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Survival dynamics of mechanically topped Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) snags in Douglas-fir plantations, Oregon, USA

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ABSTRACT

Structural enrichment in commercial tree plantations is a potential tool to increase snag numbers but relatively little information is available about how species, size, and spatial distribution of created snags are associated with longevity of these structures. We created 1197 snags in 31 harvest units from 1997 to 1999 in the Cascade and Coast Ranges, Oregon, USA, by topping live trees with harvesting equipment. We used an experimental design to distribute created snags at three densities and as either single or clumped created snags. We fit Weibull and log-logistic Accelerated Failure Time models and found that the median failure time was insensitive to the choice of distribution. We found a small positive effect of diameter at breast height (DBH) and a slight negative effect of increasing distance between created snags on survival. Assuming Weibull and log-logistic distributions at mean observed values of DBH and distance between snags, median survival times for Douglas-fir (*Pseudotsuga menziesii*) were 21.0 (95% confidence interval: 19.3, 22.8) years and 21.2 (19.7, 22.8) years, respectively. For western hemlock (*Tsuga heterophylla*), median survival times were 13.0 (11.9, 14.2) years and 12.5 (11.4, 13.7) years, respectively. Although the two failure distributions had similar median failure times, the log-logistic implies a higher survival probability over time for snags that remained standing at the end of the study period. Created snags can be a useful supplement for harvest units rotated at ~45 years and Douglas-fir will be available for longer as standing structures. For example, under the log-logistic model, a predicted 5% of Douglas-fir snags are retained to rotation age, so that 40 snags per hectare would be required at harvest to maintain 2 snags per hectare through stand rotation. Snags created from western hemlock will provide an early rotation pulse but are unlikely to last longer than 20 years. Our results suggest that longevity can be increased by maximizing the snag size within the safety constraints of harvesting equipment. Scattering of snags may have a slightly negative effect on snag survival but this outcome should be weighed against potential ecological benefits of variation in snag distributions.

1. Introduction

Intensive management of forest stands reduces mortality of crop trees, decreasing the number and distribution of snags and downed logs and thus lowering habitat quality for organisms that use these structural features (Hayes et al., 2005; Homyack and Kroll, 2014; Kroll et al., 2015). In many cases, past management greatly reduced snag distributions across the landscape (Ohmann et al., 2007; Kroll et al., 2010; Homyack et al., 2011; Gustafsson et al., 2012). Maintaining adequate amounts and types of snags at both stand and landscape levels is critical to sustainable forest management (Ohmann et al., 2007; Washington State Department of Natural Resources, 2007; Kozma and Kroll, 2012). In these cases, structural enrichment (Rosenvald and Lõhmus, 2008) and other forms of habitat supplementation (Lindenmayer et al., 2009; Linden and Roloff, 2015) may enhance wildlife populations and biological diversity.

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Evaluation of different methods of topping live trees has determined survival is associated with snag attributes (including species), causes of mortality (mechanical topping, chemicals, or girdling), and landscape factors including topography and aspect (Cline et al., 1980; Morrison and Raphael, 1993; Angers et al., 2010). Similarly, ecological responses to structural enrichment can vary based on many of the same factors (Kroll et al., 2012b; Otto et al., 2013). For example, creation of high stumps in Scandinavia was found to be an effective habitat compensation tool for many species that respond negatively to dead wood harvesting (Lindhe and Lindelöw, 2004; Ranius et al., 2014) but a diversity of structural types and methods of creation were required for conservation across broad taxa groups (Gustafsson et al., 2010). In the Pacific Northwest, USA, native avian species colonize artificially created snags and demonstrate nesting survival rates comparable to those from natural snags (Chambers et al., 1997; Brandeis et al., 2002; Hane et al., 2012). However, Barry et al. (2018) reported muted responses by avian populations two decades after snags were created by tree climbers using a chain-saw. Finally, most snags will become downed logs (Maser and Trappe, 1984) and relatively few studies follow tree fates from snag creation through log disintegration. As a result, forest managers would benefit from additional information about regional effectiveness of specific structural enrichment practices including spatial distribution of snags within harvested areas.

