrate our methods using an example for one vegetation condition. The statistical summaries in DecAID use a probabilistic approach, which works well in a risk analysis and management framework, rather than a deterministic approach. Our methods may prove useful to others faced with similar problems of combining information across studies in other regions or for other data types. FOR. SCI. 56(4):391–404.

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MANAGING STANDING AND down dead trees (snags and down wood) in forests for wildlife and biodiversity requires knowing how wildlife use dead wood and how conditions of forest vegetation relate to those uses. In the Pacific Northwest United States and elsewhere, information on wildlife species' use of dead wood resides in many disparate field studies. In a wildlife-habitat relationships database, O'Neil et al. (2001b) summarized wildlife use of dead wood in Washington and Oregon, but in terms too general and qualitative to guide management decisions at local and watershed levels. At the other extreme, detailed habitat capability models have been developed for individual, focal wildlife species that use dead wood (e.g., McComb et al. 2002), but such models lack applicability to broader communities of wildlife species. Furthermore, many assumptions underlying existing conceptual models that were used to develop agency standards and guidelines for managing dead wood for wildlife have been invalidated over the last 20 years (Rose et al. 2001).

In managing forests for broader ecological goals, including wildlife, it is also useful to know how dead wood varies across a forest landscape as a function of forest development, disturbance history, and environment. Vegetation conditions in wildlife habitat types in Washington and Oregon are sampled in regional forest inventories, but data on snags and down wood are collected with different sample designs and methods and have not been summarized across all ownerships and vegetation conditions for the explicit purpose of comparing with wildlife use in particular wildlife habitat types.

Limitations of Existing Approaches for Assessing Wildlife–Dead Wood Relations

Models of relationships between wildlife species and snags in the Pacific Northwest typically are based on calculating potential densities of bird species and expected number of snags used per pair. This approach was first used by Thomas et al. (1979). Marcot expanded this approach in Neitro et al. (1985) and in the Snag Recruitment Simulator (Marcot 1992) by using published estimates of bird population densities instead of calculating population densities from pair home range sizes. This approach has been criticized because the numbers of snags suggested by the models seem far lower than are now being observed in field studies (Lundquist and Mariani 1991, Bull et al. 1997). In addition, the models provided only deterministic point values of snag sizes or densities and of population response ("population potential") instead of probabilistic estimates

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that are more amenable to a risk analysis and risk management framework.

In addition, existing models have focused on terrestrial vertebrate species that are primary cavity excavators. Thomas et al. (1979) and Marcot (1992) assumed that secondary snag-using species would be fully provided for if needs of primary snag-excavating species were met. However, McComb et al. (1992) and Schreiber (1987) suggested that secondary cavity nesting birds may be even more sensitive to snag density than are primary cavity excavators. Furthermore, existing models do not address relationships between wildlife and down wood, nor do they account for species that use different types of snags and partially dead trees, such as hollow live and dead trees used by bats (Ormsbee and McComb 1998, Vonhof and Gwilliam 2007), Vaux's swift (*Chaetura vauxi*) (Bull and Hohmann 1993), American marten (*Martes americana*) (Bull et al. 2005), and fisher (*Martes pennanti*) (Zielinski et al. 2004).

The need to incorporate the best available science into existing guidelines for managing dead wood led us to develop DecAID Advisor (Mellen-McLean et al. 2009). DecAID (as in "decayed" and "decision aid") contains a synthesis of data on wildlife and forest vegetation for use in managing snags, down wood, and other dead wood elements in forests of Oregon and Washington. In this article we (1) describe how DecAID's conceptual basis differs from that of existing frameworks, (2) present the statistical methods used in our meta-analyses of original data sets and research studies, (3) illustrate our methods and data interpretation using an example for one vegetation condition, and (4) discuss implications of the DecAID methods and syntheses for forest management in the Pacific Northwest United States and beyond. We believe that presenting details of our meta-analysis methods and results can provide a framework for others to use for similar ecological questions and management objectives.

Methods

DecAID Advisor—A Major Departure from Previous Efforts

Although DecAID was developed for use in the Pacific Northwest United States, our conceptual framework and methods for data synthesis should be of interest to a wider audience and equally applicable to other regions. Our earlier articles introduced the purpose and conceptual basis of DecAID (Mellen et al. 2002) and described the forest inventory data we used (Ohmann and Waddell 2002). Since then, methods for synthesis of wildlife data for DecAID reported by Marcot et al. (2002) have been substantially revised to use tolerance intervals, and DecAID has been updated to version 2.1, which incorporates additional wildlife studies published through October 2008. Ohmann and Waddell (2002) did not describe their methods, presented here, for summarizing inventory data specifically for DecAID (tolerance intervals and relative frequency distributions, with an emphasis on unharvested forests).

DecAID departs from previous efforts, described above, in several important ways. Rather than relying on untested assumptions about wildlife species' use of and requirements for snag (or down wood) sizes or numbers, DecAID is based strictly on a statistical synthesis of empirical data from field studies. DecAID provides information expressed as proportions of wildlife populations using various sizes or amounts of snags and down wood, instead of single, deterministic levels. This approach is better for a risk analysis and risk management framework for wildlife habitat assessment and forest management. DecAID also provides information on all wildlife for which empirical data exist within our region and encompasses down as well as standing dead wood, rather than focusing solely on primary cavity-excavating bird use of just snags.

DecAID represents a novel application of statistical methods for combining empirical data from many disparate field studies that used different sample designs and methods and to summarize and visualize wildlife and vegetation information together in compatible ways that facilitate integrated use by managers and researchers. Combining information across studies, particularly among a variety of conditions within a wildlife habitat type and structural condition, improves representation of the range of variability in dead wood as well as of wildlife species and type of use.

The two primary kinds of statistical summaries in DecAID are wildlife species use of dead wood and distributions of amounts and sizes of dead wood in unharvested forests sampled by inventory plots. The wildlife and vegetation summaries are compiled for 26 vegetation conditions defined by combinations of wildlife habitat type, structural stage, and geographic location (Mellen-McLean et al. 2009).

Use of Tolerance Intervals

We used statistical intervals, specifically tolerance intervals, to summarize both the wildlife and inventory data. Tolerance intervals are a useful way to represent proportions of observations (Krishnamoorthy and Mathew 2009; e.g., Smith et al. 2005) and in ways that depict potential effects of alternative levels of dead wood for wildlife. Tolerance intervals are based on the spread of values of individual observations and predict response of individuals of a wildlife population as a whole or the forest area sampled by inventory plots. In contrast, confidence intervals and prediction intervals depict means or SDs from subpopulations of additional or future samples (studies) (Hahn and Meeker 1991; e.g., Bender et al. 1996, Cherry 1996, Nigh 1998, Guida and Penta 2010). Tolerance intervals are the most appropriate type of interval to use for DecAID Advisor, for which the driving questions are the following: What proportion of a wildlife population uses or selects for particular sizes or amounts of snags or down wood? What proportion of the observed wildlife population uses specified sizes or amounts of snags or down wood? What proportion of the landscape contains dead wood densities or sizes above (or below) a particular threshold?

