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Snag longevity in relation to wildfire and postfire salvage logging

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Abstract

Snags create nesting, foraging, and roosting habitat for a variety of wildlife species. Removal of snags through postfire salvage logging reduces the densities and size classes of snags remaining after wildfire. We determined important variables associated with annual persistence rates (the probability a snag remains standing from 1 year to the next) of large conifer snags ($\geq$23 cm diameter breast height (dbh)). Our study sites were located within two wildfires in western Idaho (Foothills fire of 1992 and Star Gulch fire of 1994). Study sites in the Foothills were partially salvage-logged (one-half of standing snags $\geq$23 cm dbh removed), and sites in the Star Gulch burn were unlogged. Snags were monitored within 0.04 ha plots for 8–9 years beginning in 1994 in Foothills Burn and 1995 in the Star Gulch Burn. A total of 1131 ponderosa pine (*Pinus ponderosa*) and Douglas-fir snags (*Pseudotsuga menziesii*) were monitored during the study period. Data were collected on snag species, height, decay class, and diameter at breast height. We also collected stand-level data (e.g., slope, aspect) and quantified information on remotely sensed data (e.g., pre-fire crown closure, burn severity) at the pixel-level (30 m $\times$ 30 m) and within 1 km of the plot centers (landscape-level). We modeled annual snag persistence as a function of data on all three scales using non-linear mixed-effects models. Additionally, we expected that variables on multiple scales, including information on burn severity and pre-fire crown closure, would be influential in determining snag persistence. The best models of snag persistence were selected using an information theoretic approach (i.e., AICc). Small-scale variables (age, height, dbh, tree species, decay, and snag density) were best predictors for both wildfire areas. In contrast to our expectations that large-scale variables would influence annual persistence rates, these factors did not appear in top models. Persistence was shorter for ponderosa pine than Douglas-fir snags. Additionally, smaller snags in plots with fewer snags fell sooner than did larger snags in more dense stands. Age of snag was also an important variable predicting snag persistence (older snags are more likely to fall). Snag longevity (the total amount of time the snag remained standing) also varied between the two sites. The predicted half-life of a ponderosa pine snag was 7–8 years in salvage-logged plots and 9–10 years in unlogged plots. The predicted half-life of Douglas-fir snags was longer than ponderosa pine, at 12–13 years in the salvage logged burn versus 15–16 years in the unlogged burn. On the partially logged sites, the primary effects of salvage logging on snags appeared to be the reduction of the average snag size (diameter and height) and density, which in turn reduced the subsequent longevity of individual snags. We concluded that the main effects of the partial-salvage logging appeared to be a reduction in overall snag density and average snag size which in turn reduces average persistence time. Management practices that preserve dense stands of snags will promote the longer-term persistence of suitable snags as nesting habitat for cavity-nesting birds.
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1. Introduction

Snags are important components of wildlife habitat for numerous vertebrate species (Raphael and White, 1984; Bull et al., 1997; Machmer, 2002). Snag densities in burned coniferous forests were reported as the principal factor in determining nest-site selection by cavity-nesting birds (Saab et al., 2002). In addition to providing nesting locations, snags create habitat for bark- and wood-boring beetles that are the primary foods of several woodpecker species (Machmer and Steeger, 1995; Dixon and Saab, 2000; Nappi et al., 2003). To maintain habitat for cavity-nesting birds including several species designated as management indicators and sensitive species by federal and state agencies [e.g., Lewis's (*Melanerpes lewis*), Black-backed (*Picoides arcticus*), Three-toed (*P. tridactylus*), and White-headed (*P. albolarvatus*) woodpeckers]

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(USDA Forest Service, 2004), it is important to identify key variables affecting the retention of snags.

Wildfire is a natural component of ponderosa pine forests in the Rocky Mountain region, and fire creates large areas of snags suitable as habitat for cavity-nesting birds (Everett et al., 1999; Schoennagel et al., 2004; Saab et al., 2005). The frequency, size, and severity of wildfires in the western United States has increased in recent years (Beschta et al., 2004; DellaSala et al., 2004; Saab and Powell, 2005) and has lead to increased opportunities for postfire salvage logging. By influencing the density and available size classes of snags, salvage logging has been shown to affect nest-site selection by cavity-nesting birds (Saab and Dudley, 1998; Haggard and Gaines, 2001). For example, partially salvage-logged wildfires in Idaho contain fewer Black-backed Woodpecker nests but more Lewis's Woodpecker nests than unlogged areas (Saab et al., 2002, 2004). Despite documented effects of salvage logging on understory vegetation, densities and diameters of snags, plant community composition, and volume of coarse downed wood (Stuart et al., 1993; Purdon et al., 2004; Hanson and Stuart, 2005), no studies have investigated the effects of postfire salvage logging on snag longevity.