Earlier research documented wildlife responses to created snags in the short term (~10 years post-harvest; Kroll et al., 2012a). We build on previous studies of snag creation to develop a survival model based on physical characteristics of individual snags and experimental treatments to predict the proportion of created snags available long-term for wildlife use. We used an Accelerated Failure Time (AFT) with frailty model to determine whether survival rates of Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) snags varied by species, diameter at breast height (DBH), and inter-snag distance. We predicted survival time at two points of biological interest: the age at which the live canopy overtops the snags (23 years) and stand age at next harvest (45 years). In areas where snag numbers are depleted, managers can apply this information to distribute beneficial structures throughout the stand rotation.

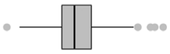
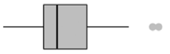
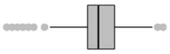
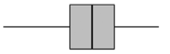
2. Material and methods

Snag creation occurred from 1997 to 1999 on intensively managed forest owned by Weyerhaeuser near Cottage Grove, OR, USA (Fig. S1). The study area occurred in the Western Cascades Physiographic Province and was characterized by a maritime climate with wet, mild winters and cool, dry summers (Franklin and Dyrness, 1988). Elevations ranged from 180 to 1375 m. Second-growth Douglas-fir dominated the stands, with lesser components of western hemlock and western red-cedar (*Thuja plicata*).

Since the 1960s, these forests have been managed primarily for wood production by planting of nursery-grown seedlings, fertilization, control of competing deciduous vegetation, precommercial and commercial thinning, and clearcutting on 45–60 year rotations (Talbert and Marshall, 2005). At the landscape level, conifer forests were interspersed with riparian reserves and other inoperable areas, recent clearcuts, and small gaps associated with streams, topography, and roads.

We used a completely randomized design with a 3 × 2 factorial treatment structure of snag density (3 levels: 0.5, 1 and 2 snags/ha) and distribution pattern (2 levels: scattered and clumped). A mechanical harvester extended to maximum height removed the top of the tree, leaving the bottom portion as the snag. We provided the operator with the treatment prescription and latitude to select trees as they saw fit. We created 1197 snags of varying height and diameter on 31 stands (Table 1). Eight hundred and seventy-four snags were Douglas-fir (73%), 182 were western hemlock (15%), and the remainder were other conifers or hardwoods. The initial study phase included survival monitoring through 2002 and here we provide additional descriptions of snag survival monitoring through 2016. Further details for the initial study design can be found in Arnett et al. (2010). Information about wildlife use of created snags from this study is presented in Arnett et al. (2010) and Hane et al. (2012).

Table 1
Diameter at breast height (DBH; at 1.3 m), height, and distance from the created snag to the nearest other created snag for 874 Douglas-fir (*Pseudotzuga menziesii*) and 182 western hemlock (*Tsuga heterophylla*) created snags in 31 harvest units, Oregon, USA, 1997–2016.

Variable	Species	Mean	Range	Distribution
DBH (cm)	Douglas-fir	47.96	5.1–99.1	
	Western hemlock	48.97	22.9–88.9	
Height (m)	Douglas-fir	6.42	1.2–10.1	
	Western hemlock	6.13	3.7–7.9	
Distance (m)	Douglas-fir	24.31	0–374.5	
	Western hemlock	21.54	0–160.2	

We sampled a random subset (*n* = 31) of stands in 2007, all stands from 2008 to 2010, and a non-random sample of 10 stands in 2011–2013. Although the 2011–2013 subset was not selected randomly, survival analysis is robust to non-random selection so long as site selection is not predicated on any of the covariates (Clark et al., 2003). We made a final count of snags across all units in 2016. All monitoring took place in late spring or early summer except in 2016 when monitoring continued through September. Seasonal risk of falling is greatest in the winter due to saturated soils and wind events; we assumed that snags surviving until late April were stable enough to last into the fall. We recorded species, height, and decay stage for each created snag. We recorded new heights for broken snags. If the new height was less than 1.4 m, the snag was considered down. We recorded leaning snags as standing until the majority of the bole was touching the ground at which point we considered the structure to be a downed log.

