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Simulations of snag dynamics in an industrial Douglas-fir forest

George F. Wilhere*

Washington Department of Fish and Wildlife, Wildlife Program, 600 Capitol Way North, Olympia, WA 98501, USA

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Abstract

Industrial silviculture is known to reduce snag density, but snag dynamics in industrial forests are poorly understood. I developed a simulation model that integrated a snag model and a well-known forest growth model, the forest vegetation simulator (FVS). A new snag model was developed by averaging the outputs of four independently created snag models. The four models were for Douglas-fir snags in forests west of the Cascade Crest in Oregon, Washington, and British Columbia. Forest growth and snag dynamics were simulated under a typical silvicultural regime and current occupational safety and environmental regulations. The results indicate that management practices like those simulated yield: (1) small and medium diameter snags at moderate densities (20 snags per hectare (sph)) for short periods of time (5–10 years); (2) a snag population with high temporal variation fluctuating between 4.2 and 22.5 sph; (3) mean densities of small, medium, and large snags equal to approximately 3.9, 6.2, and 0.1 sph/decade; and (4) a soft snag density of 0.1 sph/decade. Snag recruitment curves generated through simulations showed that to increase mean snag density per decade by 1 sph, the number of snags retained must be increased by about 1.4 sph. The mean density of snags per decade produced under the typical silvicultural regime was projected to be about 20% that found in unmanaged stands. The density of large snags was projected to be less than 1% that found in unmanaged stands. Sensitivity analysis showed that simulator output was slightly sensitive to error in snag model parameter estimates. Considering the lack of long-term empirical studies on snag dynamics, and the dearth of information on compliance with safety and environmental regulations, models like this one represent the best available scientific information upon which to base forest management decisions affecting snag resources.

Keywords: Snag dynamics; Coarse woody debris; FVS; Forest simulation; Silviculture

1. Introduction

Snags, i.e., dead trees, are a vital component of forest ecosystems (Neitro et al., 1985; Harmon et al., 1986). This relatively recent realization by forest managers has led to general principles for snag management (Franklin et al., 1997). However, forest managers desire more prescriptive, scientifically defensible recommendations for managing snag resources. Unfortunately, our current understanding of snag ecology is inadequate for the task. Our ignorance stems from former silvicultural paradigms that strove to eliminate stand "decadence" and maximize harvestable wood fiber. "New forestry" paradigms (Franklin, 1989) acknowledge the ecological value of snags and

* Tel.: +1-360-902-2369; fax: +1-360-902-2162.
E-mail address: wilhegfw@dfw.wa.gov (G.F. Wilhere).

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recognize that proper stewardship of forest ecosystems demands attention to the creation, condition, and longevity of snags, i.e., snag dynamics (Rose et al., 2001).

1.1. Snag dynamics

The study of snag dynamics in the Pacific Northwest goes back to the first half of the 20th century (Keen, 1929; McArdle, 1931; Dahms, 1949). These studies were situated in the drier Ponderosa pine and Douglas-fir ecoregions where snags were branded a ''menace'' because they increased fire hazard. Forest managers wanted information with which to predict the degree of fire hazard posed by snags over time. In contrast, recent studies of snag dynamics have emphasized the essential ecological role of snags (Cline et al., 1980; Harrod et al., 1998; Everett et al., 1999; Parks et al., 1999).

Snag dynamics refers to changes in a snag population over time. The population attributes of greatest interest to forest managers are: abundance or density, size (both diameter and height), state of decay, and tree species. These attributes can be represented by stand averages or distributions that change over time. The population dynamics of live trees profoundly influence snag dynamics. Suppression mortality, disease, and physical injury (e.g., damage by wind or ice) affect the number, sizes, and species of dead trees entering a snag population (Harmon et al., 1986). Episodic events such as wildfire and timber harvest can dramatically increase or decrease snag density and alter other characteristics of a snag population, such as the distribution of snag heights. Snags exit the population by falling down or by losing height.

West of the Cascade Crest, all published studies of snags have been static. That is, they characterized snags in a set of stands at a single point in time (Cline et al., 1980; Spies et al., 1988; Ohmann et al., 1994). If the set of stands forms a chronosequence, then snag dynamics can be inferred. This was the approach taken by Cline et al. (1980), who studied snags in 20 unmanaged and 10 managed forest stands. However, the silvicultural regimes applied to their managed stands bore little resemblance to the regimes used in privately owned, intensively managed forests. Hence, their results provide little insight into snag dynamics under industrial silviculture.

The lack of empirical data on snag dynamics in managed forests has motivated computer simulations. Simulations by Neitro et al. (1985) explored snag dynamics in an even-aged stand managed on a 100-year rotation. Oliver et al. (1994) simulated both even-aged and uneven-aged regimes applied east of the Cascade Crest. Neither study is applicable to industrial forests west of the Cascade Crest.

1.2. Snags in managed forests

Managed forests typically have fewer snags and smaller snags than unmanaged forests (Cline et al., 1980). For coniferous forests on nonfederal lands in western Washington and Oregon, Ohmann et al. (1994) estimated the density of snags ($\geq$27.9 cm dbh, $\geq$2 m tall) to be 3.1 snags per hectare (sph) in managed stands but 46.8 sph in old-growth stands. Managed stands less than 55 years old had only 1.0 sph larger than 63.5 cm dbh, but old-growth stands had 19.5 sph this size. These data clearly demonstrate an anthropogenic impact on snag resources, but they do not describe the temporal dynamics of snags within managed forests.

Degradation of snag resources in managed forests has come about for five reasons. First, snags are dangerous (DNR et al., 1992); they can fall unexpectedly during silvicultural operations. If a snag strikes a worker, the injuries incurred can be fatal (Myers and Fosbroke, 1995; Egan, 1996). Hence, if workers are in the vicinity of an unstable snag, occupational safety regulations (OSRs) require that it be felled (e.g., Washington Administrative Code 296-54-507(7); Oregon Administrative Rules 437-006-0035; Code of Federal Regulations 29, Part 1910). The snag can be retained if a no-entry safety zone is established around the snag, but valuable timber within the zone becomes unharvestable. Second, snags that get in the way of yarding corridors or skidder trails are felled. Third, recently dead trees may still be merchantable and are harvested for their monetary value. Fourth, intermediate silvicultural treatments, such as commercial thinning, strive to reduce tree mortality but suppression mortality is a major cause of small snags in developing forests (Oliver and Larson, 1990). Fifth, industrial forests in the Pacific Northwest employ relatively short harvest rotations of about 50 years (Lippke et al., 1996). Fifty year-old managed stands of Douglas-fir rarely contain boles large enough to satisfy the habitat needs of wildlife species that depend on large snags (≥63.5 cm dbh). In short, the number of snags in industrial forests is declining because maintaining or enhancing snag resources raises the financial cost of forest management.

Providing snags is costly to private forest managers, but eliminating snags is detrimental to wildlife, which are public resources. Numerous wildlife species use snags for forging or nesting. In Washington State, for instance, approximately 102 terrestrial vertebrates use snags and 56 of those species nest or den only in the boles of dead or dying trees (WDFW, 1995). A number of species, such as pileated woodpecker (*Dryocopus pileatus*; Bull and Jackson, 1995), Vaux's swift (*Chaetura vauxi*; Bull and Collins, 1993) and fisher (*Martes pennanti*; Lewis and Stinson, 1998), depend on large diameter snags (≥63.5 cm dbh) for nesting or denning. The density of cavity-nesting birds has been repeatedly found to correlate with the density and size of snags (Mannan et al., 1980; Raphael and White, 1984; Zarnowitz and Manuwal, 1985; Schreiber and deCalesta, 1992). Therefore, ecologically significant reductions in the snag density and size increase the risk of significant adverse impacts to wildlife resources.