Current models of snag dynamics designed to assist land managers in maintaining wildlife habitat include the snag recruitment simulator (SRS; Marcot, 1992), snag dynamics projection model (SDPM; McComb and Ohmann, 1996), and Table Interpolation Program for Stand Yields (forest vegetation simulator; TIPSY; Stone, 1996). These models rely on information regarding snag longevity to estimate how land management practices will affect the availability of snags for wildlife (Garber et al., 2005). Previous research on snag longevity has identified tree species, tree size, decay stage, crown scorch, and stand density as important factors determining snag longevity (Bull, 1983; Morrison and Raphael, 1993; Everett et al., 1999; Garber et al., 2005). For example, Everett et al. (1999) concluded that Douglas-fir snags in smaller size classes (<23 cm dbh) generally fell sooner than did similar-sized, thin-barked species such as lodgepole pine (*Pinus contorta*). Large diameter Douglas-fir snags (>41 cm), however, remained standing longer than others of comparable size. Many studies have found that larger diameter snags remain standing longer (Bull, 1983; Morrison and Raphael, 1993; Harrington, 1996; Ganey and Vojta, 2005). Some studies have found decreased longevity for snags in high density stands (Garber et al., 2005; Ganey and Vojta, 2005), whereas others found no relationship with snag density (Lee, 1998). In contrast, Chambers and Mast (2005) reported that longevity increased with increasing basal area of live and dead trees in the 1 ha surrounding the plot. Additional factors such as soil erosion (Meaghan and Kidd, 1972; McIver and Starr, 2001; Beschta et al., 2004) and increased susceptibility of windthrow with the creation of forest openings associated with timber harvest, may influence longevity of snags after postfire salvage logging.

Characteristics of landscapes surrounding snags may be important predictors of snag longevity and density, yet we lack information on the influence of these multi-scale factors. For example, immediately following wildfire burn severity and prefire crown closure (estimated from satellite imagery) may provide an index to the densities of snags and trees in the surrounding environment. Additionally, large scale data are more useful to land managers as predictors of ecological responses because this information is more easily obtained.

In this study, we monitored Douglas-fir and ponderosa pine snags 10 years postfire (8–9 years of monitoring) after two wildfires in western Idaho to examine the influence of salvage logging and other factors on annual snag persistence and determine overall longevity of snags in both wildfires. We determined the most important factors associated with the annual persistence of snags and compared both annual persistence and overall longevity between partially salvage-logged and unlogged units within the wildfires. We tested the hypothesis that snag persistence and longevity are reduced in areas subject to postfire salvage logging. Soil disturbance, erosion, and increased susceptibility to windthrow in salvage-logged areas (e.g., Beschta et al., 2004) may result lower persistence rates. Also, we tested the hypotheses that models of persistence containing only large scale variables (calculated from readily available remote-sensing data) would explain as much or more of the variability in the data as models containing only small-scale data (i.e. models containing only remote-sensing data and models containing only small-scale data would be within two AICc units of each other). We expected that despite the fact that large-scale variables potentially provide an index to small scale variables, it is unlikely that large-scale variables would have the predictive power of on the ground, field collected data. Lastly, we expected that larger diameter, younger snags in high density stands would stand longer, and that Douglas-fir snags would persist longer than ponderosa pine.

2. Methods

2.1. Study site description

Snags were monitored after two adjacent wildfires in western Idaho (43°35′N, 115°42′W). A mixed-severity, stand-replacing fire created the Foothills Burn (89,159 ha) in August 1992. Postfire salvage logging within the Foothills Burn removed approximately half the snags over 23 cm dbh (Saab and Dudley, 1998). The Star Gulch Burn (12,467 ha) was created by a patchy, moderate-severity fire in August 1994 and bordered the 1992 Foothills Burn on the north. Our study sites within this wildfire were unlogged. Elevation ranged from 1130 to 2300 m and the study areas with the perimeters of the burns were separated on average by 10 km (Saab et al., 2004). Ponderosa pine and Douglas-fir were the most common tree species at both locations. Shrubs common in the understory and in forest openings included *Artemisia tridentada*, ninebark (*Physocarpus malvaceus*), and ceanothus (*Ceanothus velutinus*) (Johnson et al., 2000; Saab et al., 2004).

2.2. Snag monitoring

Monitoring began in the Foothills Burn in 1994 and in Star Gulch during 1995. Snags were monitored through 2003,

