Fates of live trees retained in forest cutting units, western Cascade Range, Oregon

Posy E. Busby, Peter Adler, Timothy L. Warren, and Frederick J. Swanson

Abstract: Live trees, standing dead trees, and downed logs have been retained in some forest harvest sites in the Pacific Northwest to fulfill various ecological objectives. To assess the fates of retained trees following partial cutting of mature forests in the central western Cascade Range in Oregon, we inventoried standing live and dead trees and toppled trees in 21 cutting units in 1993 and 2001. In 1993, 1–10 years after cutting, an average of 65% of the initially retained trees (average of counts for all sites) were alive and standing, 12% had been toppled or topped by wind, 13% had become snags by natural processes, and 10% were converted to snags by management action, including cutting, blasting, girdling, and inoculation with fungi. By 2001, when cutting-unit ages ranged from 9 to 18 years, 54% of the retained trees were alive and standing, 10%–21% had been toppled or topped by wind, 11%–22% had become snags by natural processes, and 14% had been converted to snags by management action. The highest levels of mortality occurred at sites with abundant intentional snag creation and (or) prescribed fire following harvest. The rate of mortality due to windthrow declined over time, possibly because the remaining trees were more windfirm.

Résumé : Des arbres vivants, des arbres morts debout et des billes au sol ont été conservés dans certains sites où la forêt a été récoltée dans le Pacifique Nord-Ouest dans le but d'atteindre divers objectifs d'ordre écologique. Pour évaluer le sort des arbres qui ont été conservés à la suite d'une coupe partielle dans des forêts matures situées dans la partie centrale des Cascades, en Oregon, nous avons fait l'inventaire des arbres debout, vivants et morts, et des arbres renversés dans 21 unités de coupe en 1993 et 2001. En 1993, un à 10 ans après la coupe, 65 % en moyenne des arbres conservés à l'origine (moyenne des résultats de tout sites) étaient encore en vie et debout, 12 % avaient été renversés ou cassés par le vent, 13 % étaient devenus des chicots sous l'effet de processus naturels et 10 % avaient été convertis en chicots à la suite d'interventions d'aménagement, incluant la coupe, le dynamitage, l'annelage et l'inoculation avec des champignons. En 2001, alors que l'âge des aires de coupes variait de neuf à 18 ans, 54 % des arbres conservés étaient en vie et debout, 10 % – 21 % avaient été renversés ou cassés par le vent, 11 % – 22 % étaient devenus des chicots sous l'effet de processus naturels et 14 % avaient été convertis en chicots à la suite d'interventions d'aménagement. Le taux de mortalité était le plus élevé dans les sites où beaucoup de chicots avaient été créés intentionnellement ou dans ceux qui avaient subis un brûlage dirigé à la suite de la récolte. Le taux de mortalité due au chablis a diminué avec le temps, possiblement parce que les arbres restants étaient plus résistants au vent.

[Traduit par la Rédaction]

Introduction

Since the early 1990s, management of US federal forests in the Pacific Northwest has increasingly emphasized conservation of biological diversity and ecological processes. One widespread technique intended to promote conservation involves the retention of live trees in cutting units (Franklin 1989, 1992; Franklin et al. 2002). The Northwest Forest Plan, for example, prescribed retention of live trees plus downed dead wood in most areas where cutting was permitted under the plan (USDA Forest Service and USDI Bureau of Land Management 1994).

Live trees and dead wood are retained in cutting units for diverse purposes, such as sustaining habitat for native species and maintaining ecological processes that may be substantially altered by clear-cutting (Swanson and Franklin 1992; Franklin et al. 2002). Trees may be retained in cutting units as live trees, standing dead trees ("snags"), or logs on the ground, with each performing distinct ecological functions. Retaining these structures is intended to emulate natu-

Received 7 October 2005. Accepted 26 May 2006. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 13 October 2006.

P.E. Busby,[1,2] P. Adler,[3] and T.L. Warren.[4] H.J. Andrews Experimental Forest, Blue River, OR 97413, USA.
F.J. Swanson. USDA Forest Service, Pacific Northwest Research Station, 3200 Jefferson Way, Corvallis, OR 97331, USA.

[1]Corresponding author (e-mail: busby@post.harvard.edu).
[2]Present address: Harvard Forest, Harvard University, 324 North Main Street, Petersham, MA 01366, USA.
[3]Present address: National Center for Ecological Analysis and Synthesis, Suite 300, 735 State Street, Santa Barbara, CA 93101, USA.
[4]Present address: Department of Physiology, University of California at San Francisco, P.O. Box O444, 513 Parnassus Avenue, San Francisco, CA 94143-0444, USA.

 doi:10.1139/X06-140

ral disturbance better than clear-cutting, thus providing a “coarse-filter” approach to sustaining native species, their habitat, and associated ecological processes (Swanson and Franklin 1992; Cissel et al. 1999; Franklin et al. 2002).