For the purposes of protecting wildlife resources, environmental regulations (ERs) require that "wildlife reserve trees" (WRTs) be retained at the time of clear-cutting. WRTs can be dead, dying, damaged, or defective trees that provide habitat for wildlife. In Washington State west of the Cascade Crest, forest mangers must retain 7.4 WRTs and 4.9 live trees/ha harvested (Washington Administrative Code 222-30-020(11)). However, if the stand contains an insufficient number of WRTs to satisfy the regulation, no other mitigation is required. WRTs must be at least 30.5 cm dbh and 3.0 m tall, however, if more than enough WRTs are available to satisfy the regulation, then the largest diameter WRTs must be retained. If WRTs create a significant safety hazard, then they can be felled. The live trees retained must be least 25.4 cm dbh and 9.1 m tall. These live trees are also known as "recruitment trees" because they are intended to become snags some time in the future. In neighboring Oregon, there is no requirement to leave snags. Instead, forest managers must retain 4.9 snags or 4.9 live trees/ha harvested that are at least 27.9 cm dbh and 9.1 m tall (Oregon Revised Statutes 527.676(1)).

Regulations requiring the retention of snags and live trees are fairly recent. Washington and Oregon adopted them in 1992 and 1991, respectively. When these regulations were developed, snag dynamics in an industrial forest were not considered (DNR, 1992), primarily because the information to do so was not readily available.

1.3. Purpose and objectives

Forest managers regularly make decisions regarding the management of snag resources. But since our current understanding of snag dynamics is inadequate, forest managers may inadvertently make decisions that cause adverse impacts to snag-dependent wildlife species. Managers and policy makers need the best available science distilled into a form that can guide management decisions. Often the distillation process involves modeling. A model that links snag dynamics to different management scenarios could be used to project likely impacts. This study's purpose was to develop such a model. The objectives were to: (1) develop a simulation model for snag dynamics in a commercial forest; (2) simulate snag dynamics under silvicultural regimes typical of commercial forests in west of the Cascades; (3) project the likely effects of commercial forest management on snag dynamics; and (4) explore how changes to regulations and silvicultural regimes effect snag dynamics.

2. Methods

In Washington and Oregon, snag dynamics in commercial forests are largely determined by: (1) silvicultural regimes designed to maximize fiber production; (2) government regulations for worker safety; and (3) government regulations for wildlife conservation. How these conflicting concerns interact to affect the density and size of snags over a single harvest rotation or multiple rotations is largely unknown. A computer simulation model was developed to explore the effects of current silvicultural practices and government regulations on snag dynamics. My approach was to meld two models—the forest vegetation simulator (FVS) and a snag dynamics model.

2.1. Defining snags

How a snag is defined will affect the model's output. The minimum physical dimensions of snags have been variously defined (e.g., Thomas et al., 1979; Cline et al., 1980; Neitro et al., 1985; Spies et al., 1988). For the purposes of modeling, I too had to define minimum snag dimensions. Because most of the information I used was derived from the forest inventory and analysis program (FIA) of the US Forest Service, the minimum dimensions of FIA were used. FIA defines snags as dead trees at least 22.5 cm dbh and 2 m tall (J.L. Ohmann, USDA Forest Service, personal communication). Luckily, these dimensions are smaller than the regulatory definition of WRTs, e.g., at least 30.5 cm dbh and 3.0 m tall.

A snag's state of decay, or hardness, affects its probability of falling. In the Pacific Northwest, the five-class system of Cline et al. (1980) is commonly used to describe a snag's state of decay (but see Bull et al., 1997). Decay class I is the least decayed and decay class V is the most decayed. Prior to Cline et al. (1980), snags were often classified as either hard or soft (Thomas et al., 1979). Cline et al. (1980) identified decay classes I and II as hard snags and classes III–V as soft snags. Subsequent users of similar five-class systems (Neitro et al., 1985; Marcot, 1992; Everett et al., 1997) equated class III with hard, but others have equated class III with soft (Jimerson, 1989; Everett et al., 1999). The discrepancy over decay class III could be because it is neither hard nor soft but "intermediate", with physical properties very different from classes II and IV (Mellen and Ager, in press; J.L. Ohmann, personal communication). For the purposes of modeling, I had to choose a system for describing snag decay. FIA data from the 1970s used the simple hard/soft classification system, and since much of the information I used originated from the 1970s, this simple two-class system was used. More recent data collected by FIA has designated class III snags as hard (J.L. Ohmann, personal communication).

2.2. Modeling snag dynamics

By far, the most common tree species in commercial forests of the Pacific Northwest is Douglas-fir, and therefore, my snag model was developed for Douglas-fir only. At present, four snag models are available for Douglas-fir snags west of the Cascade Crest: the snag recruitment simulator (SRS; Marcot, 1992), the snag dynamics projection model (SDPM; McComb and Ohmann, 1996), the coarse wood dynamics model (CWDM; Mellen and Ager, in press), and a snag model incorporated into the table interpolation program for stand yields (TIPSY; Stone, 1996). Each model is based on a different data set, although SDPM and CWDM have a large amount of data in common. Most of the data used to develop SDPM, CWDM, and the snag model in TIPSY were collected from managed stands; one-third of the stands used to develop SRS were managed stands.

None of the four models have undergone rigorous peer review. However, the models have been described in the "gray literature" (Rose et al., 2001; Mellen and Ager, in press; Stone, 1996), and at least two of the models (SRS and CWDM) have been used as planning tools by forest managers. As a whole, the four models can be considered the best available science for Douglas-fir snag dynamics. Upon examination, none of the four models seemed substantially superior to the others. For this reason, the outputs of the four models were averaged to predict the rate of snag fall. CWDM was also used to predict snag height loss and decay.

SRS is based on data from Cline et al. (1980) who reported decay rates and fall rates for Douglas-fir snags in western Oregon. SRS is similar to the life-table model in Neitro et al. (1985). SRS calculates snag densities per decade in an even-age forest, and it tracks snag density by both decay class and size class. The main limitations of SRS are the small number of site conditions represented by the data and that it is based on a chronosequence.

SDPM was developed from tree remeasurement data collected from the 1970s to 1990s on permanent plots of FIA. Plots sampled nonfederal lands across western Washington (990 plots). Remeasurement data were for one 10-year period. At the first measurement, all live and standing dead trees were tallied and measured. At remeasurement, trees previously tallied as snags were noted as still standing, fallen, or harvested. SDPM is based on more than 1000 Douglas-fir snags. SDPM uses equations developed from logistic regression to predict the probability of an individual snag falling in a 10-year period. Independent variables considered included attributes of the snag itself (diameter and height) and site attributes such as elevation, slope, aspect, mean annual temperature, and mean annual precipitation. The following equation from SDPM predicts fall rate for Douglas-fir snags:

$$N(t+1) = \frac{N(t)}{1 + \exp(b_0 + b_1\,\mathrm{ASP} + b_2\,\mathrm{DBH})} \quad (1)$$

where N is the snag density; t the decades since tree death; b_0, b_1, and b_2 are the constants derived from the regression; ASP the topographic aspect of the stand; and DBH the diameter of the snag. Since snag diameter changes as a snag decays, DBH is described by a separate time-dependent function. A generalized snag fall rate can be obtained by averaging SDPM output for different aspect values, i.e., 0°, 45°, 90°, 135°, 180°, 225°, 315°, and 270°. The main limitations of SDPM are that it is based on only one remeasurement period and that for the vast majority of snags the time since tree death is unknown.