Table 1
List of covariates included in models of snag longevity

Covariate	k	Description
Landscape variables (derived from Landsat TM data)		
PCA 1	1	Burn severity Change in normalized burn ratio (ΔNBR) was used to classify the following severity categories, unburned (Δ NBR −500 to +99); low burn severity (ΔNBR +100 to +269); medium to high burn severity (ΔNBR +270 to 1300) (Key and Benson, 2005). The percentage of burn severity categories was quantified within a 1 km radius of plot centers Pre-fire crown closure Pre-fire crown closure was classified into the following categories, low crown closure (0–40%), moderate crown closure (40–70%), high crown closure (70–100%). The percentage of each crown closure category was quantified within a 1 km radius of plot centers
Pixel-level variables (derived from Landsat TM data)		
Pre-fire crown closure	2	Pre-fire crown closure classified at the pixel level for the central plot as 0–40%, 40–70%, 70–100% at focal locations
ΔNBR (burn severity)	1	Change in normalized burn ratio, before and after fire. An index of burn severity
Plot-level variables (measurements in circular 11.3-m radius plots)		
Snag numbers	1	Number of snags located within the plot
Aspect	3	Categorical variables representing NE, NW, SE, SW
Slope	1	Slope calculated as a percentage
Individual-tree variables		
Tree diameter	1	Diameter at breast height (dbh) in centimeters
Tree decay	1	Decay class (0–5; Cline et al., 1980) (0 = live tree, 5 = most decayed tree)
Tree height	1	Height of tree in meters
Tree species	1	Species (ponderosa pine or Douglas-fir)
Time variable		
Snag age	1	Continuous, snag age (equivalent to time since fire) as a continuous variable

excluding 2000. Fifty-three plots were located randomly within the Foothills Burn and 29 plots were located within the smaller Star Gulch Burn. Each plot contained four 11.3-m radius circular subplots (0.04 ha). The four subplots were arranged with one central subplot surrounded by three subplots 30 m from the edge of the central subplot and situated 120° apart. Within each subplot, data were collected on all snags and trees at least 1.37 m height. Snags were recorded as a one if standing or a zero if it had fallen over with the root wad or broken off below breast height (1.37 m). Measurements of snags within a subplot included decay class, dbh, tree height, and tree species (Table 1). In addition, we recorded the slope and aspect, and calculated snag densities for each subplot.

2.3. Remote-sensing data

Pixel-level (30 m × 30 m) data containing random plots included pre-fire crown closure and burn severity (Table 1). We used pixel-level information because these data are commonly available to land managers. Vegetation and burn severity were classified using Landsat Thematic Mapper (TM) images representing pre- and postfire conditions taken in September 1991 and September 1995, respectively. In addition to the 1991 pre-fire image, aerial photographs (1,16000) from July 1988 and August 1996 were used to improve accuracy and assist in the classification of pre-fire crown closure (Johnson et al., 2000; Saab et al., 2002). An assessment found that overall accuracy for the pre-fire forest crown closure map was 77.6% (Johnson et al., 2000). Pre-fire crown closure maps were reclassified using a 3 × 3 window, where the center pixel was assigned the value of the most frequently occurring class (Booth and Oldfield, 1989). Postfire TM images do not have adequate resolution to assess snag numbers; consequently, pre-fire canopy closure was used as an index to postfire snag densities (Johnson et al., 2000; Saab et al., 2002). Pre-fire canopy-closure categories were (1) low, 0–40%; (2) moderate, 40–70%; (3) high, 70–100%.

The pre- and postfire Landsat imagery was used to quantify burn severity by calculating the change in the normalized burn ratio (ΔNBR) between pre- and postfire conditions (Cocke et al., 2005; Key and Benson, 2005). The ΔNBR was described as a continuous variable (between −500 and 1200) to classify burn severity at the 30 m × 30 m pixel. To calculate landscape-level metrics, ΔNBR was classified into the following three categories (Table 1; Key and Benson, 2005): (1) unburned, −500 to 99, (2) low severity, 100–269, and (3) medium-high severity, 270–1300.

Landscape-level data quantified crown closure and burn severity within 1 km of the central random plot to correspond with the home range sizes of most cavity-nesting birds that depend on snags for foraging and nesting (Saab et al., 2004). For landscape-level data, we used neighborhood statistics in the Spatial Analyst extension of ArcMap software (Environmental Systems Research Institute, 1999–2002) to calculate the percentage of pixels within a 1 km radius of the focal location classified as each of the three pre-fire crown closure and three burn-severity categories (unburned, low, and medium-high, see above for classification). The six variables representing burn severity and crown closure in a 1 km radius surrounding the center point of each plot were highly correlated. Therefore, we used principal components analysis (PCA) to create one variable from the six variables (Proc PRINCOMP, SAS Institute, 2002–2003a) (Appendix A).