The success of tree-retention treatments depends on the fate of retained trees following harvest. Retained live trees may survive, become snags by either natural processes or intentional management action, or fall to the forest floor and function as downed dead wood. Mortality of live trees could increase, since removal of adjacent trees often increases vulnerability to wind and other damaging processes (Wiedman 1920; Issac 1940; Savill 1982; Huggard et al. 1999; Moore et al. 2003). Additionally, live trees slated for retention may be damaged or killed during harvest and slash-burning. To make decisions about scheduling the amount and form of wood dedicated to perform ecological functions in harvest units over time, managers need quantitative information on fates of retained trees.

To assess the fates of live trees retained in dispersed patterns across cutting units in the central western Cascade Range of Oregon, we conducted repeat surveys (1993 and 2001) of sites cut as early as 1983. Our objectives in this study were to (*i*) survey the survival and mortality of trees retained at the time of harvest, (*ii*) explore the relationship between site conditions and tree mortality, (*iii*) describe temporal patterns of windthrow and other causes of mortality, and (*iv*) project the future fate of retained live trees to guide long-term management.

Background

Previous research on windthrow following partial harvest shows that retained trees are initially at increased risk of wind damage, but often become less susceptible over a period of 2–5 years after cutting (e.g., Wiedman 1920; Savill 1983). Initial susceptibility to wind damage is determined by many factors, including the ratio of tree height to diameter, stand history, climatic and soil conditions, and topographic position (Mitchell 1995; Wilson 2004). In the years following cutting, pruning of foliage and limbs reduces the crown area of surviving trees and, therefore, their susceptibility to windthrow. Toppling of the least windfirm trees leaves a stand of more stable trees (Wiedman 1920; Savill 1983).

Studies in British Columbia, Oregon, and Washington have addressed the effects of windthrow in areas of partial cutting. Isaac (1940) reported that windthrow of residual Douglas-fir trees on partially cut lands in the Cascade Range of Oregon and Washington ranged from 3% to 50% across eight old-growth forest sites after 11–15 years. Wind toppled more than 40% of the standing trees at half of the sites. More recent studies in the region report lower rates of wind damage in retention units over shorter study periods. The Montane Alternative Silvicultural Systems experiment in British Columbia reported windthrow rates of 10%–30% for western hemlock and Pacific silver fir 6 years after cutting, with the highest mortality in sites with low-density (5% basal area) dispersed retention (Moore et al. 2003). Coates (1997) reported much less wind damage for western hemlock in similar sites, but with higher densities of retained trees: 3% mortality 2 years after cutting for sites with 40% aggregated retention, and 2% mortality 2 years after cutting for sites with 70% dispersed retention. Huggard et al. (1999) found 3% windthrow for subalpine fir and Engelmann spruce in British Columbia 3 years after harvest in sites with 66% dispersed and aggregated retention. Five years after harvest, mortality rates in Huggard et al.’s (1999) sites were similar to levels in uncut control plots (Moore et al. 2003). In Oregon and Washington, the Demonstration of Ecosystem Management Options study has shown 1%–2% mortality 2–3 years after harvest in sites with 40% basal area retained, and up to 6% mortality in sites with 15% basal area retained (Halpern and Halaj 2005).

In general, these and other studies report low levels of windthrow, with higher density and aggregation of retained trees favoring survival. The sites with the highest levels of windthrow were those in which the longest time had elapsed since harvest. To our knowledge, however, no long-term studies have tracked the fate of residual trees over the course of decades following harvesting in partial cutting units.

Retention units surveyed in this study are similar to live-tree-retention units prescribed by the Pacific Northwest Forest Plan, which became policy in 1994 (USDA Forest Service and USDI Bureau of Land Management 1994). Live trees retained in most of the surveyed units were dispersed and some were intended to be converted to snags over the first few decades after cutting, whereas the Pacific Northwest Forest Plan prescribes retention of live trees with some degree of clumping for more diverse purposes and assumes that many of them will persist through the 80-year period until the next cut and beyond. Criteria for selecting retained trees in the surveyed sites varied among sites, but in most units they were based on wildlife or other habitat considerations.

USDA Forest Service records indicate that artificial snag creation to provide wildlife habitat began in the surveyed units in 1989 and was used increasingly thereafter. Methods included blasting or sawing the tops of trees, inoculating trees with heart-rot fungi, and girdling at a height of 15–30 m up the bole. Blasting and sawing the upper boles of trees were the most common methods used in the area in the early 1990s.