The snag model in TIPSY was based on data collected throughout the Vancouver forest region (Stone, 1996; J. Stone, British Columbia Ministry of Forests, personal communication). Between 1971 and 1975, 85 experiment installations were established to determine the effects of fertilization and thinning treatments. Permanent plots were revisited four times at 3-year intervals and thereafter at 6-year intervals (Darling and Omule, 1989; Stone, 1994). Snag data collected from about 110 untreated control plots were used to develop a linear logistic equation that relates the probability of a snag standing to its age and diameter. The equation is of the form (Mitchell et al., 2000):

$$\mathrm{prob(standing)} = \frac{1}{1 + \exp(c_0 + c_1\,\mathrm{YEARS} + c_2\,\mathrm{DBH})} \quad (2)$$

where c_0, c_1, and c_2 are the constants derived from the regression, YEARS the time since tree death, and DBH the diameter of the snag.

Data for CWDM were taken from about 1258 FIA plots in western Washington. Data were collected in the late 1970s and again in the late 1980s. To predict snag fall, CWDM assumes an exponential decay Cequation of the form (Mellen and Ager, in press):

$$N(t) = \begin{cases} N_0, & t \le L, \\ N_0 \exp(-b_x[t-L]), & t > L \end{cases} \quad (3)$$

where N_0 is the initial number of snags, t the years since tree death, b_x a fall rate for size/decay class x, and L a lag period during which no snags fall. Values for L are given in Mellen and Ager (in press). CWDM has three size classes (<38.1, 38.1–63.4, ≥63.5 cm dbh). The FIA program only tallied and measured snags that were at least 22.5 cm dbh. Hence, the smallest size class is more accurately described as 22.5–38.0 cm dbh. CWDM has three decay classes: hard, intermediate, and soft. Hard corresponds to decay classes I and II, intermediate to decay class III, and soft to decay classes IV and V. Because the older FIA measurements used only hard and soft decay classes, parameter values for the intermediate class were impossible to estimate directly. Instead, they were arrived at indirectly through interpolation between the parameter values of the hard and soft decay classes.

In my model, snags cease to be functional when they are less than 2 m tall. CWDM was used to determine the height of snags over time, and hence their maximum lifetime as snags. To predict snag height loss, CWDM uses an equation of the form

$$H(t) = \begin{cases} H_0, & t \le L, \\ H_0(1-p_x)^{t-L}, & t > L \end{cases} \quad (4)$$

where H_0 is the initial height of the snag, p_x the annual proportional loss of height for size/decay class x, and again, L is a lag period.

CWDM includes equations that describe the loss of biomass (i.e., wood density) over time (Mellen and Ager, in press), and CWDM uses these equations to predict when snags will transition from one decay class to the next. CWDM assumes that when a snag's wood density drops below a certain value it crumbles into duff. In CWDM this determines the maximum age of a snag. The crumbling of a snag as predicted by the biomass equations could happen before the snag shrinks to the minimum height as predicted by Eq. (4). According to CWDM, this will happen for small snags, and therefore, I used wood density to determine the maximum age of small snags. For other size classes, height loss determined a snag's maximum lifetime. The maximum life spans of small, medium, and large snags were 70, 110, and 200 years, respectively.

I made three modifications to CWDM. The first was motivated by the intended application—exploring the effects of commercial forest management on snag dynamics. Preliminary simulations with FVS indicated that in an intensively managed industrial forest, snag diameters would rarely exceed 88.9 cm. However, the FIA data for the largest snag size class spanned a range from 63.5 to 289.6 cm, with a median diameter of approximately 101.6 cm. The large proportion of snags greater than 88.9 cm would bias the simulation results. To correct this bias, I redefined large snags to be 63.5–88.9 cm, obtained the data used to develop CWDM (K.L. Mellen, USDA Forest Service, personal communication), and re-estimated b_x values for the new truncated large size class using Eq. (3). Using equations relating tree height to diameter (Donnelly, 1997), I determined that all large hard snags in the data set had lost height prior to the first measurement, and therefore, I assumed that no large snags were in the lag period. Hence, L was set to zero for the purposes of parameter estimation. I also re-estimated p_x values for the height loss equation. Using Eq. (4), p was calculated for each snag. p_x is the mean p for size/decay class x.

The second change to CWDM was a reinterpolation of parameter values for the intermediate decay class. For my own interpolation, I assumed that b_x and p_x change at the same rate as wood density. I further assumed that for a given size/decay class, the values of b_x and p_x occur at the temporal midpoint of that class's duration. Under these assumptions, the curve generated by CWDMs biomass equation can be used to interpolate between the parameter values of hard and soft snags. The third modification to CWDM was to correct a programming error.

I averaged the outputs of the four models to create a new model—the mean snag model (MSM). The output of each model was transformed to a snag survivorship curve, i.e., the percentage of snags remaining per decade. This was done by size class, where the size classes were 22.5–38.1, 38.1–63.4, and 63.5–88.9 cm dbh; hereafter referred to as small, medium, and large snags, respectively. To obtain 90% confidence intervals about the mean survivorship curve, the variance was calculated using arcsin transformed percentages (Zar, 1984). Finally, decadal survival probabilities were calculated from the mean survivorship curves and confidence limit curves. MSM is a life-table model of the form

$$
\begin{aligned}
N_{z+1} &= 0 \\
N_z &= S_z N_{z-1} \\
&\vdots \\
N_3 &= S_3 N_2 \\
N_2 &= S_2 N_1 \\
N_1 &= S_1 N_0
\end{aligned}
$$

where N_t is the number of snags in a cohort t decades old and S_t the proportion of snags that survive (i.e., remain standing) from decade $t-1$ to decade t. N_z is the number of snags in the oldest cohort and z the maximum age allowed for the size class. A snag cohort consists of trees of the same size class that died in the same decade.

2.3. The FVS

The FVS was used to simulate forest growth and development. FVS is based on the Prognosis Model (Wykoff et al., 1982; Wykoff, 1986), which was developed as a tool for comparing the stand-level response of forests to different silvicultural treatments (Teck et al., 1996). FVS is an individual-tree/distance-independent growth model (Ritchie, 1999). Two particularly powerful features of FVS are the event monitor (Crookston, 1990; Van Dyck, 1999) and regional variants. The event monitor allows the user to (1) schedule silvicultural treatments or other actions according to events occurring in the stand; and (2) incorporate user-defined mathematical equations and logical expressions. The latter allowed me to integrate the MSM equations into FVS, resulting in a single simulation model. The event monitor is programmed through "key word files".

FVS is made region-specific through regional variants of the model. That is, model parameters are estimated with data collected in a particular ecoregion. I used the Pacific Northwest Coast Variant (Donnelly, 1997). The small tree sub-model of the Pacific Northwest Coast Variant generates slightly inaccurate height growth predictions (Gary Dixon, USDA Forest Service, personal communication). To correct this problem, I modified the sub-model output using the regeneration height growth multiplier of FVS (Hamilton, 1994). I iteratively searched for a corrective multiplier by adjusting its value until the height of the 10 tallest trees approximately equaled the desired site index at total age of 58 years. On sites of moderate productivity, total age equals approximately breast height age plus 8 years (King, 1966).

FVS has its shortcomings. For example, FVS assumes that the stand is uniform across space, and therefore, FVS is not an appropriate model for exploring stand dynamics when stems are clumped. Clumping of snags and live trees is sometimes done to comply with regulations for structural retention. Also, the event monitor has a limited memory capacity, which restricts the number of variables, mathematical equations, and logical expressions that can be implemented. For instance, because of memory limitations, the model could track only two decay classes per snag size class. Hence, the number of snags in the intermediate decay class were not tallied but were lumped with hard snags.

2.4. Other sub-models

In addition to MSM, two other sub-models added realism to the simulations. These sub-models described: (1) decisions regarding the felling of snags for safety; and (2) windthrow of live trees in clear-cuts.