2.4. Statistical analysis

We modeled annual persistence of ponderosa pine and Douglas-fir as a function of snag characteristics (including snag age as determined by time since fire) and the surrounding plot, pixel, and landscape variables (Table 1). Few pre-fire large snags survived the wildfires (J. Dudley pers. obs.). Only 2% of live trees died during the monitoring period. These newly created snags were excluded from the snag longevity analysis and fire was assumed to be the primary cause of death. Consequently, snag age was equivalent to time since fire and because both of these factors were confounded with year, we included only snag age in our analysis. In addition to treatment effects (salvage-logged versus unlogged), several other variables were confounded by wildfire location, including burn severity (higher in Foothills), snag density and diameter (higher in Star Gulch), and composition of the tree community. For example, the composition of tree species at the two sites differed. Star Gulch was dominated by Douglas-fir (71% of monitored snags), and ponderosa pine was the most common tree in the Foothills Burn (60% of monitored snags). Therefore we conducted analyses on the two wildfires separately to avoid including long lists of interaction terms and to check for consistency in important predictive factors between the two fires. The first principal component explained 68% of the variability in the crown closure and burn severity. This axis represented high crown closure areas with high burn severity on one side of the scale and unburned areas with low crown closure on the other end of the scale. This axis was included in models of annual snag persistence as an index of burn severity and crown closure on the landscape scale (Table 1).

We modeled the probability that a snag would persist from 1 year to another as a function of covariates measured at several spatial scales using Proc NLMIXED (Proc NLMIXED, SAS Institute, 2002–2003b) as described by Rotella et al. (2004) for survival analysis. This procedure allowed us to use likelihood-based information-theoretic methods to evaluate a set of competing logistic regression models of the probability of snag persistence. The method was chosen because it allowed us to properly handle several key aspects of our snag data, (1) binomial response variable (standing snag or fallen snag between status checks), which was dealt with by specifying a binomial error distribution and using a logit link function in model statements; (2) unequal time intervals between some snag observations due to 1 year of missing data, which was analyzed by using programming statements within NLMIXED to iteratively do logistic regression for each year in an interval between status checks; (3) plots were a random sample of a larger population of plots and each was treated as a random effect, which incorporates potential effects of unmeasured variables on the plot. Observations of snags within the same plot may be correlated with one another, and the random effect parameter estimates the deviation from the overall mean attributable to the ''effect'' of the snag being within a particular plot (cf. Pinheiro and Bates, 2000; Rotella et al., 2004). We used Akaike's Information criterion adjusted for small sample size (AIC_c) to evaluate models (Burnham and Anderson, 2002).

One of the drawbacks of using this method is that currently no goodness-of-fit tests are available for large data sets (for smaller data sets see Sturdivant et al., in press). Therefore, we evaluated goodness-of-fit on the global model using the Hosmer and Lemeshow goodness-of-fit test (Hosmer et al., 1997) in PROC LOGISTIC (SAS Institute, 2002–2003c) by removing the random effect and data with interval lengths greater than one (approximately 10% of the data). We evaluated the goodness-of-fit of the global model and proceeded on to conducting model selection only after confirming that the model fit our data (Burnham and Anderson, 2002; Le Cessie and van Houwelingen, 1991; Hosmer et al., 1997). Additionally, we calculated the overdispersion parameter ($\hat{c}$ = Pearson's χ^2 divided by degrees of freedom; McCullagh and Nelder, 1989) to determine if quasi-likelihood corrections were necessary (Burnham and Anderson, 2002).

We evaluated 17 candidate models, including a global model containing all variables, to assess which variables most strongly relate to annual snag persistence (Table 2). Interaction terms between snag diameter and decay, snag height and snag diameter, and slope and aspect were also included in these models. Interaction terms were incorporated because we expected the influence of snag diameter on snag longevity to vary as a function of decay class and height (i.e. we expected larger diameter and taller snags to stand longer). Additionally, plots with northern aspects, generally contained higher snag densities (Appendix C), and therefore snags within them should persist longer even on steep slopes and vary as a function of aspect. Data were inspected for non-linearity prior to analysis; as a result snag age, diameter, and density were log transformed to improve model fit.

To predict the probability of annual snag persistence as a function of covariates, we set the random effect to zero, i.e., the mean, and therefore predictions represent persistence probability for a ''typical'' tree, rather than for a tree from a single plot that was included in this particular study (Pinheiro and Bates, 2000; Skrondall and Rabe-Hesketh, 2003). Population means of snag diameter at breast height, decay class, and height, were calculated for each tree species in each wildfire, and subplot means of snag densities were calculated for each wildfire. We used these values to compare longevity of snags with the characteristics of (1) average ponderosa pine and (2) average Douglas-fir snags in each wildfire (see Appendix B for population means). Snag diameters (dbh) and snag densities are two variables potentially manipulated by land managers. For this reason, we compared snag persistence rates between Star Gulch and Foothills as a function of dbh and snag densities by evaluating the logistic expression over a range of values for dbh and snag density while holding other predictor variables constant. Last, we calculated cumulative longevity and snag half-life (age at which the cumulative probability of persistence