To model survival, we used the AFT model (an increasingly common alternative to the Cox Proportional Hazard (PH) model; Wang et al., 2015). Unlike PH models, which assume a common hazard function across all subjects of interest, AFT models survival time directly and provides easily interpretable summary measures (Bradburn et al., 2003a). The AFT covariate effects act multiplicatively on the location parameter of the failure time distribution, effectively ‘speeding up or slowing down time’. Following Parish et al (2010), we used the *survival* package (Therneau, 2015) in R (R Development Core Team, 2017) to model the failure times of created snags as:

$$T_i \sim f_T(\mu_i, \sigma_T)$$

$$\log \mu_i = \beta_0 + \beta_1 \cdot I(\text{Hemlock})_i + \beta_2 \cdot DBH_i + \beta_3 \cdot d_i^* + \alpha_{j:i \in J_j}$$

$$\alpha_j \sim f_a(\theta_a)$$

where T_i is the failure time of snag *i*, and follows the distribution f_T with parameters scale μ_i and shape σ_T; β_0, β_1, β_2, and β_3 are model coefficients; $I(Hemlock)_i = 1$ if snag *i* is a hemlock and 0 if it is a Douglas-fir; DBH_i is diameter at breast height of snag *i*; d_i^* is distance to the nearest neighbor snag; J_j are indices of snags at site *j*; and $\alpha_{j:i \in J_j}$ is the random effect (frailty) associated with site *j* where snag *i* is located, and follows the group (site)-level distribution f_a with parameter θ_a. Random effects for each site (also known as shared frailties) are included to account for unmeasured site-level variation not captured by the covariates. If the variance of the frailty distribution is small, differences from site to site are due primarily to measured covariates. Conversely, if the variance of the frailty distribution is large, unobserved factors vary between stands and have a large effect on the failure times. We assumed the site-level frailty distribution f_a is gamma for both models.

We considered the Weibull and the log-logistic families of distributions to model failure times. The Weibull is a popular and flexible family for modeling failure times in a variety of settings (Lawless, 2003), including for modeling snag survival times (Parish et al., 2010). The hazard function is the instantaneous probability of failure given that a snag survived to a given time, and the Weibull is flexible as it can model increasing, constant, or decreasing hazards depending on the value of the shape parameter. For the Weibull distribution, a shape parameter less than one indicates a hazard decreasing monotonically over time, a shape parameter equal to one indicates a constant hazard, and a shape parameter greater than one indicates a monotonically increasing hazard. Similar to the Weibull, the log-logistic distribution has been applied widely (Lawless, 2003). As an alternative to the log-normal distribution, the log-logistic distribution has simple expressions for both the survivor and hazard functions, even under censoring (Kalbfleisch and Prentice, 2002). The log-logistic can imply a monotonically decreasing hazard function when the shape parameter is less than one, a monotonically increasing hazard function when the shape parameter is equal to one, and a hazard function that increases to a maximum and then decreases eventually to zero when the shape parameter is larger than one. These characteristics make the log-logistic an appropriate comparison to results obtained using the Weibull distribution.

Diagnostics for AFT fit are not well-defined (Bradburn et al., 2003b). We used a graphical format to compare curves and conduct residual analysis as suggested by Kay and Kinnersley (2002) and Swindell (2009).

3. Results

Of the 1197 topped trees, we removed 41 (0.03%) trees from the analysis because they remained living and all but one remained standing in 2016. Douglas-fir and western hemlock were the only species with sufficient sample sizes to fit a model. At 11 years post-harvest when we conducted a complete census of created snags, 91% of all stems and 95% of Douglas-fir stems were standing. At nine and 13 years post-creation, 96% of all stems and 85% of all Douglas-fir stems were still standing, respectively. At 19 years, ~90% of hemlock snags had fallen, whereas only about 40% of Douglas-fir snags had fallen.

We predicted median survival time to be 24 years for Douglas-fir while actual median survival time was unknown. Actual median survival and predicted survival for western hemlock was 14 years (Fig. 1). For both species, model results indicated a slight positive effect of increasing DBH and a slight negative effect of increasing inter-snag distance on survival. The Weibull shape parameter indicated that the hazard increases over time (Table 2). The log-logistic shape parameter indicates that the Douglas-fir hazard increases until about twenty-five years and then slowly decreases (Table 2, Fig. 2). For hemlock, hazard increases until about year 15 and then decreases more rapidly than the Douglas-fir hazard (Fig. 2). The shared frailty variance for both the Weibull and log-logistic models suggests shared frailties on the same order as included covariates (Table 2). Site to site variation in survival was more pronounced for Douglas-fir than western hemlock under both distributions (Table 2, Fig. 3). Modeling minor species besides Douglas-fir and western hemlock as a group would have been inappropriate as species have different survival probability distributions (Parish et al., 2010).