During thinning or harvest operations, hazardous snags are felled for worker safety. This practice is thought to have a significant impact on snag resources. Deciding which snags pose a serious hazard is rather subjective, and hence, difficult to model. I assumed that all soft snags are considered hazardous (hazard probability = 1) and that the newest hard snags are considered safe (hazard probability = 0). For older hard snags, I further assumed that the hazard probability was related to its survival probability. I then created snag hazard functions based on snag survivorship curves that interpolate the hazard probability between the newest hard snags and soft snags. Snags of decay class III could be considered either hard or soft. To address this uncertainty, I constructed the functions twice: once with decay class III as hard and once with decay class III as soft, and then averaged the two functions. The resulting functions

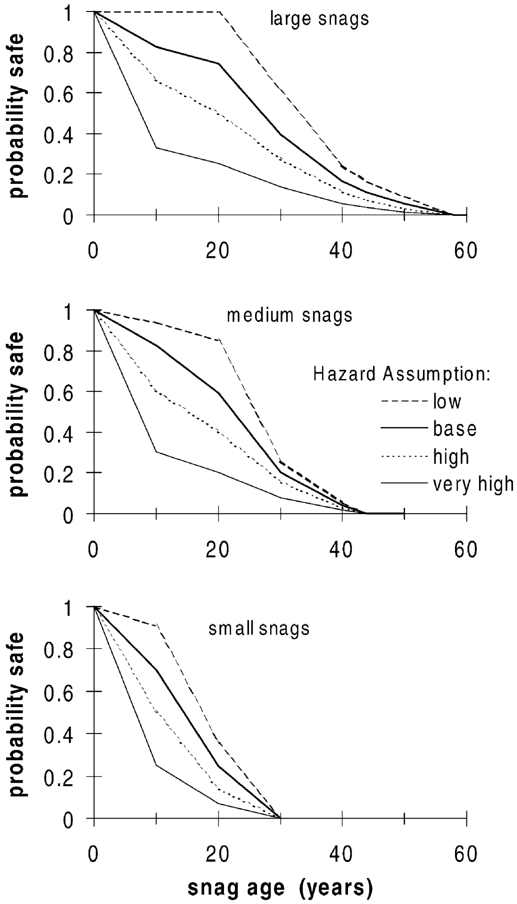

Fig. 1. Hazard curves for snags by diameter class. Base assumption derived from mean survivorship curves of MSM (Fig. 2). Low and high hazard assumptions derived from upper and lower limits of 90% confidence interval (Fig. 2). Very high hazard assumption equals half of high hazard assumption for snag age greater than 0.

(Fig. 1) give the proportion of snags in each cohort considered unsafe, and consequently, felled. Four curves were created for each snag size class. The curves were based on the mean survivorship curve (the base assumption), the upper and lower 90% confidence limits of the survivorship curve (the low and high hazard assumptions), and one-half of the lower 90% confidence limit (the very high hazard assumption).

Live trees retained in a clear-cut are exposed to winds and are vulnerable to windthrow. These trees are intended to become future snags, and therefore, windthrow could have a significant impact on snag resources. Unfortunately, few data were available with which to develop a model. I calculated geometric mean annual windthrow rates from data in Issac (1940), Adler (1994), and Schreiber (1998). Values from each study were 4.0, 5.0, and 3.1% of live trees per year, respectively. The arithmetic mean windthrow rate of the three studies was 4.0% per year. Therefore, the rate of windthrow over 10 years was 33.7% of live trees. Some proportion of windthrown trees are broken stems that become snags. Adler (1994) reported that about 19% of windthrown trees were broken stems, and Schreiber (1998) reported that 43% were broken. The mean is equal to 31%.

I assumed that trees retained in clear-cuts are completely windfirm after 10 years. Literature reviewed in Adler (1994) suggests that trees should be stable after 10 years, while Issac (1940) observed that most windthrow occurs during the first 10 years after logging. In the model, the probability of windthrow was not a function of stem diameter, the same proportion of trees were damaged in each diameter class, but broken trees were assigned to snag size classes according to stem diameter.

2.5. The complete simulation model

The complete simulation model consisted of FVS and keyword files that modeled snag dynamics, windthrow, and silvicultural treatments such as planting, thinning, and final harvest. Forest management scenarios and snag fall rates were changed by modifying program code or parameters in key word files. FVS can be run as a stochastic or deterministic simulation (Hamilton, 1991); my simulations were deterministic.

FVS was programmed to report tree mortality by size class every simulation cycle. Most cycles were 10 years, but some were altered to 5 years when silvicultural treatments occurred mid-decade. The number of dead trees was then passed on to the snag model. Snags were lost from every cohort each decade due to natural fall rates. The 10-year cumulative effect of windthrow was simulated as a single event 10 years after a clear-cut harvest. Some snags were felled immediately prior to pre-commercial thinning, commercial thinning, or final harvest because they were unsafe or because the number of snags exceeded regulatory requirements.

2.6. Forest management scenarios

I simulated realistic management scenarios to explore the effects of silvicultural regime and government regulations on snags. However, I made two unrealistic assumptions regarding ERs. First, I assumed spatially uniform snag and tree retention, but in practice, loggers typically minimize operational difficulties by retaining most snags or trees along the edges of a stand. Second, I equated WRTs with snags, but in fact, WRTs can be live trees that are dying, damaged, or defective.

The simulated silvicultural regime is typical of those used in industrial forests of the Pacific Northwest (J. Light, Plum Creek Timber Company, personal communication), and consisted of: (1) planting 2 year-old, Douglas-fir seedlings at 1075 ha^{-1}; (2) pre-commercial thinning from below at age 15 years to a residual density of 741 trees/ha; (3) commercial thinning from below at age 30 to a residual density of 346 trees/ha; and (4) clear-cut harvest at age 50 years. Final harvest and planting occurred simultaneously, but in reality could be separated by many months.

All simulations assumed a Douglas-fir site index of 105 (base age 50; King, 1966), which represents a site of moderate productivity (site class III) fairly typical of western Washington. Simulation duration was three harvest rotations. The first rotation started from bare ground. The lack of snags and live trees represented typical starting conditions before regulations for snag retention were instituted. Snag and live tree retention at the beginning of the second and third rotations was dictated by the management scenario.

The various snag management scenarios were: (1) retain none; (2) retain all; (3) OSR-only; (4) ER-only; and (5) both sets of regulations simultaneously, known as OSR and ER. For retain none, all snags were felled during every silvicultural treatment and no live trees were retained at the time of final harvest. For retain all, all snags were retained during every treatment and 4.9 "big" trees/ha were retained at final harvest. For OSR-only, hazardous snags were felled during every treatment according to the snag hazard functions (Fig. 1). For ER-only, safety considerations were ignored, but only enough snags and trees to meet the minimum ERs were retained, i.e., 7.4 of the largest snags available and 4.9 "little" live trees/ha. For OSR and ER, both occupational safety and minimum environmental regulations were enforced.

Trees are referred to as big and little to avoid confusion with large and small snags. When retaining little trees, the selected trees are greater than 25.4 cm dbh but the smallest diameter available. When retaining big trees, trees selected are either greater than 63.5 cm dbh or the largest available.

To compare different scenarios the mean snag density per decade was calculated. This metric is the snag density averaged across all decades of the second and third rotations, i.e., post-harvest in year 50 to pre-harvest in year 150 for simulations with a 50-year rotation. To compare variability, the maximum and minimum snag densities in the second or third rotation were used.

2.7. Snag recruitment curves

Recruitment curves illustrate an input–output relationship between snags or trees retained and the mean snag density per decade. Snag recruitment curves indicate how snag dynamics respond to changes in the amount of structural retention. To generate such curves, successive simulations were run with the density of snag and/or live tree retention changed incrementally each simulation. Separate recruitment curves were generated for the retention of snags, little trees, and big trees. The recruitment curve's slope has units of either sph/decade/rsph or sph/decade/rtph, where rsph means retained sph and rtph means retained trees per hectare.