Synthesis of Data from Wildlife Studies

Combining Information from Wildlife Studies

We summarized data on wildlife use of dead wood from about 100 studies of 112 terrestrial wildlife species or species groups. The wildlife component of DecAID focuses on species' use or selection of types, sizes, amounts, and distributions of dead wood, primarily snags and down wood in forests of Washington, Oregon, and sometimes adjacent locations. We extensively reviewed the literature, contacted researchers, and summarized quantitative data on dead and decaying wood relationships of amphibians, birds, mammals, and a few insects. Reported data needed to provide mean, variation, and sample size to be included. Studies reporting significant relationships using models (e.g., logistic regression) could not be included because basic descriptive statistics and individual observations were not provided. We found many data gaps for some habitats and species groups (e.g., no quantitative data meeting our criteria were available on reptiles). Where possible, we filled gaps with unpublished data from ongoing studies or manuscripts in preparation after consultation with the researchers.

Because sample sizes varied by study, we calculated weighted means and SDs before combining data (Draper et al. 1992, Dominici et al. 1997, Pena 1997). We weighted parameters by sample size (Gurevitch and Hedges 1999) under the assumption that all studies were independent and from the same subpopulation (i.e., from the same vegetation condition, defined by forest vegetation type and structural condition class). We weighted by sample size instead of by variability because we could not partition variation between sample size and subpopulation effects. We recalculated the data from each study to a per-ha basis. To check for bias related to plot size, we conducted simple linear regressions between plot size and per-ha snag density, by wildlife habitat type, and results were not statistically significant (various tests, $P > 0.05$). We also regressed SE of snag and down wood density against plot size, and found little correlation ($P \gg 0.05$).

We calculated a composite mean across studies. For K studies, each with n_i sample size, the composite mean $\bar{y}$ over $\bar{x}_i$ study means is

$$\bar{y} = \frac{\sum_{i=1}^{K}(\bar{x}_i n_i)}{\sum_{i=1}^{K} n_i}. \quad (1)$$

We estimated composite variation among studies by weighting SD by sample size (n) (or by degrees of freedom (df), $[n - 1]$). This provided the estimate of $\mathrm{SD}^2(n - 1) = \mathrm{SS}$ (sums of squares), which was summed over all K studies and divided by the composite df:

$$V_1 = \frac{\sum_{i=1}^{K}[(\mathrm{SD}_i)^2(n_i - 1)]}{\sum_{i=1}^{K}(n_i - 1)}. \quad (2)$$

(This was based on

$$\frac{\mathrm{SS}}{N_i - 1} = \mathrm{SD}^2 \quad (3)$$

for each study i.) That is, for each species and vegetation condition, the composite variance was estimated by Equation 2 over all K pertinent studies. We chose not to estimate composite variance as a simple average of SD across all K studies because sample sizes varied, sometimes markedly, across studies.

The purpose of calculating composite variation was to calculate tolerance limits. Tolerance limits, also called tolerance levels in DecAID, are specific values that bound ranges of values in a tolerance interval, just as confidence limits (or levels) bound confidence intervals. However, the wildlife studies reported variation as SD, SE, or confidence interval (CI). To use Equation 2 and to calculate combined tolerance limits, we converted SE and CI estimates to SD. CI was first converted to SE using $\mathrm{SE} = \mathrm{CI}/t_{\mathrm{df},\,\alpha}$. SE was converted to SD by using $\mathrm{SD} = \mathrm{SE} \cdot \sqrt{n}$. When $n_i < 5$ in an individual study, we did not calculate SD for that study and omitted that study from calculations of composite variance but included it in calculations of composite mean.

To demonstrate that Equation 2 (V_1) is the appropriate estimator to use for calculating a composite variance among wildlife studies, we correlated SD with n across all studies for each of the 42 combinations of species and vegetation conditions for which data were available (results available from the authors). Only 6 of the 42 correlations were significant ($P < 0.05$), suggesting that, for the most part, n and SD were largely uncorrelated. We interpreted the 6 cases of significant correlations as random chance; 5 of the 6 cases were from studies with $n \leq 5$. This result supports our use of an estimator that accounts for SS for studies individually, as in Equation 2.

Calculating Tolerance Intervals for Wildlife Data

We tested for normality in the distribution of the wildlife data by charting values of the individual observations, where available, on probability plots. The probability plots generally showed strong linearity (results not shown), with minor variations as expected from data of this type. We therefore assumed normality in the distribution of values for the wildlife data (e.g., snag dbh or snag densities) among the individual observations.

We used a one-sided tolerance interval, referred to as a tolerance limit, with zero as the closed lower limit because values of the parameters (snag or down wood sizes or amounts) cannot be negative. For a particular value, such as a given snag dbh or density, we calculated the percentage of observations falling above or below a given value. In this way, we determined the tolerance limit represented by that value, and the percentage of individual observations bounded by that tolerance limit.

We corrected the wildlife tolerance intervals for small sample sizes, because sample sizes for the wildlife data were relatively small and with rare exception were >500. The calculation of tolerance limits requires use of a factor based on degrees of freedom, which is called the g' statistic and can be taken from textbook table values. In this approach, a one-sided lower $100(1 - \alpha)\%$ tolerance limit to be exceeded by at least $100p\%$ of a normal population is given by

$$\underset{\sim}{T} = \bar{y} - g'_{(1-\alpha;p,n)} V_1 \quad (4)$$

and a one-sided upper $100(1 - \alpha)\%$ tolerance limit to exceed at least 100p% of the population is given by

$$\tilde{T} = \bar{y} + g'_{(1-\alpha;p,n)}V_1 \quad (5)$$

where $\bar{y}$ is the composite mean (Equation 1), V_1 is the composite variance (Equation 2), and g' is the table value based on the acceptable level of error $1 - \alpha$, the desired confidence level p, and sample size n (Hahn and Meeker 1991, p. 60). (Throughout this article, α refers to the error rate $1 - p$.)

The 50% tolerance limit for normally distributed data is the mean itself or $T \equiv \bar{y}$. Values of g' can be found in Table A.12 of Hahn and Meeker (1991, p. 312–315). The table is based strictly on sample size n, not df, but it can be used as if $\mathbf{n} \approx$ df for practical purposes because df $= n - 1$ (that is, we are estimating only one parameter) from each study. In combining information (Draper et al. 1992), degrees of freedom can be calculated as the composite among all K studies, as $\sum_{i=1}^{K}(n_i - 1) =$ composite df. Then we assumed that the table value of n (in Hahn and Meeker 1991) approximates the value of composite df.

We used an error rate of $\alpha = 0.10$, which was a compromise between statistical confidence and statistical power (Steidl et al. 1997, Thomas 1997). We justify this level of confidence on the basis of increased statistical power for the type of error incurred. When there is an error, it is on the side of including larger snag or down wood diameters or abundance levels rather than smaller ones.

For the 30% tolerance limit we used $P = 0.700$ to derive the g' table value from which to subtract from the mean (in Equation 4), and for the 80% tolerance limit we used $P = 0.800$ to derive the g' table value from which to add to the mean (in Equation 5), both at the confidence level of $P = 0.90$. For any other tolerance limit, the table values can be read directly or interpolated, although we eventually used the software package StatCalc (Krishnamoorthy 2001, 2006) to generate tolerance values, and we cross-checked results with the above equations and table values to ensure correct calculations.

Constructing Cumulative Species Curves

We constructed "cumulative species curves" for each tolerance level by simply plotting species by increasing value of each parameter (size and abundance of snags and down wood) and connecting the points. The cumulative species curves are not mathematical functions but instead serve as a visual aid to quickly determine which species may correspond to specific parameter values (i.e., which species use a particular size or abundance of snags or down wood). Alternatively, the curves can be used to show what parameter values would be needed to correspond with some or all species (i.e., what size or abundance of snags or down wood is required to meet the needs of desired species), for each tolerance limit.