Material and methods

Study area

Study sites were located in the Blue River Ranger District (now part of the McKenzie River Ranger District) of the Willamette National Forest in western Oregon. These sites are located in steep terrain between 485 and 1350 m elevation in the central western Cascade Range (Table 1). Mean annual precipitation ranges from 1250 to over 3000 mm. Strong storm winds come mainly out of the southwest during the fall and winter. Hill slope gradients are moderate to steep and the thin soils are derived from volcanic parent material. Native forest cover in the area is dominated by 80- to 500-year old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) – western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) stands established primarily after wildfire. Study sites were mainly in mature (80–200 years old) forest, commonly with a component of old-growth (>200 years old) trees. Dispersed-patch clear-cutting after World War II created scat-

Table 1. Characteristics of sites sampled in 1993 and 2001.

Unit name	Date of harvest	Forest type*	Elevation (m)	Aspect	Slope (%)	Area (ha)	No. of live trees/ha	No. of snags/ha
Mendel 2	1983	OG	670.6	S	30	13	8.9	2.8
Wildwood 2	1987	MA	975.4	N	5–25	4	37.8	0
Wildwood 4	1987	MI	1005.8	E	15–20	3.6	48.6	8.9
Elindel 15.1 and 15.2	1888	MI	853.4	W, S	0–35	4	7	1.2
Elindel 15.3	1888	MI	853.4	N	40	1.2	5.8	2.5
Lytle 7	1889	OG	823	W	20–35	10.1	16.6	1
Lookout Sentinel 5	1990	OG	579.1	E	20–25	1	36	2
Lookout Sentinel 2 and 3	1990	MA	518.2	E	30	10.1	5.1	1.4
French Removal 9	1990	MA	1524	W	20–25	8.5	5.3	0.1
Three Bears 1.1 and 1.2	1990	MA	1097.3	S, W	25–30	16.2	3.8	0.3
Three Bears 5	1990	MI	1097.3	E	25	8.5	8.1	0.4
Paws 6	1990	MI	609.6	N	20–30	5.3	7.2	0
Roar East 6.1 and 6.2	1990	MA	1097.3	W, E	5–22	6.5	6.3	0
Roar East 7	1990	MA	1158.2	W	8–14	9.7	4.9	0
Tital Too 1	1990	MA	670.6	S	0–15	23.5	5.4	0.3
O'Leary 6	1991	MA	1097.3	S	15–25	8.9	11.9	0.3
Slim Scout 3b	1991	OG	731.2	S	30	2	18	1.5
Slim Scout 4	1991	OG	883.9	N	30	4.9	23.1	1.8
Starrbright 6	1991	OG	731.5	E	7	3.2	10.9	0.9
Elk/Mink 4	1991	MA	1219.2	N	30–40	9.3	16.5	0.6
Starbright 1	1992	MI	914.4	E	10–25	6.1	6.9	0.2

*OG, old growth, >200 years of age; MA, mature, 80–200 years of age; MI, mix of mature and old growth.

tered openings that developed into conifer plantations over about 25% of the area.

Site selection and characteristics

Forty-four sites with silvicultural prescriptions for live-tree retention were surveyed in 1993 (Adler 1994). We randomly selected 21 of these for the 2001 survey (Table 1). In the 2001 sample, year of harvest of the selected sites ranged from 1983 to 1992, with 17 of the 21 cutting units 2–5 years old in 1993. The area of the individual surveyed cutting units varied from 1.2 to 23.5 ha, and the density of retained live trees ranged from 4.4 to 50.4 trees/ha, with an average of 12.1/ ha.

Inventory and categorization of trees

Live trees and snags were counted and classified by direct observation at each site within the boundaries interpreted by examining aerial photographs and by USDA Forest Service markers commonly found at the edges of cutting units (Table 2). We estimated the initial number of live trees retained at harvest by summing field counts for all live and dead trees observed in 1993. Unlike the 1993 inventory, the 2001 survey did not directly inventory windthrown trees on the ground because they were obscured by vegetation that had grown in the intervening 8 years.