Mean height to bottom of live canopy for the regenerating stands will exceed median snag height at 23 years (Fig. S2). At 23 years, just under 50% of Douglas-fir are predicted to remain standing under both distributions. For hemlock, < 5% will remain assuming a log-logistic distribution and none will remain assuming a Weibull distribution (Fig. 4). At a nominal rotation age of 45 years, < 5% of Douglas-fir created snags will remain standing assuming a log-logistic distribution. No Douglas-fir will remain standing assuming a Weibull distribution; no hemlock will remain standing under either assumed distribution.

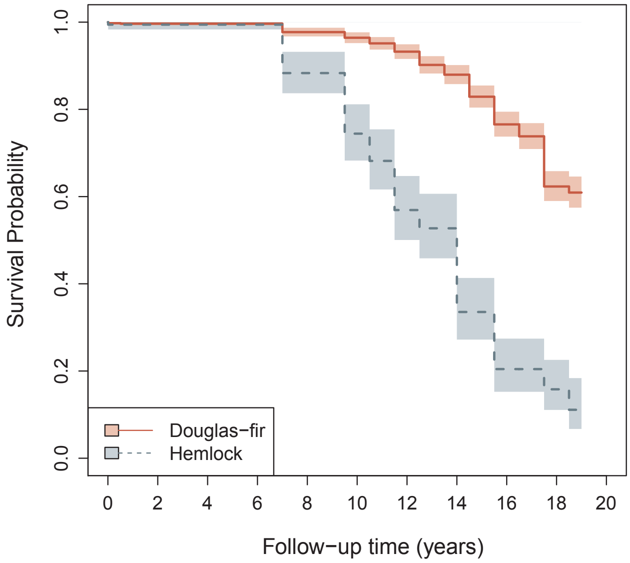


Fig. 1. Kaplan-Meier empirical survival curves by tree species for created snags, Oregon, USA, 1997–2016. The proportion of western hemlock snags that had fallen by the end of the study period was estimated to be 0.89 (0.82, 0.93) whereas the proportion of Douglas-fir snags that had fallen by the end of the study period was estimated to be 0.39 (0.35, 0.43). Kaplan-Meier estimates with 95% confidence intervals based on the logarithm of survival are plotted.

The Kaplan-Meier curves are closely approximated by the model fitted curves (Fig. 4). Based on the generalized probability plot, our confidence in the AFT assumption is low early in the snag history but increases over time (Fig. 5). Early hemlock failures occur sooner than would be expected based on Douglas-fir failures under the AFT assumption but this deviation diminishes after the first 12–15% of snags have fallen. Examination of model residuals indicates the chosen modeling framework was appropriate (Figs. 4 and 5).

4. Discussion

Supplemental structures can be created to increase habitat quality at the local level (Bunnell et al., 2002; Vuidot et al., 2011; Linden et al., 2012) but more information is required about temporal persistence of these structures to increase ecological value at the regional scale (Moorman et al., 1999; Linden and Roloff, 2013; Barry et al., 2018). Survival of created Douglas-fir snags in our study appeared to be equivalent to, or more prolonged than, natural snag longevity. Our created snag half-life was ~25 years, in contrast to a half-life of 12–16 years for Douglas-fir of all size classes in western Idaho, USA (Russell et al., 2006), and coastal British Columbia, Canada (Parish et al., 2010). East of the Cascade crest in Oregon, Dunn and Bailey (2012) reported a half-life for Douglas-fir > 41 cm of 23 years. In the Sierra Nevada, California, USA, half of all conifer snags fell within 10 years of death (Raphael and Morrison, 1987). The rapid fall rate of created hemlock snags is expected as hemlock boles decay much faster than Douglas-fir (Graham, 1981) and decrease in density an order of magnitude faster than Douglas-fir (Means et al., 1985). Brandeis et al. (2002) encouraged more work with regards to how methods of creation affect snag longevity given highly variable study results. For example, southern red oak (*Quercus falcata Michx.*) killed by herbicides decayed significantly faster than girdled or control southern red oak (Conner et al., 1983). In Michigan, natural jack pine (*Pinus banksiana*) and oak

Table 2
Model coefficient estimates for the created snag survival model using either Weibull or log-logistic distributions for failure times and gamma distribution for frailties, Oregon, USA, 1997–2016. Model parameters were estimated by penalization of the likelihood using Akaike's AIC as the optimization criterion (see Therneau et al., 2003).