Synthesis of Vegetation Plot Data from Regional Forest Inventories

The field plot observations of dead wood summarized for DecAID were from three different regional forest inventories: Bureau of Land Management (BLM), Current Vegetation Survey (CVS), and Forest Inventory and Analysis (FIA) (Table 1). See Ohmann and Waddell (2002) for detailed information on inventory design, database development, and calculation of dead wood variables and for limitations of the regional inventory data. Most important, plots were not installed in parks, and down wood was not sampled on nonfederal plots in Oregon and western Washington. Many of these limitations will no longer apply after full implementation of the FIA Annual Inventory, with plots being installed on all forest lands.

We classified the inventory plots into wildlife habitat types (Chappell et al. 2001) and structural conditions (O'Neil et al. 2001a) using methods described in Ohmann and Waddell (2002) and further stratified the plots by geographic subregion to classify the plots into the 26 DecAID vegetation conditions. Analyses of the plot data showed that dead wood characteristics differed significantly among the subregions (data not shown), which approximate ecoregions. For each vegetation condition, we summarized dead wood data collected on unharvested and unroaded plots only (a sample of natural conditions) and for all plots regardless of disturbance history (a sample of current landscape conditions). Unharvested plots were those where no tree cutting of any kind had been recorded, including clearcut harvest, partial or selective harvest, firewood cutting, and incidental removals in both the recent and distant past, thus excluding forest that had been harvested at any time, as far back as the late 1800s. Plots with roads through or adjacent to them also were excluded from the unharvested category.

We summarized the plot data as distributions of snags and down wood by tree size and as relative frequency distributions and tolerance intervals for snag density and down wood cover. Relative frequency distributions are a simple but useful way to visualize the inherent variability in dead wood populations within a vegetation condition as sampled on the vegetation plots and do not have any associated statistical properties. We also described the dead wood populations sampled on plots using tolerance intervals for many of the same reasons cited for the wildlife data, and

Table 1. Characteristics of three regional forest inventories

Inventory	Lands sampled	Grid spacing (km)	Plot weight
BLM	BLM lands, western Oregon	5.5	1.00
CVS	National Forest wilderness	5.5	1.00
	National Forest non-wilderness	2.7	0.25
FIA	Nonfederal, all but western Washington	5.5	1.00
	Nonfederal, western Washington	Two overlapping 5.5-km grids	0.50

BLM, Bureau of Land Management; CVS, Current Vegetation Survey, Pacific Northwest Region, US Forest Service; FIA, Forest Inventory and Analysis, Pacific Northwest Research Station, US Forest Service.

to facilitate consistency with and comparison to the wildlife summaries. However, describing variation in the plot sample of dead wood presented two statistical challenges different from those associated with the combining of wildlife study data: combining plot data collected at different sampling intensities and summarizing data that are non-normally distributed.

Combining Vegetation Information for Areas Sampled at Different Intensities

The three forest inventories used very similar sampling methods at the field plot level, and plots from each of the three inventories were established on systematic grids. However, sampling intensity (the density of plots per unit area, a function of the average distance between plots, or grid spacing) differed among ownerships, land allocations, and geographic locations (Table 1). Because dead wood characteristics vary with these same factors (Ohmann and Waddell 2002), the different inventory components sampled different populations of dead wood, and plots needed to be weighted differently in the summaries. Because we summarized the plot data for DecAID by vegetation condition, sampling intensity needed to be consistent within each vegetation condition to avoid biases in terms of over- or under-representing any component ownership or land allocation. Our methods for accounting for different sampling intensities are summarized in Table 2.

Constructing Relative Frequency Distributions for Dead Wood Abundance

To construct the relative frequency distributions of dead wood from the inventory plot data, we summarized the percentage of sampled area rather than a count of observations (i.e., number of field plots) by dead wood abundance class. This allowed us to apply various plot weights (Table 1) to reflect the differing sampling intensities. The weights assigned to plots that contained multiple forest conditions were adjusted further. Whereas all FIA plots in our study were confined to a single forest condition, the BLM and CVS plots often straddled multiple forest conditions. We used the plant association code recorded for each point to identify distinct forest conditions within plots, which we defined as forest versus nonforest and as vegetation series (potential vegetation types defined by the dominant tree species) within forest conditions. Plots confined to a single forest condition were assigned the full plot weight (Table 1), and partial plots received an apportioned amount of the full plot weight consistent with the percentage of the plot area occupied by the condition class.

Calculating Distribution-Free Tolerance Limits for the Inventory Data

Observations cannot be differentially weighted in calculating the distribution-free tolerance intervals we used in summarizing the plot data. Therefore, for calculating the tolerance intervals we subsampled the component data sets to achieve consistent sampling intensity within each vegetation condition. To characterize the current landscape (forests of all ownerships and disturbance histories), we used plots from all three inventories, but only those plots on the 5.5-km grid (see Tables 1 and 2). This included all BLM plots, all CVS plots within wilderness areas, every fourth CVS plot outside wilderness, every other FIA plot in western Washington, and all FIA plots in other geographic areas. The reduced sample sizes after subsampling were used in calculating tolerance limits. Summaries of all plots are not presented in this article but are available in DecAID.

For characterizing unharvested forests, we excluded FIA plots because the overwhelming majority had been harvested at least once. Because there were so few CVS plots in wilderness, we did not subsample to achieve equal sampling intensity across all CVS plots. Furthermore, we found that subsampling to achieve equal sampling intensities between the BLM and CVS data sets yielded unacceptably small sample sizes for many vegetation conditions that contained BLM plots. For this reason, for DecAID we opted to use all BLM and CVS plots, but for those vegetation conditions affected we cautioned the user that the tolerance limits are more indicative of the more intensively sampled conditions on Forest Service lands than on BLM lands.

Dead wood abundance was distinctly non-normally distributed among the plots in our sample. This was true to varying degrees for all vegetation conditions and for both snags and down wood. Especially problematic were the

Table 2. Sampling and plot attributes used in summarizing dead wood data from inventory plots for DecAID vegetation conditions

Kind of data summary	Sampling and plot attributes	Landscape component being described:	
		Natural conditions	Current landscape
Relative frequency distributions	Plots used	Unharvested only	Harvested and unharvested
	Inventories used	All inventories (BLM, CVS, FIA)	All inventories (BLM, CVS, FIA)
	Sample grids used[1]	All grids	All grids
	Plot weights applied?[1]	Yes	Yes
Tolerance intervals	Plots used	Unharvested only	Harvested and unharvested
	Inventories used	BLM and CVS (no FIA)[2]	All inventories (BLM, CVS, FIA)
	Sample grids used[1]	All grids	5.5-km grid only
	Plot weights applied?[1]	No	No

BLM, Bureau of Land Management; CVS, Current Vegetation Survey, Pacific Northwest Region, US Forest Service; FIA, Forest Inventory and Analysis, Pacific Northwest Research Station, US Forest Service.
[1] Information on sample grids and associated plot weights are in Table 1. Plot weights reflect different grid sampling intensities and condition classes within plots. No statistical methods are currently known for differentially weighting observations in calculating tolerance intervals.
[2] By excluding the few unharvested FIA plots we were able to increase our sample size by using all CVS grids.

large number of plots where dead wood was searched for, but none was tallied, which is a function of plot size (or transect length) and the abundance and spatial distribution of dead wood. This pattern was more pronounced for larger snags and down wood (≥50 cm), which are less abundant than smaller trees. We therefore used a distribution-free method of calculating tolerance limits (see Mood et al. 1974, p. 515–518), rather than the parametric statistics applied to the wildlife data. For each vegetation condition and dead wood variable of interest, we calculated quantiles (*k*s or observation order numbers) based on the binomial probability distribution and sample size (number of plots). A given tolerance limit is the value of the dead wood variable associated with the *k*th observation. We used the same γ (level of certainty) of 0.90 and β values of 0.30, 0.50, and 0.80 that we used with the wildlife data.