All standing trees and snags with a diameter at breast height (1.4 m above the ground) at least 30 cm at the 2001 survey date were assigned to the following categories:

- Live tree: a live tree intentionally retained at harvest with the live crown still intact.
- Natural snag: (*i*) pre-harvest natural snag — a snag with a minimum height of 3 m in a state of decay more advanced than would be possible for a tree that died during or after logging, as indicated by a shorter bole, the absence of fine twigs and limbs, more decomposed wood, and greater bark loss (Cline et al. 1980); (*ii*) post-harvest natural snag — a standing dead tree with fine branch structure indicating recent death and without evidence of topping by natural or management processes and in a decay condition that suggests death during or after logging.
- Intentionally created snag: few or no live limbs remaining; the bole has a flat top without splinters, as if cut by saw, or a splintered, flat break (splinters <30 cm long) with splinters pointing in more than one direction, as if blasted with dynamite. The stage of decay indicates post-harvest death. In some cases "green snags" were created with a few lower live limbs retained to delay death.
- Wind-created snag: a standing dead tree with no live limbs remaining. The top is splintered; the break has long (>30 cm) splinters oriented in one direction, suggesting wind breakage. Wind is assumed to be the only significant mechanism of tree death. Decay condition indicate post-harvest death.

We gave special attention to wind damage because it is readily deduced, based on the assumption that it is the primary cause of toppling and stem breakage of live trees in the study area. However, mortality that we interpret as wind-caused commonly has other contributing factors, including abiotic processes, such as snow- and ice-loading of canopies, lightning, and environmental stress (e.g., sunscald of freshly exposed tree crowns), and biotic factors, especially decomposition of the bole and roots and insect damage. We counted blasted and sawed snags as a measure of snag creation. We did not document snags created by fungal inoculation or girdling because these practices occurred infrequently and were difficult to detect in the field; this might have led to a slight undercounting of intentionally created snags and a slight overestimation of naturally created snags. Damage to trees by prescribed fire following logging was noted at several sites but was not sampled quantitatively.

Wind data and analysis

To identify and quantify significant wind events that occurred during the study period, we used data on daily maximum wind speed collected from 1987 to 2001, constituting the entire record, at the nearby Vanilla Leaf meteorological (Vanmet) station located in a clear-cut area in the H.J. Andrews Experimental Forest near Blue River, Oregon. This site is in an open, upper-elevation (1273 m a.s.l.) area with southern exposure and located within the general area of the sampled cutting units. These site conditions seem to make the station location well suited to record the history of significant wind events. A wind speed of 15 m/s was arbitrarily selected to identify the subset of the highest recorded wind events during the period of record. Maximum wind speeds equaled or exceeded this value on 12 days over the 15 year observation period. We also checked the relationship of high-wind events recorded at the Vanmet station with observed windthrow events in the general area to assess their correspondence.

Error

A few potential sources of error may have affected counting and categorizing of trees. First, it was difficult to replicate inventory techniques used during the two surveys, which were conducted 8 years apart by different observers under different site conditions. Vegetation growth between 1993 and 2001 made it difficult to see trees lying on the ground during the second survey. We therefore used the difference between total standing tree counts in 1993 and 2001 as a measure of windthrow. Second, intentional snag creation outside cutting-unit boundaries may have contributed to counting error. In a few cases the number of suitable live trees within the unit was insufficient to meet management objectives, so trees outside the boundary were chosen by National Forest staff for snag creation. This practice blurred the unit boundary and may have resulted, in a few cases, in a few different trees being counted in the two inventories. Based on USDA Forest Service maps of snag creation, two sites were excluded from the analysis of created snags because of uncertainties about the interpretation of unit boundaries. Overall, we are most confident in the counts for standing live trees, which are the focus of this study.

Data analysis

Surveying live and dead trees in study sites at various time points allowed us to estimate the average annual survival rate between those time points, and to compare survivorship trends across sites where the year of initial harvest varied. Average annual survival rates also allow us to estimate future trends at these sites. At a given site, if T_0 is the initial number of live trees, a fractional survival rate, S (between 0 and 1), implies that T_0S trees will be alive the following year. If tree counts are separated by n years, and the annual survival rate is assumed to be constant during those years, the count after n years, T_{0+n} will be

$$[1] \qquad T_{0+n} = T_0S^n$$

Solving for S, eq. 1 can be rewritten as

$$[2] \qquad S = (T_{0+n}/T_0)^{(1/n)}$$

Site surveys in 1993 and 2001 allowed us to calculate average annual survival rates for three distinct time intervals for each site: harvest to 1993, harvest to 2001, and 1993 to 2001. We calculated Pearson's correlation coefficients (r) to determine whether average annual mortality rates (with and without artificial-snag component) in the three periods are correlated with site factors. R^2, which we report for various site factors, is the fraction of the variance in the mortality rate explained by a particular site factor. We also report the probability, p, of getting a correlation as large as the observed value by random chance (Edwards 1976).