2.8. Sensitivity analysis

2.8.1. Sensitivity to model uncertainties

The four models used to create MSM were of undetermined reliability. Hence, evaluating MSMs sensitivity to modeling assumptions and parameter uncertainty was essential. The two most significant sources of uncertainty were considered to be the survival probabilities of MSM and the assumptions of the hazard model. To evaluate the former, simulations were conducted using survival probabilities derived from the 90% confidence limits of the survivorship curves. To evaluate the latter, simulations were conducted using the four different hazard assumptions described above.

2.8.2. Sensitivity to silvicultural regime

Snag dynamics will be affected by changes to the silvicultural regime, but how much? To answer this question three variables of the regime were changed by +20 and −20%: the residual density of pre-commercial thinning, the residual density of commercial thinning, and the rotation length. Interactions among pre-commercial thinning density, commercial thinning density, and rotation length were not explored.

3. Results

3.1. The snag dynamics model

Values for S_t, snag survival probabilities, are given in Table 1. These values were derived from the snag survivorship curves (Fig. 2). The four snag models gave similar results for small diameter snags but diverged as snag diameter increased. This is reflected

Table 1
Snag survival probabilities by age class and diameter class. Values derived by averaging outputs of four independent snag models. Survival probability set to zero when snag height below minimum (large and medium snags) or snag wood density below minimum (small snags)

Age class (year)	Approximate midpoint age	Snag diameter class		
		Large	Medium	Small
0–9	5	0.957	0.954	0.922
10–19	15	0.930	0.889	0.783
20–29	25	0.874	0.812	0.660
30–39	5	0.780	0.699	0.553
40–49	5	0.729	0.617	0.502
50–59	55	0.703	0.621	0.545
60–69	65	0.752	0.687	0.586
70–79	75	0.814	0.714	0.000
80–89	85	0.843	0.727	0.000
90–99	95	0.837	0.718	0.000
100–109	105	0.831	0.696	0.000
110–119	115	0.852	0.000	0.000
120–129	125	0.873	0.000	0.000
130–139	135	0.874	0.000	0.000
140–149	145	0.875	0.000	0.000
150–159	155	0.876	0.000	0.000
160–169	165	0.877	0.000	0.000
170–179	175	0.878	0.000	0.000
180–189	185	0.880	0.000	0.000
190–199	195	0.881	0.000	0.000
200–210	205	0.000	0.000	0.000

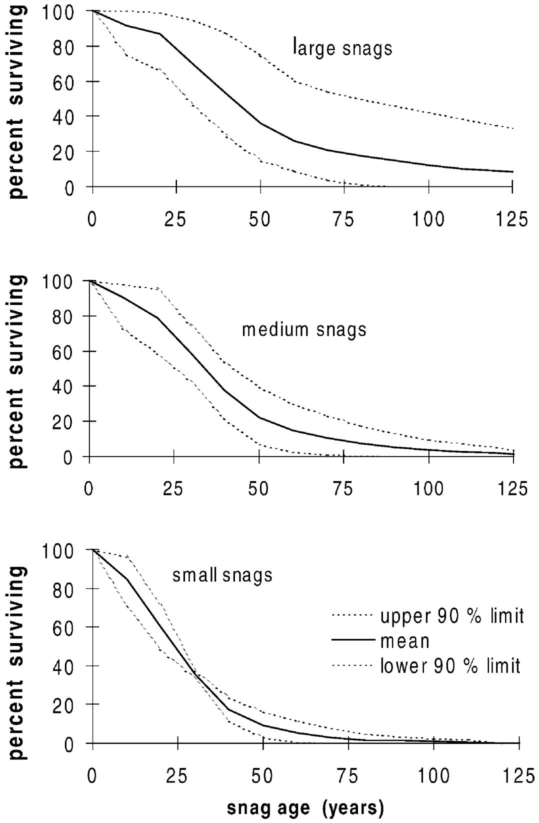

Fig. 2. Mean survivorship curve and 90% confidence interval about the mean for MSM, see text for definition of size classes.

by the relative widths of the 90% confidence intervals about the snag survivorship curves for MSM. Also note that the width of each confidence interval is not constant, but changes with time. Uncertainty is very high for survivorship of large snags older than about 30 years.

The mean survivorship curves show that large snags remain standing much longer than small snags. Starting with age zero cohorts, let t_{50} be the time to reach 50% of the initial cohort size and t_{10} be the time to reach 10% of the initial cohort size. For large diameter snags t_{50} is equal to 41 years, but t_{50} is equal to 34 years for a medium diameter cohort, while a small diameter cohort reaches t_{50} at 24 years. Survivorship curves for small, medium, and large diameter cohorts reach t_{10} at 49, 70, and 110 years, respectively. The shape of the survivorship curve differs between large snags and other snags. For instance, the ratio t_{10}/t_{50} is equal to 2.63 for large snags. In contrast this ratio is equal to 2.04 and 2.05 for small and medium snags, respectively.

3.2. Forest management scenarios

If no snags or trees are retained during silvicultural operations, then snag dynamics exhibit large fluctuations and long periods when no snags are present (Fig. 3A). Snag density peaks immediately before final harvest at 19.8 sph, but after final harvest remains at zero for about 20 years, or about 40% of the 50-year rotation. Following commercial thinning there is also a short period when the stand contains no snags. Mean snag density per decade over two rotations was 4.8, 3.1 sph for medium snags, but 0.0 sph for large snags (Fig. 4).

If all snags and 4.9 big trees/ha are retained, then snag dynamics exhibit smaller fluctuations and much greater snag densities relative to the no retain scenario (Fig. 3B). Snag density peaks just prior to final harvest at 29.1 sph and then falls over the next 20 years to 15.0 sph. The number of snags begins to rise when suppression mortality creates small diameter snags. Mean snag density per decade was 22.9, 13.6 sph for medium snags, and 0.6 sph for large snags. The retention of big trees led to the presence of large snags.

Simulations of current regulations showed that snag density exhibits two peaks over a 50-year rotation: at year 30 prior to commercial thinning and at year 50 prior to final harvest (Fig. 3C). Both silvicultural operations cause an instantaneous decrease in snag density to 7.4 sph, the minimum density required by ERs. After final harvest, snag density gradually drops to 4.2 sph and then increases as suppression mortality recruits small diameter snags. Retention of 4.9 little trees/ha leads to a small number of large snags, 0.1 sph. Mean snag density per decade was 10.3 sph for all snags and 6.2 sph for medium snags. Both densities were less than half that produced when all snags are retained (Fig. 4). Mean densities per decade of soft snags were close to zero—less than 0.1 sph/decade. At time of harvest, 4.9 little trees/ha equaled about 2% of live stems or 1% of total stem volume per hectare.

Separate simulations of occupational safety and environmental regulations demonstrated that environmental regulations dominate snags dynamics. Simulations of OSR-only and ER-only both increased the

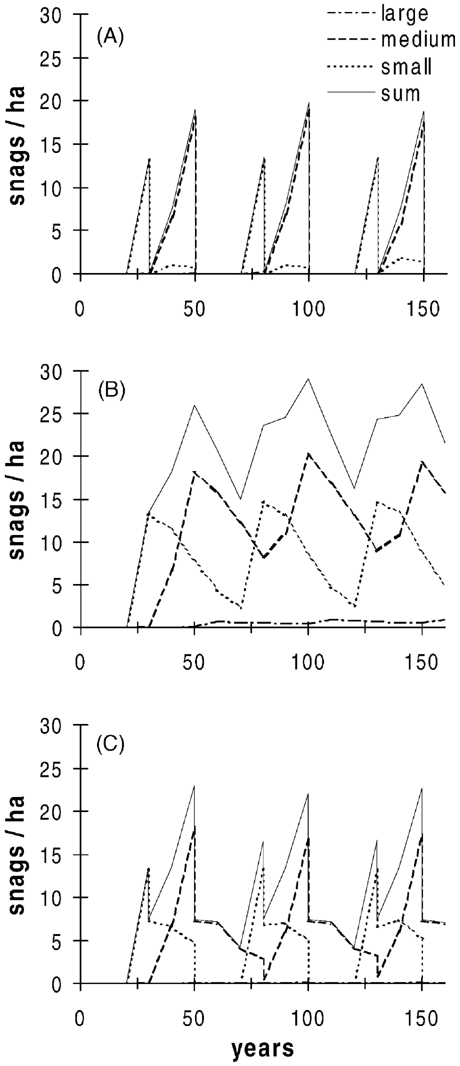

Fig. 3. Simulations of three regulatory scenarios for snag and live tree retention: no snag or live tree retention (A); retention of all snags and 4.9 big live trees/ha harvested (B); and current regulations, retention of the 7.4 largest snags and 4.9 little live trees/ha harvested (C).