For visualizing the tolerance limits side-by-side with the wildlife summaries, we portrayed them graphically using a format similar to a box-and-whisker diagram (Figures 1b and 2b). An interpretation of the tolerance limit in Figure 1b is that one can be 90% certain that 50% of the total area of unharvested forest in this vegetation condition has ≤13.1 snags/ha ≥50 cm diameter. The 50% tolerance limit can be thought of as an estimate of the median value inferred for the entire population.

Results

Wildlife and Vegetation Summaries for Eastside Mixed Conifer Forest

To illustrate the wildlife and inventory data summaries and their interpretation, we present results for just one of the 26 vegetation conditions in DecAID as an example: Eastside Mixed Conifer Forest, East Cascades/Blue Mountains, Larger Tree vegetation condition (EMC_ECB_L). For brevity, only some of the data summaries for this vegetation condition are shown. For more discussion on interpretation of the data and management implications, see Mellen-McLean et al. (2009).

The Eastside Mixed Conifer Forest wildlife habitat type is described in detail in Chappell et al. (2001). Locations of inventory plots in the East Cascades and Blue Mountains subregion of this wildlife habitat type are shown in DecAID and in Figure 3. Stands in the larger tree structural condition have an average tree dbh ≥50.0 cm and tree stocking or cover ≥10%, and often are late-successional. Very large

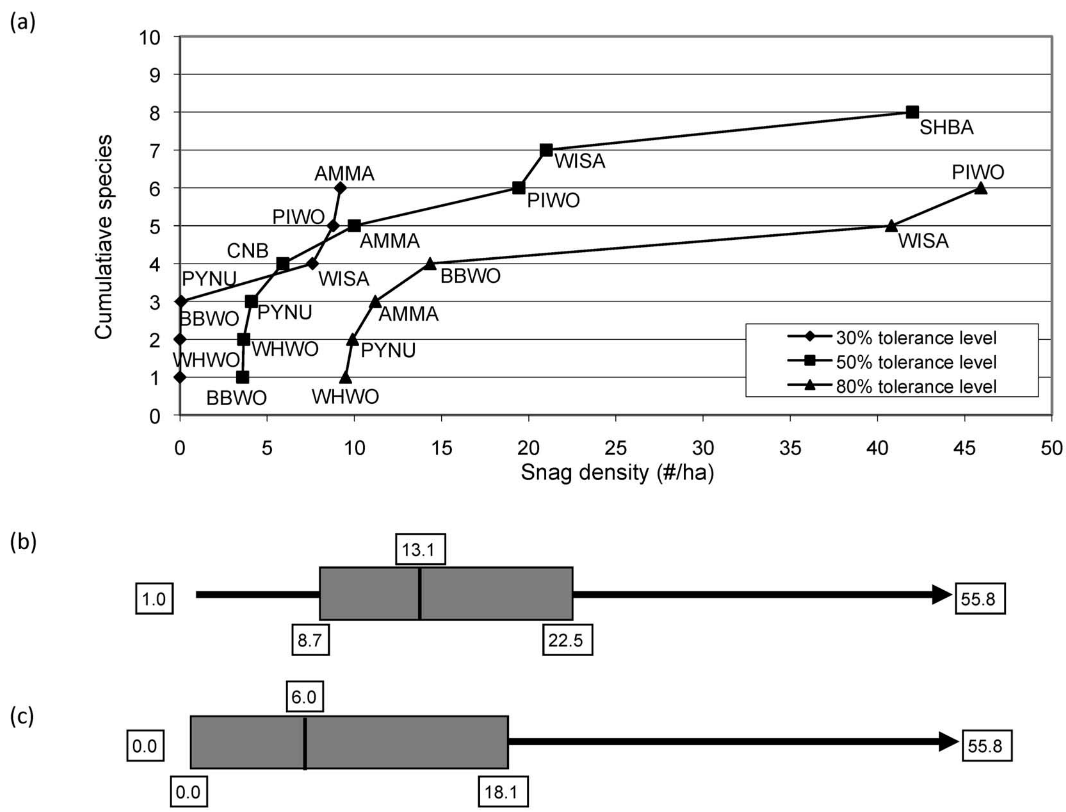

Figure 1. Integrated summary of tolerance levels for Eastside Mixed Conifer Forest, East Cascades/Blue Mountains, Larger Trees vegetation condition. (a) Wildlife species use of density of snags ≥50 cm dbh for nesting and roosting (includes data from North Cascades/Rockies and Smaller Trees). (b) Densities of snags ≥50 cm dbh and ≥2.0 m tall sampled on 95 unharvested inventory plots with snags present. (c) Densities of snags ≥50 cm dbh and ≥2.0 m tall on 159 unharvested inventory plots with and without snags present. In the upper box, the values 8.7, 13.1, and 22.5 are the 30, 50, and 80% tolerance limits, and 1.0 and 55.8 are the minimum and maximum observed values. AMMA, American marten; BBWO, black-backed woodpecker; PIWO, pileated woodpecker; PYNU, pygmy nuthatch (*Sitta pygmaea*); SHBA, silver-haired bat; WISA, Williamson's sapsucker; WHWO, white-headed woodpecker (*Picoides albolarvatus*).