Projection of future populations of retained live trees

We made projections of survival of live trees in a hypothetical cutting unit with retained live trees for a century after harvest, based on three simple scenarios: (1) natural mortality and snag creation, simulated by assuming continued mortality by natural and artificial processes; (2) natural mortality only; and (3) no additional snag creation, simulated by assuming natural mortality and snag creation within 3 years of cutting (scenario 1), followed by natural-process mortality only (scenario 2).

To project survival for a century after harvest, we assumed that survival increases with time since harvest, reflecting the higher survival rates observed in the 1993-to-2001 period than in the harvest-to-1993 period. Therefore, we used the harvest-to-1993 survival rate to estimate survival in the initial years and the 1993-to-2001 rate to estimate future survival at the hypothetical site. However, if mortality continues to decline, this approach may underestimate survival.

For the "natural mortality and snag creation" scenario we used the average annual survival rate for the harvest-to-1993 period, which includes both natural and artificial mortality, to calculate survival of live trees over the first 3 years after harvest. A 3 year period was chosen because this was the average number of years since harvest at sites inventoried in 1993 (15 sites were cut within 3 years and 20 within 6 years after 1993; Table 1). For years 4–99, we applied the 1993-to-2001 average annual survival rate to the population of live trees remaining after the third year.

The "natural mortality only" scenario is based on the natural-process average annual survival rate from the harvest-to-1993 period, which is used to calculate the first 3 years of the projection. For years 4–99, we applied the natural-process average annual survival rate from the 1993-to-2001 period to the population of trees still living after 3 years. This projection assumes no intentional snag creation at any time.

The first 3 years of the "no additional snag creation" scenario are identical with the "snag creation and natural mortality" scenario, since both scenarios assume some level of snag creation in the first 3 years of cutting. Assuming no additional snag creation in years 4–99, live-tree survival for this period is calculated using the natural-process average annual survival rate for the 1993-to-2001 period applied to the live-tree population after the third year.

Table 2. Fates of live trees.

Unit 7 name	No. of live trees retained at harvest	No. of snags retained at harvest	1993 Survey: No. of live trees	No. of natural snags, pre-harvest	No. of natural snags, post-harvest	No. of windthrown trees	No. of intentionally created snags
Mendel 2	116	37	78	37	20	18	0
Wildwood 2	151	0	112	0	4	20	15
Wildwood 4	175	32	115	32	18	42	0
Elindel 15.1, 15.2	28	5	14	5	0	14	0
Elindel 15.3	7	3	5	3	2	0	0
Lytle 7	168	10	46	10	44	78	0
Lookout Sentinel 5	36	2	32	2	1	3	0
Lookout Sentinel 2 and 3	52	14	22	14	9	5	16
French Removal 9	45	1	34	1	8	3	0
Three Bears 1.1 and 1.2	62	5	31	5	12	19	0
Three Bears 5	69	3	52	3	5	12	0
Paws 6	38	0	17	0	5	2	14
Roar East 6.1 and 6.2	41	0	18	0	15	1	7
Roar East 7	48	0	34	0	0	0	13
Tital Too 1	126	6	85	6	3	5	33
O'Leary 6	106	3	41	3	2	2	61
Slim Scout 3b	36	3	30	3	1	0	0
Slim Scout 4	113	9	91	9	8	4	0
Starrbright 6	35	3	17	3	15	3	0
Elk/Mink 4	153	6	148	6	1	4	0
Starbright 1	42	1	37	1	5	0	0

Note: The data from this table have been used to calculate the percentages presented in the Results section.

Results

Survival of live trees

In 1993, across all sites an average of 65% of retained live trees were alive and standing (Table 2, Fig. 1). Tree survival in individual cutting units ranged from 27% to 97% (Table 2). By 2001, 54% of the originally retained trees were living, with survival at individual sites ranging between 23% and 85% (Table 2, Fig. 1). Excluding the trees intentionally converted to snags, 75% of retained trees were alive and standing in 1993 and 64% were living in 2001.

Tracking the relative percentages of live and dead trees in the initial population of retained stems ($N = 1674$) is another way to view changes in these categories over time. At harvest, 91% of uncut stems were live trees and 9% were dead stems (snags) (Table 2, Fig. 2). In 1993, 59% of stems were live trees, 21% were natural snags (including pre- and post-harvest natural snags, standing and fallen), 11% were toppled or topped by wind, and 9% were converted to snags by intentional management action. In 2001, 49% of stems were live trees, 16%–29% were natural snags, 9%–22% were toppled or topped by wind, and 13% were converted to snags by management action. Uncertainty in the 2001 categories reflects the inability to count fallen trees in 2001.