mean densities of small and medium snags relative to simulations of OSR and ER. However, simulations of OSR-only resulted in much larger increases than ER-only. Mean snag density per decade for all snags was 14.9 sph for OSR-only but 10.6 sph for ER-only. OSR-only resulted in a greater mean value for medium snags compared to ER-only: 9.42 versus 7.57 sph, respectively. But, OSR-only also resulted in a smaller minimum value for medium snags: 0.5 versus 4.0 sph.

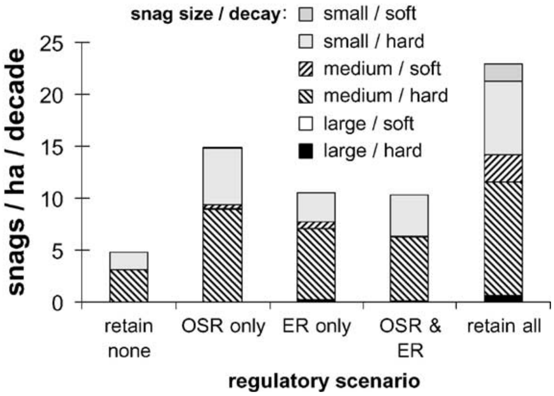

Fig. 4. Mean snag density per decade for five regulatory scenarios. "Retain none" means no retention of snags during silvicultural treatments and no retention of live trees during final harvest. "Retain all" means retain all snags during silvicultural treatments and retain 4.9 big trees/ha during final harvest. OSR-only refers to occupational safety regulations. ER-only refers to environmental regulations.

The minimum density for medium diameter snags occurred in the OSR-only simulations at the time of commercial thinning, year 30 in the rotation. Simulations of ER-only yielded more soft snags (Fig. 4).

3.3. Recruitment curves

Incremental changes to current regulations resulted in recruitment curves that are linear for lower snag retention rates and saturate at higher retention rates (Fig. 5A). Below a retention rate of 12.4 sph, the average slope for snag recruitment curves was 0.70 sph/decade/rsph for all snags and 0.41 sph/decade/rsph for medium snags. In other words, the correspondence between the number of snags retained and the mean density per decade is less than one-to-one. In effect, to increase mean snag density per decade by 1, the number of snags retained must be increased by about 1.4 sph. A unit per hectare increase in mean density per decade of medium diameter snags requires that snag retention be increased by about 2.4 sph. The slope of the curve for large diameter snags is zero and the mean snag density per decade was 0.05.

At snag retention levels greater than about 15 sph, further increases in mean snag density per decade cease. The recruitment curves saturate at 14.8 and 9.1 sph/decade for all snags and medium diameter

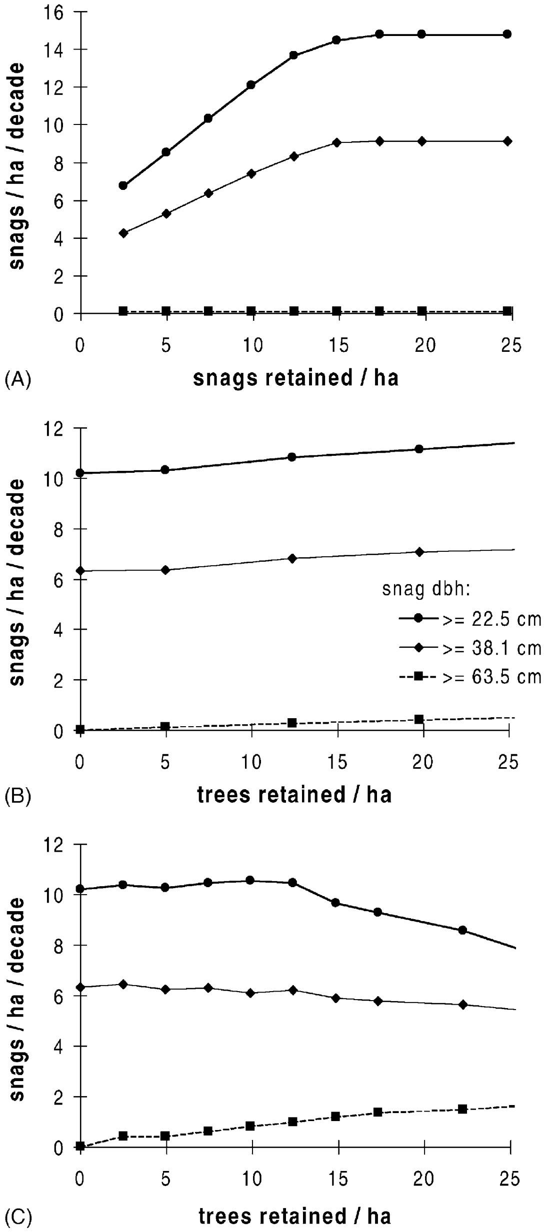

Fig. 5. Snag recruitment curves for snag retention (A), retention of little live trees (B), and retention of big live trees (C). Diameter classes refer to large snags (≥63.5 cm), large and medium snags (≥38.1 cm), and all snags (≥22.5 cm).

snags, respectively. Simulations demonstrated that saturation at these snag densities is caused by safety regulations. At the time of final harvest, snag density exceeds the requirements of environmental regulations, but safety regulations require felling of snags to a density below environmental regulations. Without safety regulations the recruitment curves would saturate at 22.9 and 13.6 sph/decade for all snags and medium snags, respectively; the same values as the retain all scenario.

Snag recruitment curves versus retention of little live trees show much smaller gains per stem retained (Fig. 5B). The average slope for all snags was 0.05 sph/decade/rtph. Hence, a unit increase in mean snag density per decade requires that an additional 20 live trees/ha be retained at the time of final harvest. At time of harvest, 20 little trees/ha equaled 6% of live stems or 4% of total stem volume per hectare. The average slope of the recruitment curves for large snags was 0.02 sph/decade/rtph. A unit per hectare increase in the number of large snags requires retention of an additional 50 little trees/ha. Recruitment curves generated by increasing snag and live tree retention simultaneously showed no nonlinear synergistic effects.

When large live trees are retained, segments of a snag recruitment curve can acquire a negative slope (Fig. 5C). When more than 13 trees/ha are retained the recruitment curve for all snags has a slope equal −0.21 sph/decade/rtph. Simulations indicated that the number of snags recruited declines because the overstory of large trees suppresses growth of the regenerating understory. Less growth leads to less competition and consequently less mortality over the course of a rotation. Retaining big live trees results in greater gains in the recruitment of large snags. The slope of the large snag recruitment curve is equal to 0.05 sph/decade/rtph. On the other hand, repeated retention of big trees has a severe economic impact. At the time of harvest, 12.3 big trees/ha equaled about 4% of live stems but 21% of total stem volume per hectare.