Model	Parameters	Coefficient	Standard error	Chi-square	DF	p-value
Weibull[a]	β_0 (Intercept)	2.7825	0.0727	1463.5	1	0
	β_1 (Hemlock)	−0.4774	0.0344	193.1	1	0
	β_2 (DBH)	0.0082	0.0013	39.5	1	0
	β_3 (Distance)	−0.0014	0.0004	10.6	1	1.1×10^{-3}
	Frailties			71.2	24.6	2×10^{-6}
Log-logistic[b]	β_0 (Intercept)	2.6778	0.0759	1245.4	1	0
	β_1 (Hemlock)	−0.5284	0.0386	187.8	1	0
	β_2 (DBH)	0.0086	0.0014	36.2	1	0
	β_3 (Distance)	−0.0016	0.0005	10.6	1	1.1×10^{-3}
	Frailties			59.4	22	2.7×10^{-5}

[a] Weibull shape = 3.60; variance of frailty distribution = 0.041; range of frailties: −0.430 to 0.264.
[b] Log-logistic shape = 4.34; variance of frailty distribution = 0.028; range of frailties: −0.356 to 0.228.

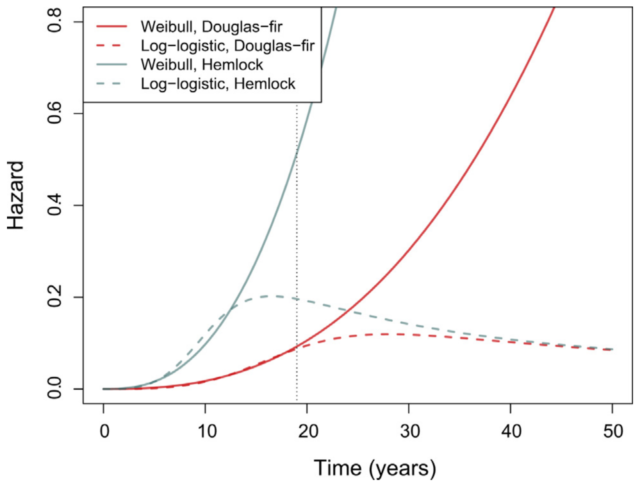


Fig. 2. A comparison of AFT model-predicted hazard functions for Douglas-fir and western hemlock snags when diameter at breast height and nearest neighbor distance are at the whole sample average values (48.1 cm and 23.8 m, respectively), Oregon, USA, 1997–2016. Although the two failure time distributions have similar hazards up to year 19, particularly for Douglas-fir, they imply different hazard functions beyond year 19.

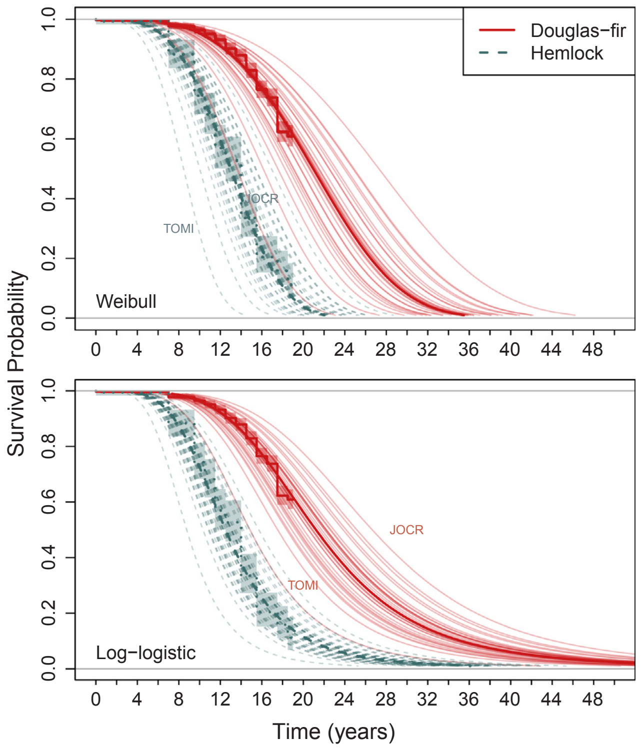


Fig. 3. AFT model-predicted survival curves (Weibull, top panel; log-logistic, bottom panel) for Douglas-fir and western hemlock snags, plotted over Kaplan-Meier empirical survival curves, Oregon, USA, 1997–2016. The heavy smooth curves are the average survival curves across sites for each species. Lighter smooth curves are survival curves for each site when diameter at breast height and nearest neighbor distance are set to the whole sample average values (48.1 cm and 23.8 m, respectively).

snags were more likely to fall than snags created by girdling (Corace et al., 2010). In contrast, snags created from Douglas-fir in western Oregon fell at a rate similar to Douglas-fir snags killed by natural agents (Huff and Bailey, 2009).