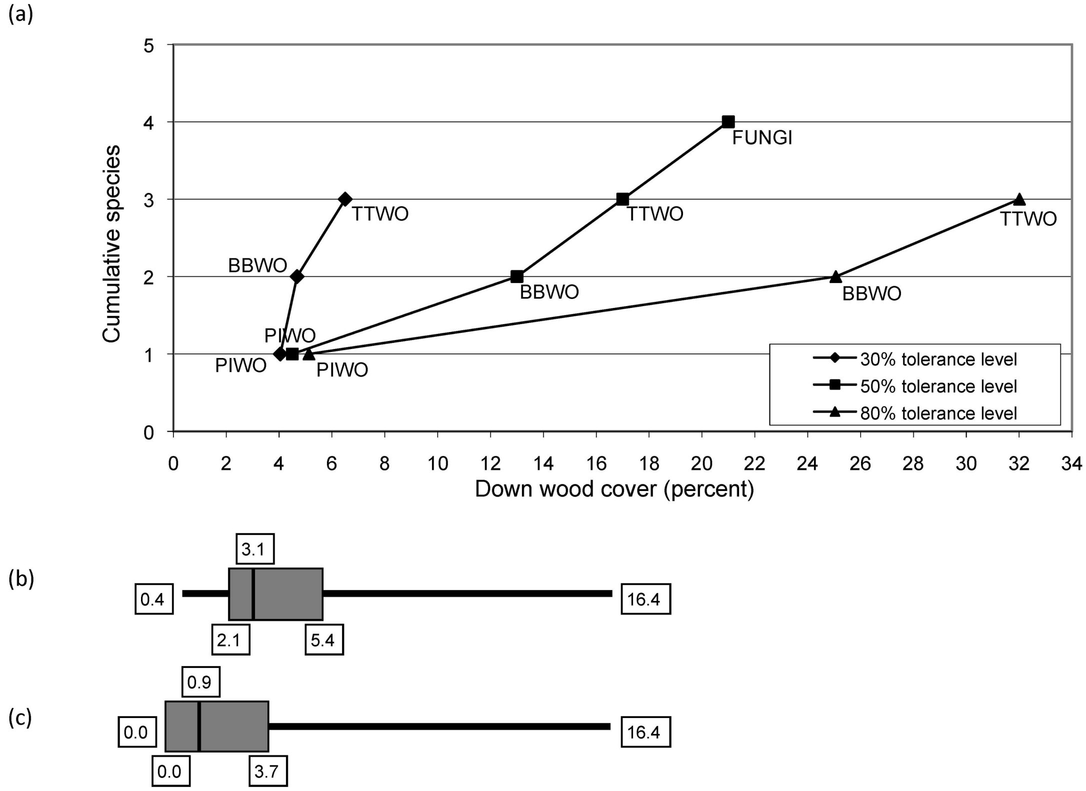

Figure 2. Integrated summary of tolerance levels for Eastside Mixed Conifer Forest, East Cascades/Blue Mountains, Larger Trees vegetation condition. (a) Wildlife species use of cover of down wood ≥ 10.0 cm diameter for nesting and occupied sites (includes data from North Cascades/Rockies and Smaller Trees). (b) Cover of down wood ≥12.5 cm diameter sampled on 81 unharvested inventory plots with down wood present. (c) Cover of down wood ≥12.5 cm diameter sampled on 159 unharvested inventory plots with and without down wood present. See the legend to Figure 1 for explanation of the box plots. BBWO, black-backed woodpecker; PIWO, pileated woodpecker; TTWO, three-toed woodpecker; FUNGI, various species of ectomycorrhizae and hypogeous fungi.

trees may be scattered throughout the stand, a grass-forb or shrub understory is often present, and stands may or may not have distinct canopy layers. Based on the inventory sample, 75% of the area of EMC_ECB_L is on federal lands and 64% has never been harvested in the past, and 77% of the unharvested area is federally owned.

Available Wildlife and Inventory Data

Wildlife data were not stratified by geographic subregion in this wildlife habitat type because few wildlife studies were available, and habitat conditions in the subregions are similar. Data on wildlife use of snags at nesting, roosting, denning, and foraging sites were available for 26 species and three species groups from 31 studies for snag dbh (Figure 4a) and on 10 species and one species group from 11 studies for snag density (Figure 1a). Data on wildlife (including ants) use of down wood size at foraging, denning, resting, or occupied sites were available for four species and three groups from four studies for down wood diameter (Figure 4c), and for three species and one group (fungi) from three studies for down wood cover (Figure 2a). Studies were primarily from eastern Oregon and Washington; however, because data were limited, we included data from adjacent areas (British Columbia and western Montana) where studies were from habitats similar to those in Oregon and Washington. An annotated bibliography of all wildlife studies used in DecAID is found on the DecAID website.

Snags were sampled on 277 inventory plots in the EMC_ECB_L vegetation condition, 168 of which were unharvested plots. Down wood data were collected on 273 plots, 166 of which were unharvested. Snags were sampled on all ownerships, whereas down wood was sampled only on federal lands in Oregon but on all ownerships in Washington. Tolerance levels for unharvested forests were calculated using 159 plots on federal lands (e.g., lower box plots in Figures 1b and 2b). We also calculated tolerance levels using just those plots ($n = 95$) on which at least one piece of dead wood was tallied (e.g., upper box plots in Figures 1b and 2b). Inventory estimates discussed here are based on plots with at least some dead wood present, because wildlife data were collected primarily on plots where they were associated with a piece of dead wood.

Snag and Down Wood Sizes: Abundance and Wildlife Use in Unharvested Forests

In EMC_ECB_L, cumulative species curves for snag dbh indicate that most species use large snags ≥50 cm dbh at the 50 and 80% tolerance levels for nesting, roosting, and foraging (Figure 4a–c). Inventory data indicated that snags

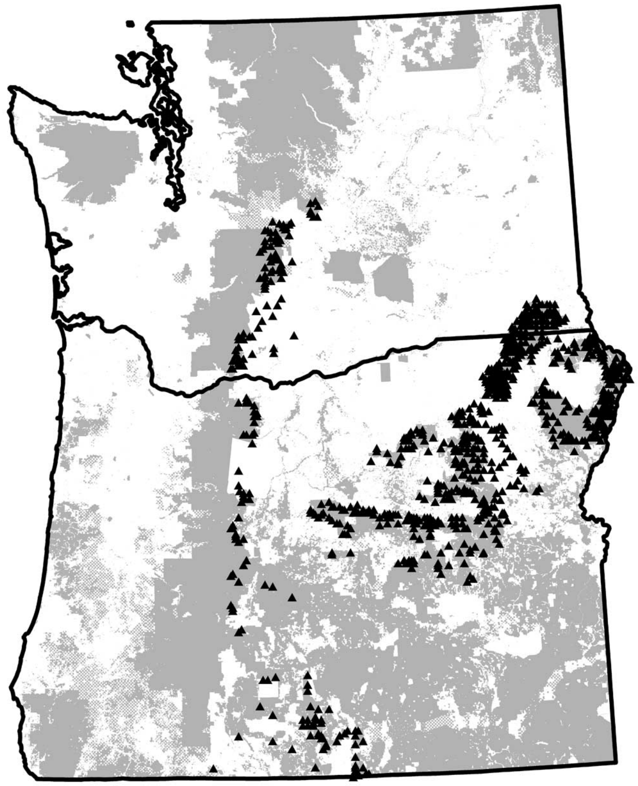

Figure 3. Approximate locations of unharvested inventory plots (n = 168) in the Eastside Mixed Conifer Forest, East Cascades/Blue Mountains, all structural conditions, in eastern Oregon and Washington, United States. Harvested plots in this vegetation condition (n = 277) are not shown. Gray shaded areas are federal lands.

of this size or larger are relatively common in unharvested stands of this vegetation condition: 39% of all snags sampled were ≥50 cm dbh and they occurred in 60% of the unharvested area (Table 3). Very large snags (≥80 cm dbh) used as roost sites by many species at the 80% tolerance level were less common but still occurred in 51% of the unharvested forest.

The cumulative species curves for down wood diameter indicate that American marten and black bear (*Ursus americanus*) use large down wood (≥50 cm diameter) at all tolerance levels for denning (Figure 4d). Inventory data showed that large down wood is relatively common in unharvested stands of this vegetation condition: 37% of all down wood sampled was ≥50 cm and it occurred on 39% of the unharvested area (Table 3). Very large logs (≥80 cm diameter) used as den sites by black bears were rare, occurring on only 9% of unharvested area.