3.4. Sensitivity analysis

3.4.1. Sensitivity to parameter estimates and model assumptions

Simulations using snag survival probabilities calculated from the confidence limits of the snag survivorship curves resulted in modest changes in snag dynamics (Table 2). Simulations using survival probabilities calculated from the upper bound had 8% more snags, 9% more medium snag, and 15% more large

Table 2
Results of sensitivity analysis for MSM snag survival probability values and L and I hazard assumptions. Results reported in both mean sph/decade and as percent change from base simulation (number in parentheses). "Base simulation" is the OSR and ER scenario

	Snag diameter class/decay class						
	Small/hard	Small/soft	Medium/hard	Medium/soft	Large/hard	Large/soft	Total
Base simulation	3.95	0	6.18	0.06	0.13	0	10.31
Snag survival probabilities 90% confidence bounds (see Fig. 2)							
Upper bound	4.16 (5.3)	0 (0)	6.72 (8.7)	0.09 (50.0)	0.15 (15.4)	0 (0)	11.12 (7.9)
Lower bound	3.69 (−6.6)	0 (0)	5.40 (−12.6)	0.03 (−50.0)	0.10 (−23.1)	0 (0)	9.21 (−10.7)
L and I hazard assumptions (see Fig. 1)							
Low hazard	3.85 (−2.5)	0 (0)	6.48 (4.9)	0.09 (50.0)	0.16 (23.1)	0 (0)	0.58 (2.6)
High hazard	4.02 (1.8)	0 (0)	5.85 (−5.3)	0.03 (−50.0)	0.11 (−15.4)	0 (0)	10.01 (−2.9)
Very high hazard	4.09 (3.5)	0 (0)	5.45 (−11.8)	0.01 (−83.3)	0.08 (−38.5)	0 (0)	9.63 (−6.6)

snags. Simulations using survival probabilities calculated from the lower bound had 11% fewer snags and 13% fewer medium snags. The density of large snags decreased by 23% from 0.13 to 0.10 sph/decade. The low sensitivity of total snag density to changes in snag survival probabilities can be attributed to the composition of the snag population. Nearly all snags were small and medium, the size classes with narrow confidence intervals about their survivorship curves. As more large snags are retained, the model will become more sensitive to snag survival probabilities and projections of snag dynamics will become more questionable.

Under the OSR and ER scenario, the overall density of snags was relatively insensitive to the hazard assumptions (Table 2). The very high hazard assumption changed snag density by −7%. In contrast, the size/decay class distribution of the snag population was sensitive to the hazard assumptions. The very high hazard assumption changed the densities of small and hard medium snags by 4 and −12%, respectively, but the densities of large snags and soft medium changed by −38 and −83%. Simulations showed that model sensitivity to the hazard assumptions increases as snag retention increases.

3.4.2. *Sensitivity to the silvicultural regime*

Changing the residual density of commercial thinning by +20 and −20% changed mean snag density per decade by +17 and −12%, respectively (Table 3). The largest percent change was exhibited by large snags. Large snag density increased by 51% when

Table 3
Results of sensitivity analysis for silvicultural prescriptions. Results reported in both mean sph/decade and as percent change from base simulation (number in parentheses). Base simulation is OSR and ER scenario

	Snag diameter class/decay class						
	Small/hard	Small/soft	Medium/hard	Medium/soft	Large/hard	Large/soft	Total
Base simulation	3.95	0	6.18	0.06	0.13	0	10.31
Commercial thin residual density							
Decrease 20%	3.49 (−11.4)	0 (0)	5.36 (−13.3)	0.06 (0)	0.11 (−15.4)	0 (0)	9.03 (−12.4)
Increase 20%	4.69 (18.7)	0 (0)	7.11 (15.0)	0.06 (0)	0.20 (53.8)	0 (0)	12.06 (17.0)
Pre-commercial thin residual density							
Decrease 20%	3.32 (−15.9)	0 (0)	6.11 (−1.1)	0.05 (−16.7)	0.65 (400.0)	0 (0)	10.13 (−1.7)
Increase 20%	4.44 (12.7)	0 (0)	6.19 (0.2)	0.06 (0)	0.17 (30.8)	0 (0)	10.86 (5.3)
Stand age at clear-cut harvest							
Decrease 20%	3.95 (0)	0.02 (–)	4.15 (−32.8)	0.02 (−66.7)	0.05 (−61.5)	0 (0)	8.20 (−20.5)
Increase 20%	3.73 (−5.6)	0.16 (–)	8.08 (30.7)	0.06 (0)	1.14 (776.9)	0.01 (–)	13.17 (27.8)

residual density was increased by 20%. Changing the residual density of pre-commercial thinning by +20 and −20% changed mean snag density per decade by only +5 and −2%, respectively. However, when residual density was decreased by 20% the mean density of large snags increased by 400% from 0.13 to 0.65 sph/decade. This was caused by more rapid growth into the larger diameter class and subsequent mortality.

Changes to rotation length had a greater impact on snag resources than changes to thinning prescriptions. The +20 and −20% changes to rotation length changed mean snag density per decade by +28 and −20%, respectively (Table 3). Increasing rotation length by 20% to 60 years increased the density of large snags by over 700%, from about 0.1 to about 1.1 sph/decade. Increasing rotation length also resulted in the development of more soft snags, especially in the small size class.

4. Discussion

4.1. Critique of the model

Simulation models are powerful tools for informing management decisions. Though empirical data are preferable to simulations, such data are often unavailable. There were no available data on snag dynamics in industrial forests managed according to current government regulations. Hence, I used existing models and the best information available to create a new model that describes Douglas-fir snag dynamics in an industrial forest. The model was used to explore how changes to current practices affect snag dynamics and it can be readily modified to simulate many other management scenarios.

My model has a number of shortcomings. First, FVS models only one cause of tree mortality—competitive suppression; although insect and disease extensions are available for some variants. Hence, my simulations do not account for mortality due to physical injury (e.g., wind, ice) or disease (e.g., root rot), and therefore, probably underestimate mortality and consequent snag density. Second, the accuracy of the snag model, MSM, has not been rigorously assessed. However, four different snag models yielded very similar survivorship curves for small snags and somewhat similar curves for medium snags. This lends considerable credibility to the survivorship curves produced by averaging the four models.

Third, I found little data on the fate of live trees retained in clear-cuts. The fate of such trees and their benefit to wildlife is an open question, especially with respect to small diameter trees. The retention of live trees is occasionally a point of contention because some forest managers view windthrow as a waste of timber. More data are needed to improve models and resolve conflicts. Fourth, assumptions addressing the effect of OSRs were based on an interpretation of current guidelines (DNR et al., 1992) and on conversations with agency field staff. To the best of my knowledge, no data on the felling of hazardous snags have been collected. As one reviewer put it, safety regulations are the ‘‘wildcard’’ in snag management. Concerns for safety, both genuine and feigned, allow felling of any snag. This aspect of snag dynamics was especially difficult to model.

Fifth, ERs clearly state the minimum requirements for snag and live tree retention, but the regulations are thought to be laxly enforced and regular compliance is suspect. On occasion loggers may leave more than the minimum density of snags, but since snags are hazardous and interfere with operations, it is generally believed that the number of snags retained does not usually meet the regulatory minimums. Unfortunately, there are no data on compliance with which to confirm or dispel these rumors. In summary, each shortcoming of the model affects the projections in a different way, but their net effect is difficult to judge. The best solution to model uncertainty is more and better data.

4.2. Snag dynamics in an industrial forest

The results suggest that silvicultural regimes like the one simulated yield: (1) small and medium diameter snags at moderate densities (20 sph) for short periods of time (5–10 years); (2) a snag population with high temporal variation fluctuating between about 4.2 and 22.5 sph; (3) mean snag densities of small, medium, large, and all snags are equal to approximately 3.9, 6.2, 0.1 and 10.3 sph/decade; and (4) a soft snag density less than 0.1 sph/decade.