Rates of survival of live trees changed over the two time intervals (Table 2, Fig. 1). An average of 84% of the trees that were alive in 1993 were alive and standing in 2001, whereas only 65% of the originally retained trees were alive in 1993. Average annual survival across sites was 86% for the harvest-to-1993 period, and 98% for the 1993-to-2001 period. In 20 of the 21 sites, average annual mortality in the harvest-to-1993 period was greater than in the 1993-to-2001 period. When trees intentionally converted to snags are excluded, the average annual rate of natural tree mortality was 8.9% and 1.7% in the two periods, respectively.

Site factors

Average annual mortality (with and without artificial-snag component) was not significantly related to aspect, elevation, or slope at the 21 study sites in either period (Table 3). The best predictor of mortality in the harvest-to-1993 period, albeit not a significant one, was the number of trees retained per hectare (Table 3); a higher mortality rate was found in sites with fewer trees retained per hectare (Fig. 3). This trend was marginally significant in the harvest-to-2001 period (Table 3). Time of harvest was a weak predictive factor in all three periods, with trees in more recent cuts experiencing a higher mortality rate (Table 3).

Wind damage

In 1993, 12% of retained live trees had been toppled or topped by wind. In the harvest-to-1993 period wind mortality accounted for 35% of total tree deaths. By 2001, as few as 10% and as many as 21% of retained live trees had been toppled or topped by wind, accounting for 26%–49% of total tree deaths (26% were observed to be wind-created snags, 23% were assumed to be due to windthrow). The ranges reflect the uncertainty of interpreting wind damage in the 2001 survey.

Changes in annual survival rates over time show decreases in windthrow. In the harvest-to-1993 period, annual mortality due to windthrow averaged 5%, with a range of 0%–16%

2001 survey				
No. of live trees	No. of natural snags, pre-harvest	No. of natural snags, post-harvest	No. of wind-created snags	No. of intentionally created snags
76	20	23	12	0
86	1	1	16	17
110	0	18	27	0
14	10	0	0	0
4	1	0	0	0
39	6	33	26	0
26	1	2	5	0
20	1	5	7	16
22	4	6	11	0
24	7	11	8	20
51	19	10	0	0
13	0	5	2	14
14	1	7	3	7
33	0	2	1	13
60	2	4	1	51
42	1	6	11	55
29	4	0	8	0
96	8	6	7	3
11	0	16	9	0
100	1	18	8	16
21	0	3	6	15

Fig. 1. Numbers of live trees in each cutting unit immediately after cutting and in the 1993 and 2001 inventories. Note that the data from this figure have been used to calculate the percentages presented in the Results section.