Table 2
Candidate models of snag longevity for two wildfire areas in Idaho

Global (all variables and interactions)
Age, NBR, crown closure, aspect, slope, snag density, decay, dbh, species, height, height × dbh, dbh × decay, aspect × slope
NBR, crown closure, aspect, slope, snag density, decay, dbh, species, height, height × dbh, dbh × decay, aspect × slope
Age, aspect, slope, snag density, decay, dbh, species, height, height × dbh, dbh × decay, slope × aspect
Aspect, slope, snag density, decay, dbh, species, height, height × dbh, dbh × decay, aspect × slope
Age, decay, dbh, species, snag density, height, height × dbh, dbh × decay
Decay, dbh, species, snag density, height, height × dbh, dbh × decay
Age, decay, dbh, species, height, height × dbh, dbh × decay
Decay, dbh, height, spp., decay × dbh, dbh × height
Age, aspect, slope, snag density, aspect × slope
Aspect, slope, snag density, aspect × slope
Age, PCA, NBR, crown closure
PCA, NBR, crown closure
Age, NBR, crown closure
NBR, crown closure
Age
PCA

See Table 1 for description of covariates.

is 0.5) for Douglas-fir and Ponderosa pine. Confidence limits on predicted annual persistence and longevity for all comparisons were estimated using the delta method (Seber, 1982).

3. Results

3.1. Percentage of snags standing

We monitored 390 ponderosa pine and Douglas-fir snags in the unlogged burn, and 741 snags in the logged burn (Appendix B). A larger percentage of Douglas-fir snags than ponderosa pine snags remained standing by the end of the study in both sites (Fig. 1). At 9 years after fire, 90% (±0.03) of Douglas-fir and only 45% (±0.06) of ponderosa pine snags that were standing 1-year postfire remained standing in the unlogged Star Gulch Burn. At 11 years after fire in the partially logged Foothills Burn, 85% (±0.03) of Douglas-fir and only 25% (±0.03) of ponderosa pine snags that were standing 2 years postfire were still standing. Trends in percentage of snags standing by species for each year after fire were similar in the partially salvage-logged and unlogged wildfires (Fig. 1).

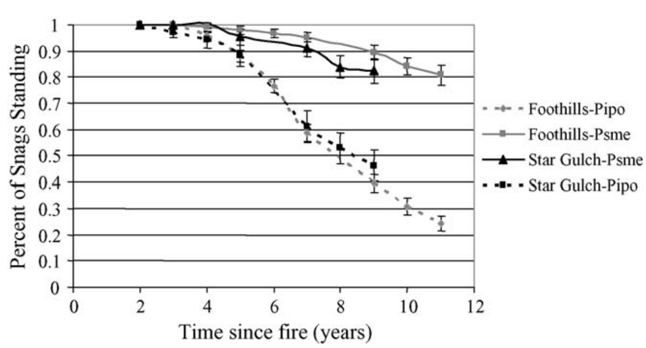

Fig. 1. Percentage of snags standing as a function of time since fire in two wildfire locations in Idaho. Study sites within the 1994 Star Gulch (SG) burn were unlogged and within the 1992 Foothills (FH) were partially logged. Pipo = ponderosa pine, Psme = Douglas-fir.

3.2. Snag persistence models

Hosmer–Lemeshow goodness-of-fit tests indicated adequate fit for global models without random effects and with intervals greater than two ($p = 0.15$ for Star Gulch Burn and $p = 0.43$ for the Foothills Burn) (Hosmer et al., 1997). Also, deviance values (c) were less than 1.2, therefore quasi-likelihood corrections were not necessary. Results supported our prediction that variance in snag persistence was influenced by the plot in which a snag was located. There was no support for models that did not include a random plot effect ($\Delta AIC_c \geq 25$). Consequently, all subsequent results pertain to models that contain a random plot effect. The best model, which included a random plot effect ($\Delta AICc = 0$), estimated spatial process variance as 0.38 (S.E. = 0.15) in the Foothills and as 0.44 (S.E. = 0.31) in Star Gulch.

There was little model-selection uncertainty for both burns, and the covariates in the top-fitting models that were most associated with snag persistence were consistent for the salvage-logged and unlogged burns (Table 3). Despite our observations that differences in pre-fire crown closure and aspect lead to differences in snag densities (Appendix C), neither factor appeared in top models of snag longevity. Snag age, dbh, decay class, height, and snag density, an interaction between height and diameter, an interaction between diameter and decay class, and the random effect of plot were all included in the top-fitting models (Tables 3 and 4). Models containing only larger scale variables were not among the top three models for either wildfire location. Parameter estimates were negative for snag age, tree height, and the interaction with decay and diameter, and positive for diameter at breast height, decay class, snag density, and the interaction of diameter and height (Table 4). These results were consistent for both wildfires and indicate that small-scale variables at the level of the individual tree have the greatest effects on estimated annual persistence of snags and overall snag longevity.