Survival times of natural snags could be caused by pre-existing conditions such as pathogen stress or mechanical damage that caused the mortality and reduced the structural integrity of the stem (e.g., heart rot; Garber et al., 2005). Naturally formed snags often contain all or some portion of the canopy which causes increased wind drag and may result in uprooting or breakage (Stephens, 1956; Peltola and Kellomäki, 1993; England et al., 2000). We created snags from healthy trees and the snags did not have a gradual time to death with the corresponding degradation of the supporting root structures and were typically devoid of all limbs, reducing wind related drag. Thus, the main factors contributing to reduced survival were not present in the created snags. In addition, studies of natural snag fall rates only consider natural failure mechanisms. In our study, no differentiation existed between snags that fell or broke and those removed for fire-wood and/or safety purposes (8 snags; < 1% of total created).

Created snags dynamics in our study corresponded with the industrial forest Douglas-fir snag simulations done by Wilhere (2003). These simulations predicted that 80–85% of snags will be standing at 10 years and 50% of small snags (< 38 cm dbh) will fall by 24 years. However, at nominal rotation age, Wilhere's (2003) model predicted approximately 18% of small snags will be standing with a lower 90% confidence limit around 15%, values well above our predicted value of 5% standing. This result suggests that as created snags age, they may become more susceptible to mortality agents (although the pathways are unclear). Further research is warranted to validate the modeling predictions.

Ample evidence documents that large snags will persist on the landscape longer than smaller snags (Cline et al., 1980; Smith and Cluck, 2007). In our study, machinery limits constrained the size of snags we could create. The snags did not have enough height variability

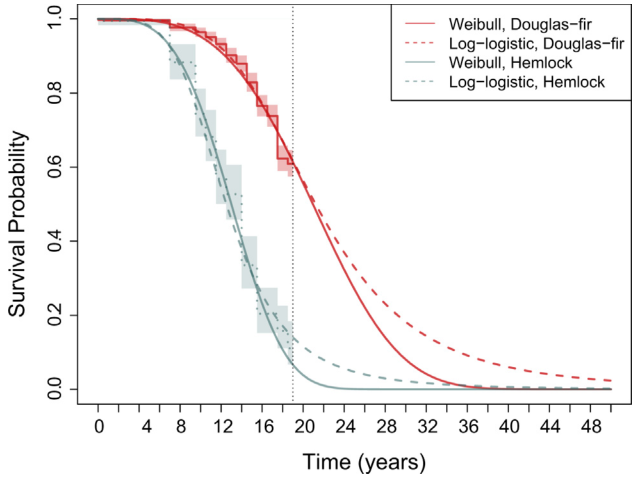


Fig. 4. A comparison of AFT model-predicted survival curves for Douglas-fir and western hemlock snags when diameter at breast height and nearest neighbor distance are at the whole sample average values (48.1 cm and 23.8 m, respectively), plotted over Kaplan-Meier empirical survival curves, Oregon, USA, 1997–2016. The two failure time distributions imply different trajectories for future survival of snags, particularly for Douglas-fir. The close relationship between the Kaplan-Meier curve and the model curves suggests the chosen models are appropriate.