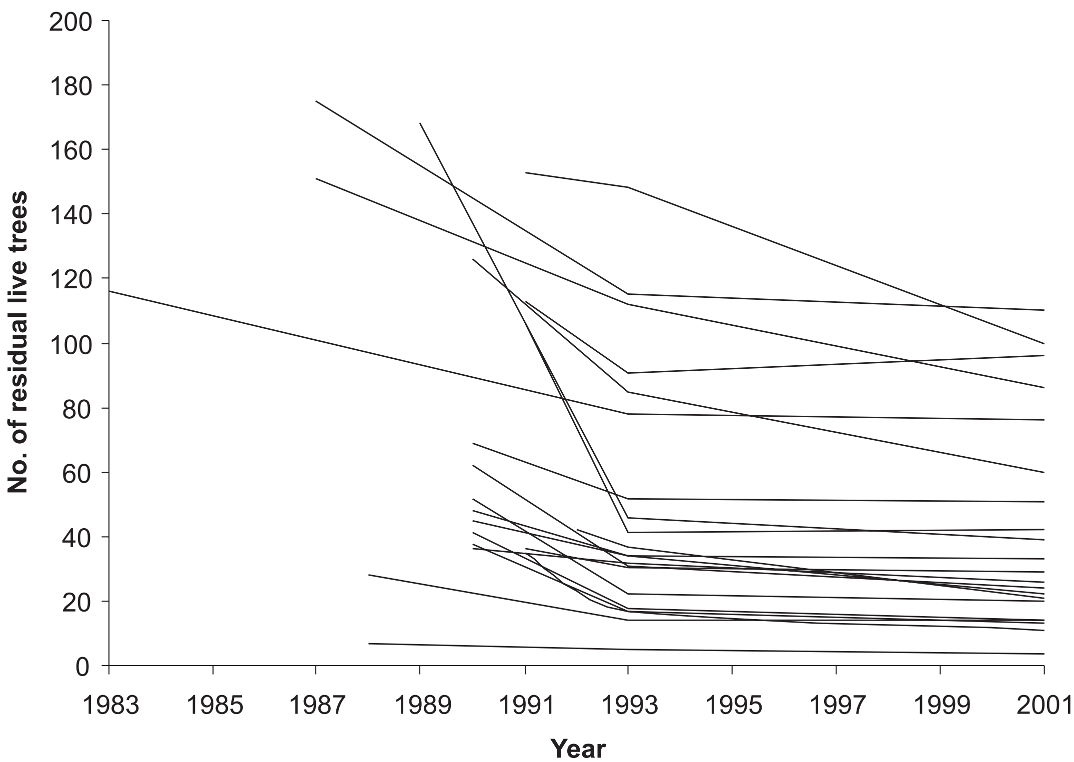


Fig. 2. Percentages of stems in live- and dead-tree categories immediately after cutting and in the 1993 and 2001 inventories (N = 1674). Percentages represent means of values for individual sites. A total of 13% of stems were unaccounted for in the 2001 survey and are assumed to have fallen during the period between the two surveys. These fallen trees could have been natural snags, or live trees toppled by wind. Error bars for the 2001 categories pre- and post-harvest natural snags and windthrow/wind-created snags represent the range (0%–13% of stems) that can be attributed to these categories.

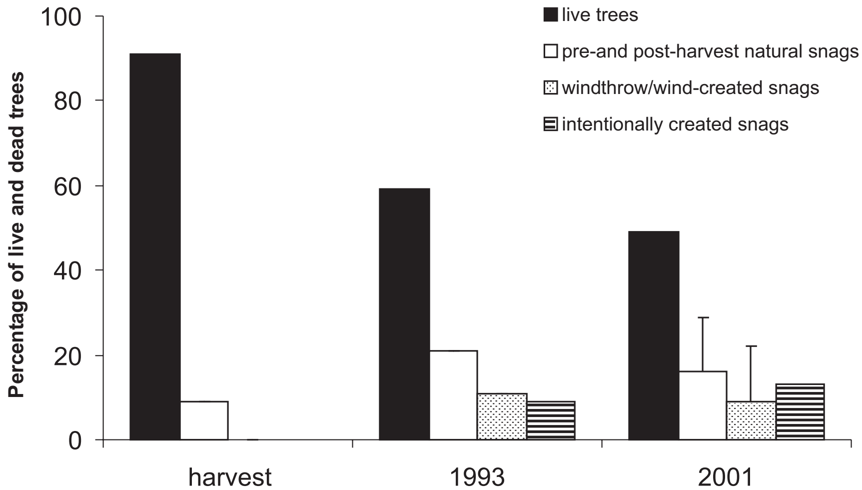


Table 3. Correlations between average annual mortality rates (with artificial-snag component) and site factors.

	Harvest-to-1993 period		Harvest-to-2001 period		1993-to-2001 period	
	r^2	p	r^2	p	r^2	p
Harvest year	0.117	0.128	0.095	0.175	0.121	0.122
Elevation	0.015	0.592	0.006	0.742	0.023	0.512
Aspect	0.055	0.306	0.047	0.348	0.001	0.876
No. of trees retained/ha	0.124	0.118	0.147	0.087	0.032	0.435
Slope	0.081	0.21	0.097	0.168	0.048	0.341

in individual cutting units. In the 1993-to-2001 period, average annual mortality caused by wind was in the range 0.62%–1.2%. Thus, the rate of windthrow mortality declined by approximately 80% between the period 1–10 years after cutting (2–5 years in 17 of the 21 cases) and the following 8 year period.

Records of wind speed between 1987 and 2001 at the Vanmet station in the H.J. Andrews Experimental Forest and central to the study area show that days with wind speed exceeding 15 m/s occurred during both inventory periods. Wind speeds of 15 m/s or greater were recorded on only 2 days during the 1987–1993 period, whereas 10 wind events exceeded 15 m/s between 1995 and 2001. However, major windthrow did occur in the study area during winter storms in 1990 and 1991, and toppled trees were observed in many of the cutting units sampled in 1993. These wind events are not reported as >15 m/s events in the Vanmet station records.