Snag dynamics in industrial forests of Washington and Oregon are determined by ERs and the silvicultural regime. According to my model, OSRs are a minor constraint at current levels of snag retention, and therefore, enhancing snag resources is operationally feasible. However, OSRs are a major constraint on the retention of soft snags. This component of wildlife habitat is essentially eliminated from managed stands.

Snag recruitment curves will be useful tools for managing snags. Such curves specify retention levels needed to meet snag density objectives, reveal limitations imposed by current practices, and indicate the most effective means of managing snags. In particular, the curves show that: (1) a unit increase in the number of snags retained produces less than a unit increase in the mean snag density per decade; (2) retaining snags is about 10 times more effective at increasing mean snag density than retaining little live trees; (3) safety rules reduce the maximum snag density that can be achieved with a 50-year rotation; and (4) increasing the density of large snags depends on increasing the density of large live trees retained.

Snag management for the benefit of wildlife has emphasized the retention of snags (Hansen et al., 1991; Franklin et al., 1997) and the artificial creation of snags (Bull and Partridge, 1986; Chambers et al., 1997). Simulations indicate that these tactics for snag management may be greatly augmented through simple changes to conventional silvicultural treatments. Surprisingly, reducing the residual density of precommercial thinning by 20% yielded a fivefold increase in the density of large snags. The growth and mortality projections of FVS are subject to error; nevertheless, such results suggest interesting possibilities for snag management. Conventional thinning prescriptions aim to maximize tree growth or minimize tree mortality. For the purposes of snag management, thinning prescriptions might aim for an optimal balance between mortality and growth—a balance that meets the needs of wildlife and of forest managers.

4.3. Snag management policy

Do current practices provide enough snags for wildlife? The answer depends on goals for wildlife populations, and such goals are the purview of policy makers. A starting point for policy discussions are natural forest conditions prior to commercial timber management. Published estimates suggest that in the early 1800s about 60–70% of forests in western Oregon and Washington were old-growth (Spies and Franklin, 1988; Booth, 1991). The remaining landscape was covered by earlier stages of forest succession. In the most thorough study of unmanaged forests in the Pacific Northwest to date (Spies and Franklin, 1991), snags were almost equally abundant in young (40–80 years), mature (80–195 years), and old-growth (>195 years) forest stands. The density of snags $\geq$27.9 cm dbh and $\geq$2 m tall was found to be 49.7, 56.3, and 49.4 sph in young, mature, and old-growth forest, respectively (R. Hess, Oregon State University, personal communication). Large snags (>63.5 cm dbh; $\geq$2 m tall) were present in young, mature, and old-growth stands at densities of 21.5, 15.4, and 21.5 sph, respectively. Differences were found in the ratio of hard snags to soft snags—3:5, 8:5, and 7:5 for young, mature, and old-growth stands, respectively. Data from Ohmann et al. (1994) corroborate the findings of Spies and Franklin (1991).

Differences in snag resources between unmanaged and industrial managed forests are striking (Fig. 6). The density of snags in unmanaged forest is over five times the mean density per decade produced by silvicultural regimes like the one simulated. The density of large snags produced by current forest management could be as much as 100 times less that found in unmanaged forest. The density of soft snags could be as much as 200 times less that found in unmanaged forest. If structural retention is greatly increased to 17.3 snags and 12.3 big trees per ha, then the mean density of large snags per decade is still only 6% of that occurring in unmanaged forest. My results indicate that industrial silvicultural regimes cannot mimic the snag dynamics of unmanaged forests; current regimes cannot even come close.

How can these adverse impacts to snag resources be minimized or mitigated? First, increase the structural retention required by environmental regulations. Snag recruitment curves for the 50-year rotation show that mean snag density per decade for medium snags can be increased substantially through greater snag retention. The curves also show that a significant increase in the density of large snags requires greater retention of big trees.

Second, since safety regulations cannot be relaxed, the snag retention must involve planning over longer time spans and larger land areas. Most managed landscapes contain places unsuitable for silviculture, such as forested buffers to protect streams and wetlands,

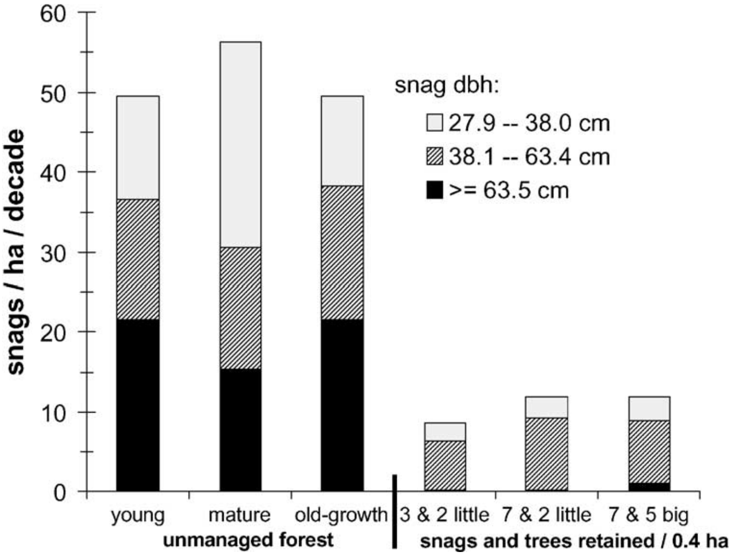

Fig. 6. Comparison of snag densities in simulated managed forest with snag densities in unmanaged young, mature, and old-growth forest (T. Spies, unpublished data). Retention of 17.4 snags and 4.9 little live trees per ha is the OSR and ER snag management scenario.

very steep slopes, or ground too unproductive for commercial forestry. Such places will provide soft snags, and they should be inventoried to determine how much they contribute toward landscape-level objectives for snags. The shifting mosaic concept of landscape management (Harris, 1984; Hunter, 1990) could be applied to snags. Over time, snag densities shift around a landscape as different stands develop, are thinned, and are harvested. Snag densities across a landscape can be projected over time through simulations, and silvicultural operations across the same landscape can be planned in order to achieve landscape-level objectives. Managing a small subset of stands on a longer rotation could be a practical tactic for achieving large and soft snag objectives. These stands would be distributed across a landscape, and their management could be timed such that sub-divisions of the landscape, e.g., small watersheds, always met snag objectives.

Third, stands can be managed at finer scales. Stand-level snag objectives might be met through higher snag densities in different parts of a stand at different points in time. For instance, variable density thinning (Carey and Curtis, 1996) and selective cutting (Curtis, 1998) may provide ecological benefits to wildlife and operational flexibility for managers. These silvicultural systems prescribe more frequent entries into stands and this could result in more frequent felling of hazardous snags. However, the ever increasing mechanization of silvicultural operations provides safety advantages. Loggers can safely reach timber in hazardous areas using long booms mounted on mobile all-terrain machinery (DNR et al., 1992).

5. Conclusion

The simulation model developed for this study provides approximate projections of snag dynamics in an industrial forest. The results show the degree to which silvicultural regimes typically used in industrial forests affect the density and quality of snags. Relative to unmanaged forests the impacts of industrial forestry on snag resources are clearly significant. The results also indicate the degree to which various changes in silvicultural regimes and/or government regulations could reduce these effects. Changes to ERs could lead to more snags and larger snags, but OSRs impose an upper limit on the degree of improvement that can be attained under current silvicultural regimes. Innovative silvicultural regimes and harvesting techniques are needed.

Our current understanding of snag ecology is inadequate for effective snag management. Snag life history may be affected by the cause of death, stand age, or by site conditions such as topography and microclimate, but no one has reported on these aspects of snag ecology. The reliability of snag models will improve with more data from empirical studies. However, most forest management decisions cannot wait for the ultimate snag model. Managers and policy makers must proceed, albeit with caution, with the best available information that science has to offer. Models that integrate aspects of forest ecology and forest management are essential tools for proper stewardship of forest resources.

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