Confidence limits for predicted annual persistence rates of snags with average characteristics of ponderosa pine or

Table 3
Model selection results based on non-linear mixed effects models of snag longevity in two wildfire areas in Idaho

Foothills Burn	AICc	K	ΔAICc	AICc (w_i)	w_I/w_i
Age, height, dbh, decay class, species, snag density, height × diameter, diameter × decay	1773.95	10.00	0.00	0.89	1.00
Global (all variables and interactions)	1778.60	18.00	4.65	0.09	10.23
Age, height, dbh, decay class, species, aspect, slope, snag density, height × diameter, diameter × decay, aspect × slope	1781.69	14.00	7.74	0.02	47.92
Star Gulch Burn					
Age, height, dbh, decay class, species, snag density, height × diameter, diameter × decay	605.37	11.00	0.00	0.92	1.00
Age, height, dbh, decay class, species, aspect, slope, snag density, height × diameter, diameter × decay, aspect × slope	610.66	15.00	5.28	0.07	13.14
Global (all variables and interactions)	613.21	19.00	7.83	0.02	46.00

The 1992 Foothills Burn was salvage-logged. Study areas in the 1994 Star Gulch Burn were unlogged. Models are ranked from most plausible (ΔAICc = 0) to least plausible; k is the number of parameters. The two most plausible models and the global model are listed for each species. The ratio of Akaike weights (w_I/w_i) indicates the plausibility of the best-fitting model compared to other models. See Table 1 for explanation of variable names.

Douglas-fir in Star Gulch and Foothills, overlapped for young and old snags, but not for middle-aged snags (Fig. 2, Appendix B). Ponderosa pine snags with average characteristics aged 4–18 years were significantly less likely to fall in the unlogged Star Gulch Burn than in the Foothills (Fig. 2a). Seven to 15-year-old Douglas-fir snags with average characteristics were also less likely to fall in Star Gulch than in Foothills (Fig. 2b). Annual persistence rates were higher at both sites for Douglas-fir snags with average characteristics versus ponderosa pine with average characteristics, and this difference became statistically significant as snag age increased (Fig. 2).

Predicted cumulative longevity rates varied between the two sites. The expected half-life of a ponderosa pine in the salvage-logged area was 7–8 years postfire versus 9–10 years for the unlogged area (Fig. 3a). For Douglas-fir snags, the expected half-life was longer (12–13 years in the salvage-logged area and 15–16 years in the unlogged area) (Fig. 3b). Our estimates of cumulative longevity are extrapolated beyond the length of our study (10 years postfire), and therefore, should be viewed with caution.

Larger diameter snags survived longer in both burns (Fig. 4a). However, confidence limits overlapped for salvage-logged and unlogged areas, suggesting no significant difference in predicted annual persistence for a tree with the same characteristics at each location. Confidence limits also overlapped for 50 cm dbh trees at average snag densities in the Foothills (41.3 snags/ha) and Star Gulch (62.5 snags/ha). Snags in denser stands remained standing longer as well (Fig. 4b). Confidence limits overlap for this comparison indicating that trees of the same species with the same decay class and dbh have similar predicted annual persistence rates in salvage logged and unlogged areas.

4. Discussion

Our falling rates were comparable to rates found in other studies. For example, Bull (1983) observed that 11% of burned ponderosa pine snags fell within 4 years after fire in an unlogged area. In the partially logged Foothills Burn, 10% of ponderosa pine snags (that were standing 2 years after fire) had fallen by 5 years postfire, whereas in the unlogged burn, only 6% of ponderosa pine snags (that were standing 1-year postfire) had fallen by year 5 after fire. In contrast, Chambers and Mast (2005) reported that 6–14% of burned ponderosa pine snags had fallen within 3–5 years after fire on high severity, unlogged sites in Arizona. The falling rates recorded by Chambers and Mast (2005) may be faster due to differences in climate or fire severity between the Idaho and Arizona sites, or other unknown factors (e.g., differences in local insect populations).

Mean snag diameters and heights were higher in Star Gulch versus Foothills for both tree species. This was likely an effect of pre-fire site conditions and partial-salvage logging in

Table 4
Parameter estimates for best model as selected by AICc for snag longevity in two wildfire sites in Idaho

	Foothills		Star Gulch	
	Estimate	S.E.	Estimate	S.E.
Intercept	0.04	2.18	−8.55	3.31
Age	−6.23	0.56	−8.83	1.16
Ponderosa pine vs. Douglas-fir	−2.15	0.21	−2.13	0.30
Diameter at breast height	5.83	1.58	12.74	2.45
Decay class	1.30	0.96	5.86	1.55
Tree height	−0.15	0.08	−0.13	0.13
Snag number in plot	1.82	0.21	1.94	0.40
Diameter × height	0.04	0.05	0.02	0.08
Decay × diameter	−0.40	0.70	−3.59	1.05
Random effect	0.38	0.15	0.44	0.31