Large Snags and Down Wood: Abundance and Wildlife Use in Unharvested Forests

The density of large (≥50 cm dbh) snags used by species within and across tolerance levels ranged widely, from 0 to 45 large snags/ha (Figure 1a). At all tolerance levels, pileated woodpecker (*Dryocopus pileatus*), Williamson's sapsucker (*Sphyrapicus thyroideus*), and silver-haired bat (*Lasionycteris noctivagans*) used snag densities higher than would be expected based on comparison with inventory data (Figure 1b and c). For example, both Williamson's sapsucker and pileated woodpecker nested in areas with >40 snags/ha at the 80% tolerance level, whereas the 80% tolerance level for inventory plots with at least one snag ≥50 cm dbh was only 22.5 snags/ha. This indicates that these species are probably choosing to locate nest sites in higher density snag clumps.

The cover of down wood ≥10.0 cm diameter used by species within and across tolerance levels ranged widely, from about 4 to 32% (Figure 2a). At all tolerance levels, all species used cover values higher than would be expected based on the inventory data (Figures 2b and c). Several wildlife data points actually exceeded the maximum cover measured on inventory plots. This finding indicates that these species are probably choosing sites with very high cover of down wood. Examination of the underlying data also indicates that the data for black-backed woodpecker (*Picoides arcticus*) and three-toed woodpecker (*Picoides tridactylus*) were collected during a mountain pine beetle epidemic and thus down wood occurred at high levels, which are very rare on the landscape (Goggans et al. 1988).

Landscape Distribution of Snags and Down Wood in Unharvested Forests

At the landscape scale, snags and down wood were non-normally distributed within the EMC_ECB_L vegetation condition (Figure 5). Most of the forest area supported low to moderate amounts of dead wood, with a small portion of the landscape containing very high amounts (>30 snags/ha or >6% cover of down wood). About one-third of the sampled area contained no measurable snags or down wood. This does not mean that large contiguous areas of the landscape lack dead wood but rather that dead wood is not homogenously distributed and that plot-sized areas (~1 ha) devoid of dead wood are scattered throughout the landscape.

Discussion

Interpretation of the Wildlife and Inventory Summaries

The statistical summaries in DecAID can be used to determine the sizes and amounts of snags and down wood that would meet stated goals for individual wildlife species or a specified number of species. Providing the wildlife and inventory summaries side-by-side gives users valuable information for managing wildlife habitat. For example, summaries of sizes and amounts of dead wood in unharvested forests sampled by inventory plots provide estimates of the distribution of snags and down wood in natural conditions, which indicates the capability of the vegetation condition to provide amounts and sizes of dead wood used by wildlife species. In cases for which the wildlife data points are at the high end of amounts of dead wood present in natural forests across the landscape (from the inventory summaries), this indicates that wildlife are using portions of the landscape that provide the higher amounts of dead wood. In addition, if species are selecting large snags or down wood that the inventory summaries indicate are rare on the landscape,