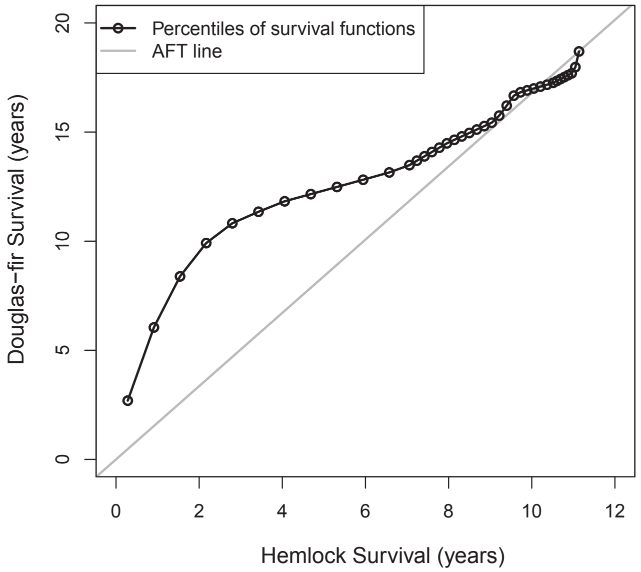


Fig. 5. The interpolated percentiles of the Kaplan-Meier empirical survival functions (with a guiding proportionality line) for Douglas-fir and western hemlock, Oregon, USA, 1997–2016. The accelerated failure time (AFT) model assumes the percentiles of the survival distributions for two groups subject to different accelerating effects are proportional. Tree species has the largest effect on survival time. Under the AFT model, the percentiles should follow the proportionality line.

(Table 1) (median height = 6.4 m, standard deviation = 1.2 m) to separate them into meaningful height related categories. We found a positive effect on survival as snag diameter increased but the effect was generally smaller than the species effect.

Similarly, effect of spatial arrangement was also generally smaller than the effect of species. We are unable to posit a reason as to why survival of snags in clumps was higher than snags distributed as individuals. Individual snags may be targeted as foraging and nesting substrates at higher rates than clumped snags, increasing decay rates and decreasing survival (A.J. Kroll, pers. obs.). Also, we evaluated a relatively low density of created snags (when compared to densities of snags in late-successional and second growth forests in the region; Cline et al., 1980). As a result, survival rates of created snags may differ substantially from natural snags regardless of whether created snags are clumped or spaced individually.

The variances for both distributions suggest that stand level differences are on the same scale as the measured covariates (Table 2). For example, the two stands on the extreme ends of the frailty distribution (TOMI and JOCR, Fig. 3) were quite similar. Both stands had fewer than ten snags; snags were created exclusively from Douglas-fir; stand-level median DBH was greater than the overall median; and snags were scattered widely. Factors such as soil type, elevation, slope, and vertebrate and invertebrate activity may be influencing snag survival in these stands.

We could not model western red cedar failure rates due to the low number of failures. The relatively large number of western red cedar that survived topping may be a result of their resistance to damaging agents (Burns and Honkala, 1990) and location adjacent to green-tree retention areas or other standing timber, which may mediate stress associated with having most limbs removed. Although we instructed operators to remove live limbs, in some cases the snags' proximity to standing timber made access to the entire bole difficult and some live limbs remained.

Species-specific survival curves have been well documented in the literature (Angers et al., 2010; Russell and Weiskittel, 2012). In a study of 19,622 snags, Parish et al (2010) demonstrated that Douglas-fir and hemlock failure rates were modeled sufficiently with the Weibull distribution. Our results indicated that both the Weibull and log-logistic distributions provided an adequate fit to the data; showed similar hazards up to 19 years, particularly for Douglas-fir; and showed similar covariate effects but resulted in different long-term projections. The Weibull model suggested that snags become increasingly susceptible to the causes of failure as time progresses. After 19 years, snags are largely under the canopy, less apt to dry out, and more susceptible to moisture-induced rot (Appendix A; Pearson, 1930; Harmon et al., 2004). The log-logistic model suggested the weakest snags fall early, leaving a cohort that may be resistant to falling (e.g., because snags are hardened by solar exposure).

5. Management implications

In the Douglas-fir region of western Oregon and Washington, USA, created snags can provide a useful supplement until the nominal rotation age if the majority of snags left are Douglas-fir. Leaving western hemlock will provide a pulse in the early portion of the rotation but snags created from western hemlock < 50 cm DBH on average will not survive longer than 20 years. Longevity can be increased by selecting the largest diameter trees given the safety constraints of the equipment. Clumping of snags may have a slight positive effect on survival and provides operators with increased flexibility for distributing created snags in harvest units. As an example, assuming 5% of Douglas-fir snags are retained to rotation age, maintaining 2 snags per ha to rotation would require leaving 40 snags per hectare at harvest. Finally, we reiterate the oft-noted ecological value of coarse woody debris as wildlife habitat and to support soil development and retention. The value of created snags cannot be measured solely on their longevity as standing structures.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2018.10.047.

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