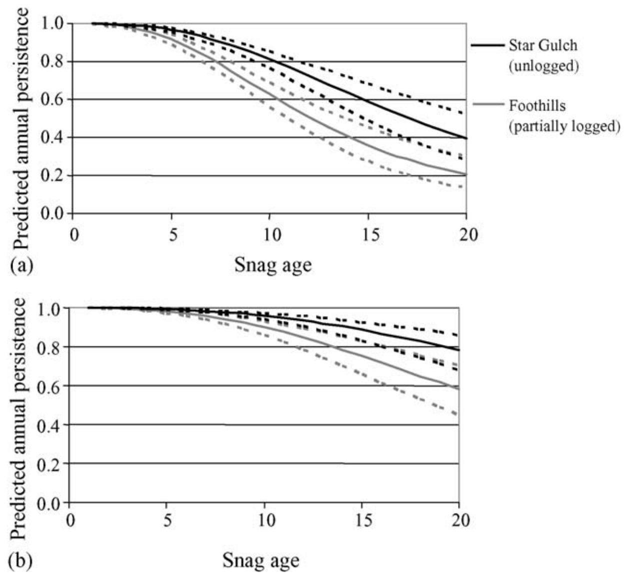

Fig. 2. Predicted probability of annual persistence (remaining standing from age $x-1$ to x) as a function of age (time since fire) for a snag with the average characteristics of (a) ponderosa pine (Foothills dbh = 29.97, decay class = 1.64, height = 13.88, snag densities = 41.3 ha^{-1}; Star Gulch dbh = 39.47 cm, decay class = 1.68, height = 14.98, snag densities = 62.5 ha^{-1}) and (b) Douglas-fir snags (Foothills dbh = 26.52, decay class = 1.79, height = 16.67, snag densities = 41.3 ha^{-1}; Star Gulch dbh = 37.28 cm, decay class = 1.73, height = 18.81, snag densities = 62.5 ha^{-1}) in two wildfire sites in Idaho. Solid lines indicate predicted persistence rates. Dashed lines indicated 95% confidence bands.

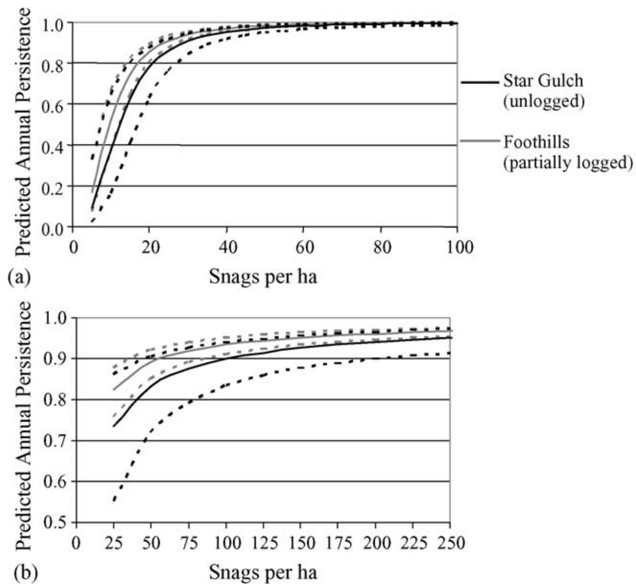

Fig. 4. Predicted probability of annual persistence (probability of remaining standing from age $x-1$ to x as a function of (a) diameter at breast height for a ponderosa pine snag 5 years postfire with a decay class of 2, a height of 14.5 m (the average height of ponderosa pine at the two sites), and a snag density of 50 ha^{-1} (average of subplots at two sites) and (b) snag density for a ponderosa pine tree with a dbh of >23 cm (a minimum diameter of interest to land managers), a decay class of 2, and a height of 14.5 m in two wildfire sites in Idaho. Solid lines indicate predicted persistence. Dashed lines indicated 95% confidence bands.

Foothills. Additionally, subplot snag densities were higher in Star Gulch as well. In both sites, larger snags, and snags surrounded by higher snag densities, survived longer than smaller and more exposed snags. Other studies have also found increased rates of snag persistence with increased basal areas (Chambers and Mast, 2005), and increased diameters (Bull, 1983; Morrison and Raphael, 1993; Harrington, 1996; Everett et al., 1999; Garber et al., 2005).

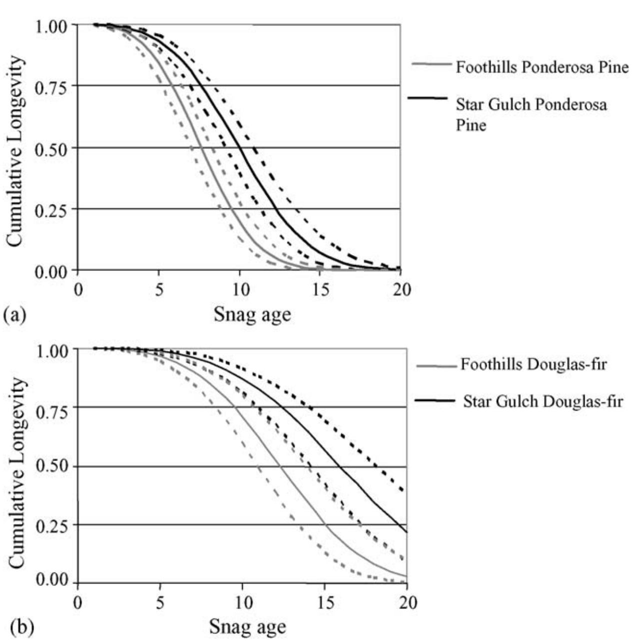

Fig. 3. Predicted cumulative longevity (probability of remaining standing to age x) as a function of age (time since fire) for a snag with the average characteristics of ponderosa pine and Douglas-fir snags in two wildfire sites in Idaho. Study sites within the 1994 Star Gulch (SG) burn were unlogged and within the 1992 Foothills (FH) were partially logged.