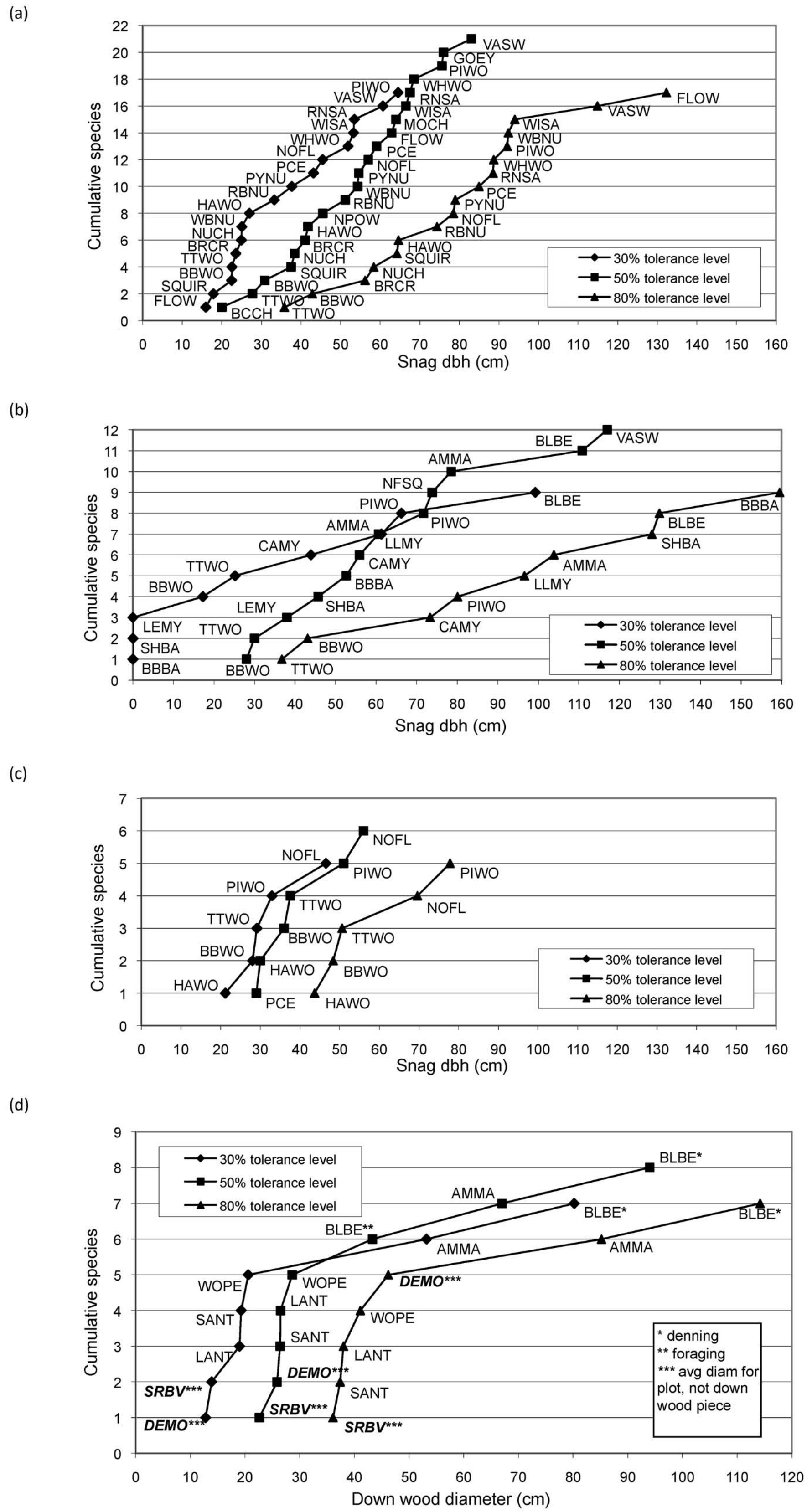

Figure 4. Cumulative species curves of tolerance levels for wildlife species use of sizes of dead wood in Eastside Mixed Conifer Forest, Larger Trees vegetation condition. Snag sizes used for (a) nesting, (b) denning or roosting, and (c) foraging; and (d) down wood sizes used at denning, resting, foraging, and occupied sites. AMMA, American marten; BBBA, big brown bat; BBWO, black-backed woodpecker; BCCH, black-capped chickadee (*Parus atricapillus*); BLBE, black bear; BRCR, brown creeper (*Certhia americana*); CAMY, California myotis (*Myotis californicus*); DEMO, deer mouse (*Peromyscus maniculatus*); FLOW, flammulated owl (*Otus flammeolus*); GOEY, goldeneye (*Bucephala* spp.); HAWO, hairy woodpecker (*Picoides villosus*); LANT, carpenter and formica ants (*Camponotus* spp. and *Formica* spp.); LEMY, long-eared myotis (*Myotis evotis*); LLMY, long-legged myotis (*Myotis volans*); MOCH, mountain chickadee (*Parus gambeli*); NFSQ, northern flying squirrel (*Glaucomys sabrinus*); NOFL, northern flicker (*Colaptes auratus*); NPOW, northern pygmy-owl (*Glaucidium gnoma*); NUCH, various species of nuthatches and chickadees; PCE, various species of primary cavity excavators; PIWO, pileated woodpecker; PYNU, pygmy nuthatch; RBNU, red-breasted nuthatch (*Sitta canadensis*); RNSA, red-naped sapsucker (*Sphyrapicus nuchalis*); SANT, small ants (various species); SHBA, silver-haired bat; TTWO, three-toed woodpecker; SQUIR, various species of squirrels; SRBV, southern red-backed vole (*Clethrionomys gapperi*); VASW, Vaux's swift; WBNU, white-breasted nuthatch (*Sitta carolinensis*); WHWO, white-headed woodpecker; WISA, Williamson's sapsucker; WOPE, woodpeckers (various species).

these structures can become an important focus for managers.

For both snags and down wood, the inventory estimates often were lower than estimates from wildlife studies. We think this occurs primarily because the latter typically describe dead wood around nest, roost, denning, or foraging sites, where dead wood may be substantially more abundant than in the surrounding area. Some wildlife species select nest sites within clumps of snags. For example, pileated woodpecker, Williamson's sapsucker, and silver-haired bat

Table 3. Distribution of snags ≥25.4 cm dbh and ≥2.0 m tall and down wood ≥12.5 cm large end diameter among size classes in unharvested forest in the Eastside Mixed Conifer Forest, East Cascades/Blue Mountains, Larger Trees vegetation condition, based on unharvested inventory plots

Size class (cm)	% of all snags	% of area with snags in size class	% of all down wood	% of area with down wood in size class
12.5–25.3	—	—	15	35
25.4–49.9	60	60	48	55
50.0–79.9	29	60	32	39
≥80.0	10	51	5	9

n = 168 for snags, n = 166 for down wood.

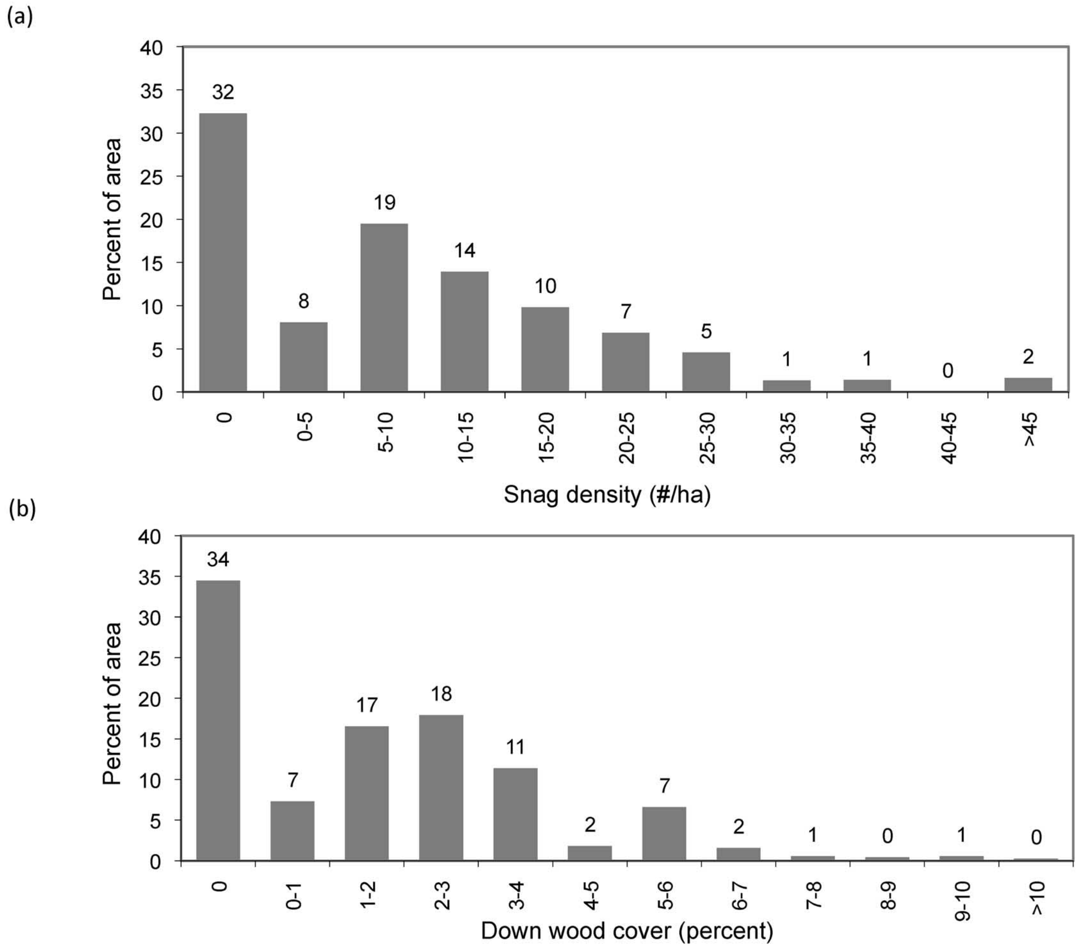

Figure 5. Relative frequency distribution of snags and down wood on unharvested inventory plots in Eastside Mixed Conifer Forest, East Cascades/Blue Mountains, Larger Trees vegetation condition. (a) Density of snags ≥50 cm dbh and ≥2.0 m tall (n = 168). (b) Cover of down wood ≥12.5 cm diameter (n = 166).

have tolerance levels above corresponding inventory tolerance levels for large snags (Figure 1). Wildlife selection of snag and down wood clumps should be taken into consideration when dead wood habitat is managed.

In addition, the inventory estimates of down wood cover may be lower than the wildlife data values because most wildlife studies included decay class 5 down wood, which often is the most abundant class (Spies et al. 1988), whereas the inventories did not consistently include decay class 5 (Ohmann and Waddell 2002). Also, the minimum diameter of down wood measured on inventory plots was 12.5 cm but for most wildlife studies was 10 cm.

Sources of Variation in the Wildlife Data

High variance among wildlife use studies can result in wide tolerance intervals (e.g., the pileated woodpecker points for large snag density, Figure 1a). Sources of variability include differences among studies in methodology, plot size, and size and decay class breaks. Authors did not always report complete information on how measurements were taken. Where provided, we included these explanations in DecAID. Variability in the data also may arise from variation among individuals in a wildlife population and from variations in habitat conditions across study sites or across entire research studies over both space and time. The various sources of variability may result in outlier values, particularly in the cumulative species curves for 30 and 80% tolerance intervals. Published studies do not provide sufficient data to partition out the relative contributions of each source of variability nor to calculate propagation of error across multiple sources. However, any potential bias in our summaries is probably reduced with greater numbers and extent of studies within a vegetation condition. We provide underlying data from all individual studies in DecAID and encourage the user to become familiar with them and potential sources of bias.