Despite reports that salvage logging increases soil erosion and disturbance (Meaghan and Kidd, 1972; McIver and Starr, 2001; Beschta et al., 2004), we detected no significant differences in longevity rates for snags with the same characteristics (i.e. same species, dbh, and decay class in stands of the same density) for either species in the Foothills and Star Gulch burns (i.e. confidence limits for predicted annual persistence overlapped). Consequently, the effects of unmeasured variables associated with salvage logging on this wildfire site in Idaho appear to be minimal. However, annual and cumulative persistence rates for the average tree in the Foothills were lower than persistence rates in Star Gulch. Salvage logging activities led to smaller snags in less dense stands, which in turn shortened the persistence ability of individual snags. On our study site, an effort was made to retain about half of large (>23 cm dbh) snags (Saab and Dudley, 1998), which likely reduced the potential negative effects of salvage logging on overall snag longevity.

Snag recruitment occurred at a very low rate on the burned sites during the 11-year study period. Wildfire kills large numbers of snags all at one time as opposed to more gradual processes of snag recruitment, such as insects, disease, and decay. Depending on the severity of the burn and number of snags that survive the fire, the population of potential recruits is low for several years following fire. Over time, wildfire areas become unsuitable habitat for some species of cavity-nesting birds such as Black-backed and Three-toed woodpeckers (Dixon and Saab, 2000; Hoyt and Hannon, 2002). These species of woodpeckers must rely on new wildfires to create high densities of standing snags for nesting and foraging.

Douglas-fir snags remained standing longer than ponderosa pine in both the partially logged and unlogged burns. These results are likely the consequence of differences in the decay rates of the two tree species. Sapwood decays more rapidly and heartwood more slowly in fire-killed Douglas-fir snags than the thicker sapwood and narrower heartwood of ponderosa pine (Kimmey, 1955; Bull et al., 1997). The sapwood of ponderosa pine is more resistant to deterioration than the sapwood of other tree species because, in part, the thick bark of ponderosa pine slows the decay process (Bull et al., 1997), and the sapwood does not begin decaying until the third year after death (Kimmey, 1955). These characteristics may also explain why more decayed snags persisted longer on average (i.e. there was a positive parameter estimate for tree decay in both fires). Douglas-fir snags tended to be classified as more heavily decayed than ponderosa pine because the sapwood of Douglas-fir decays faster and it appears more decayed. However, Douglas-fir stands longer likely because the heartwood decays more slowly than in ponderosa pine (Kimmey, 1955; Bull et al., 1997).

5. Management implications

Characteristics of individual snags and stand-level information were the most influential factors in predicting snag longevity. Salvage logging clearly impacts small-scale characteristics such as diameters and densities of snags, but had no apparent influence on the large-scale data incorporated into our models. Consequently, micro-scale characteristics affected by salvage logging activities are the features that most influence snag longevity. The shorter persistence times of ponderosa pine snags lead to patches of suitable cavity-nesting bird habitat that are ephemeral on the landscape level. Postfire salvage logging increased the rates at which snags fell and shortened the time span for providing suitable cavity-nesting bird habitat. Maintenance of large diameter snags and high densities of snags will provide wildlife habitat for the longest period of time possible (cf. Saab et al., 2002). The retention of large-diameter snags in clumps should be a priority if maintaining habitat for cavity-nesting birds is a management goal. Furthermore, prescription that retains at least half of the largest snags available may minimize soil erosion and other disturbances. More intensive salvage logging may have led to greater impacts on snag persistence in our study area. Future research should focus on controlled experiments determining which levels of salvage logging best minimize the negative effects of salvage logging activity on snag longevity.

Predicting snag longevity is useful for land mangers required to identify postfire areas that are most suitable for cavity-nesting birds and other fire-dependent species. Micro-scale, field-collected data are labor intensive and expensive to obtain. Therefore, developing snag longevity models based on larger-scale, remotely sensed data will be necessary to provide more easily implemented management guidelines for maintaining wildlife habitat in postfire forests. However, the large scale variables used in our models did not prove to be useful predictors of annual persistence. Improvements in remote sensing technology are occurring rapidly and we expect that high resolution data will lead to better predictive ability.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2006.05.068.

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