Sampling and Scale Considerations in Interpreting the DecAID Summaries

The characterizations of dead wood populations must be interpreted in light of the inherent spatial scale (grain and extent) imposed by the inventory and plot designs. Individual observations (plots) consist of a sample of dead wood over approximately 1 ha. The distribution and estimated variation of dead wood across a sample of plots in a vegetation condition is a function of the interaction of plot size with the abundance and spatial pattern of dead wood in the landscape. For example, smaller plot sizes (or shorter transects) yield estimates with greater variation, because smaller plots are more likely to sample within dense clumps of dead wood or within gaps with no wood. Because the plots sample an area that is smaller than a typical forest stand, the plot-level observations should not be viewed as representing stand-level conditions. Rather, the summaries describe the aggregate properties and variability of dead wood on multiple 1-ha plots that sample a given vegetation condition across a large landscape or region.

Wildlife data summarized in DecAID can be applied to management and planning decisions at a range of spatial scales and geographic extents. Although the calculated wildlife tolerance levels can be applied to stand-level management decisions, it usually is not appropriate to apply one value (a particular tolerance level) to every stand across a landscape because stands vary in history, composition, dynamics, and environmental setting. Instead, decisions on distributing different levels of dead wood across a landscape can be guided by the relative frequency distribution information from unharvested plots (Figure 5).

Tolerance levels and distributions summarized from inventory data also can be applied at multiple scales. As a general rule, we recommend geographic extents of no smaller than approximately 50 km^2 in size, which is the small end of the range of sizes typical of watersheds in our regions at the level of fifth-field hydrologic unit codes. The wildlife and inventory summaries also are appropriately applied to very broad planning areas, such as for regional assessments or National Forest planning. The maximum size planning area to which the DecAID summaries are appropriately applied is limited only by the geographic distribution of the wildlife studies and inventory plots used in the summaries, in most cases all of Oregon and Washington.

Spatial Distribution of Dead Wood in the Landscape

Unfortunately, the inventory data and wildlife studies do not contain information on the spatial distribution of dead wood at local (plot or stand) nor landscape scales. However, if the primary objective is to manage for natural vegetation conditions rather than focusing on wildlife species, one approach is to mimic the distribution of unharvested area in different snag density and down wood cover classes (Figure 5) across a landscape or watershed as a reference or guide. Although wildlife studies indicate that species often use clumps of snags and down wood, for most forest types there is little specific guidance in the literature on the inherent spatial distribution of dead wood nor on the number or size of dead wood clumps used by wildlife that could guide management.

Unharvested Plots as an Approximation of Natural Conditions

Current dead wood on a site is strongly influenced by disturbance and by the wood inherited from the preceding stand. Unfortunately, information on the disturbance history of the plots was limited. Plots in unharvested, unroaded forest, which we used in DecAID to characterize natural conditions, have been influenced to varying degrees by fire suppression, exotic pathogens, and other anthropogenic factors. Because of decades of fire exclusion, areas with a historical disturbance regime of frequent fires may have missed several fire cycles, often resulting in ingrowth of smaller trees of more shade-tolerant species. Suppression (self-thinning) mortality and increased insect and disease in these denser stands may have increased density of smaller snags but not necessarily larger snags (Korol et al. 2002). However, information on historic amounts of dead wood available from other sources (Agee 2002, Korol et al. 2002, Brown et al. 2003) are similar to the amounts on the unharvested inventory plots (Mellen-McLean 2006).

Limitations of the DecAID Approach for Guiding Dead Wood Management

Although based on imperfect data, DecAID represents the best data available on snags and down wood. Cautions and limitations associated with the underlying data are thoroughly documented in DecAID (Mellen-McLean et al. 2009) and need to be referenced by users when DecAID is applied to projects. Used properly, DecAID can help guide management of dead wood to meet management goals. We assume that the meta-analysis approach of DecAID, combining data from across multiple studies and providing a comparison to forest inventory data, strengthens the evidence over applying data from individual studies.

DecAID provides a static picture of relationships between wildlife and dead wood and of dead wood conditions across the current landscape. The dynamics of dead wood over time is an important consideration in managing wildlife habitat. Forest managers will need to use additional analytical tools to address temporal considerations, such as the fire and fuels extension to the Forest Vegetation Simulator (Reinhardt and Crookston 2003). A summary of available information on dead wood dynamics is provided on the DecAID website (Mellen-McLean et al. 2009).

The ultimate and really the only authentic measure of the effectiveness of snag and down wood management guidelines is how well they provide for fit individuals and viable populations. Few, if any, studies we reviewed truly measured fitness and viability, and most studies did not report demographics (population density and trend) in relation to dead wood habitat. Because of the difficulty and expense, we are unlikely to ever have rigorous, controlled, replicated experiments designed specifically to address this question. Lacking this, it is our fundamental assumption that patterns of species use and selection of dead wood size and amounts represent behaviors that have adaptive advantage for the species and that serve to bolster individual fitness. This assumption underlies our suggesting the use of the cumulative species curves to help guide dead wood management, even if they are based on post hoc observational studies in selected sites and not necessarily on more rigorously controlled manipulative experiments.

Applications to Forest Management

In the Pacific Northwest, DecAID currently is being used to assess wildlife habitat contributions of dead wood for timber sales, including salvage after wildfire, and other forest management projects and regional assessments, including forest plan revisions. The Pacific Northwest Region of the US Forest Service has developed a detailed guide to the interpretation and use of the DecAID Advisor (US Forest Service 2009) to provide suggestions and examples of how to use the data in DecAID to assess impacts of projects on dead wood and dependent species.

Conclusions

Tolerance intervals are appropriate for describing proportions of observed (sampled) populations and aid in viewing the data probabilistically and using it in risk management. We think tolerance intervals, corrected as necessary for small sample size, non-normal distributions, and differing sampling intensities, are more meaningful and appropriate than confidence or prediction intervals for representing percentages of observed populations of wildlife use and inventories of dead wood.

Moreover, we have presented details of our methods of combining information across studies because others may find value in the same approach for a wide variety of other forest management issues that pertain to questions such as how much habitat is enough to provide for particular species (e.g., Kautz et al. 2006) or land area for biodiversity conservation (e.g., Brashares and Sam 2005, Chen et al. 2006), Our approach can complement other methods of identifying management thresholds such as use of individual-based dispersal models and area-optimization models, and provides a new way to answer otherwise intractable questions with empirical data.

Tear et al. (2005) called for scientific rigor in defining quantitative objectives in conservation. Our method is rigorous but flexible in that it allows managers to view outcomes at multiple tolerance levels. Results also can be used both ways, such as discerning the proportion of a natural entity (e.g., a snag-using wildlife population) that could be provided by a particular condition (e.g., a particular density of snags of a given size), or, alternatively, what condition (snag density) would be needed to provide for a desired natural condition (population level). In this way, our approach could be generalized into a means of statistically defining thresholds for managing ranges of natural variation of forest ecosystems and communities (e.g., Cyr et al. 2009).

Our approach entails combining available inventories and studies to furnish managers with a repeatable, rigorous basis for decisionmaking. However, the degree of confidence, statistical tolerance, and proportion of a population, community, or natural system that is to be conserved ultimately is a matter of ownership goals and public policy, which, at best, would be informed by statistically sound analyses as provided by our method.

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