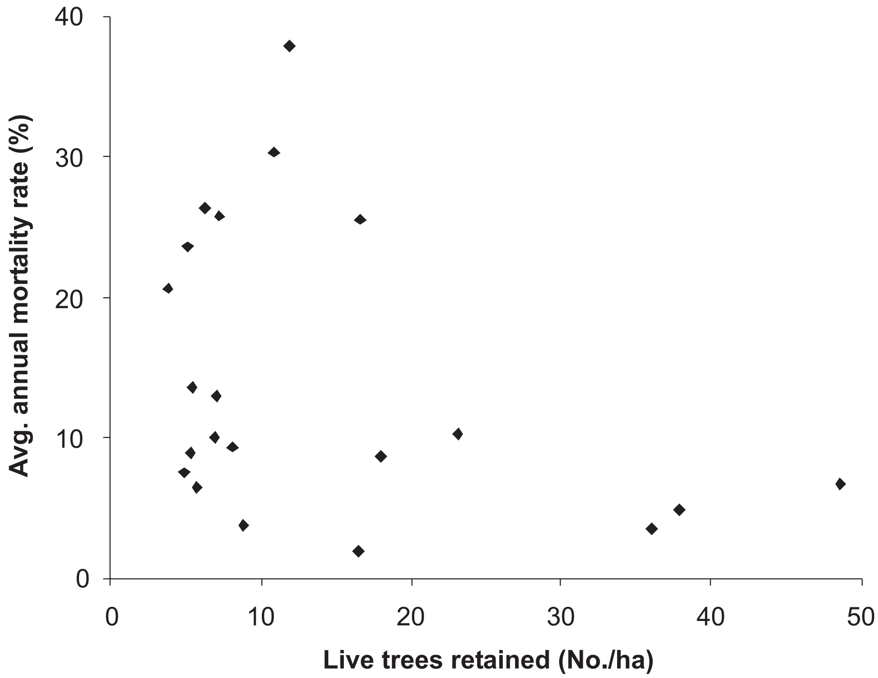
Natural and intentional snag creation

In the 1993 inventory, 13% of retained live trees died from natural causes other than wind, accounting for a total of 43% of tree deaths. By 2001, 11%–22% of retained trees had been converted to standing or fallen natural snags (the uncertainty reflects the inability to observe fallen trees in the 2001 survey). For the entire study period since harvest, 23% of tree deaths were attributed to natural causes (note that this is an underestimate, since fallen snags are included in the assumed-windthrow category, not the natural-snag category). The density of natural snags from pre-harvest stands averaged 1.3/ha, or about 9% of the density of all stems retained after harvest.

Intentional conversion of live trees to snags increased over the inventory period. In 1993, 9% of retained live trees had been converted to snags. Snag creation had occurred at 35% of the 21 sites and accounted for 22% of tree deaths across all the sites (Table 2). By the 2001 inventory, 14% of retained live trees had been converted to snags, and a total of 55% of the sites had experienced snag creation, accounting for 28% of tree deaths to that date. The ratio of created snags to live trees at treated sites rose from approximately 1:6 in 1993 to 1:4 in 2001.

Prescribed fire following harvest occurred in 12 of the 21 study sites, and field observations in 1993 indicate that fire in these sites killed some of the retained live trees. Three of the six sites with the highest average annual mortality rates during the first survey period (>24% of retained live trees) experienced prescribed fire following harvest, but minimal or no intentional snag creation. The other three sites with high mortality rates were not burned, but experienced unusually high levels of snag creation. During the second period, three of the four sites with the highest average annual mor-

Fig. 3. Scatter plot showing the relationship between average annual mortality rate in the harvest-to-1993 period and the number of trees retained per hectare.



tality rate (>5% of retained live trees) experienced intentional snag creation between 1993 and 2001. No fires occurred in any of the sites during the second period, and we saw no evidence of delayed mortality from earlier burning.

Projection of future live-tree populations

The three scenarios of future live tree populations show substantial loss of live trees and corresponding increases in standing and downed dead categories (Fig. 4). The "snag creation and natural morality" scenario projects that 6% of trees retained at harvest will still be living 100 years after harvest. The "no snag creation" scenario projects 14% survival, and the "no additional snag creation" scenario projects 12%.

Discussion

Our surveys document moderate mortality in the first two decades after harvest, with approximately 10%–20% of retained trees topped or toppled by wind and another 10%–20% converted to snags by other natural processes. As we discuss below, management activities appeared to explain more variation in mortality among sites than did physical site factors. Although our data indicate that retained trees experienced less blowdown with time, we do not know enough about the rate at which this occurs to project long-term outcomes with much confidence.

Site factors

We found evidence that sites experiencing the most mortality were those with intentional snag creation and (or) slash burns following harvest. Fire may have caused immediate death, or rendered trees more susceptible to subsequent wind damage and other agents of mortality.

The trend of lower mortality rates with higher densities of retained trees is similar to findings of other studies in the same region (Coates 1997; Halpern et al. 1999; Huggard et al. 1999; Moore et al. 2003; Halpern and Halaj 2005) and in a Norway spruce forest in Sweden (Esseen 1994). The spatial pattern of retained live trees influences survival of trees in partial cutting units and is a focus of other studies in the region (Halpern et al. 1999; Halpern and Halaj 2005).

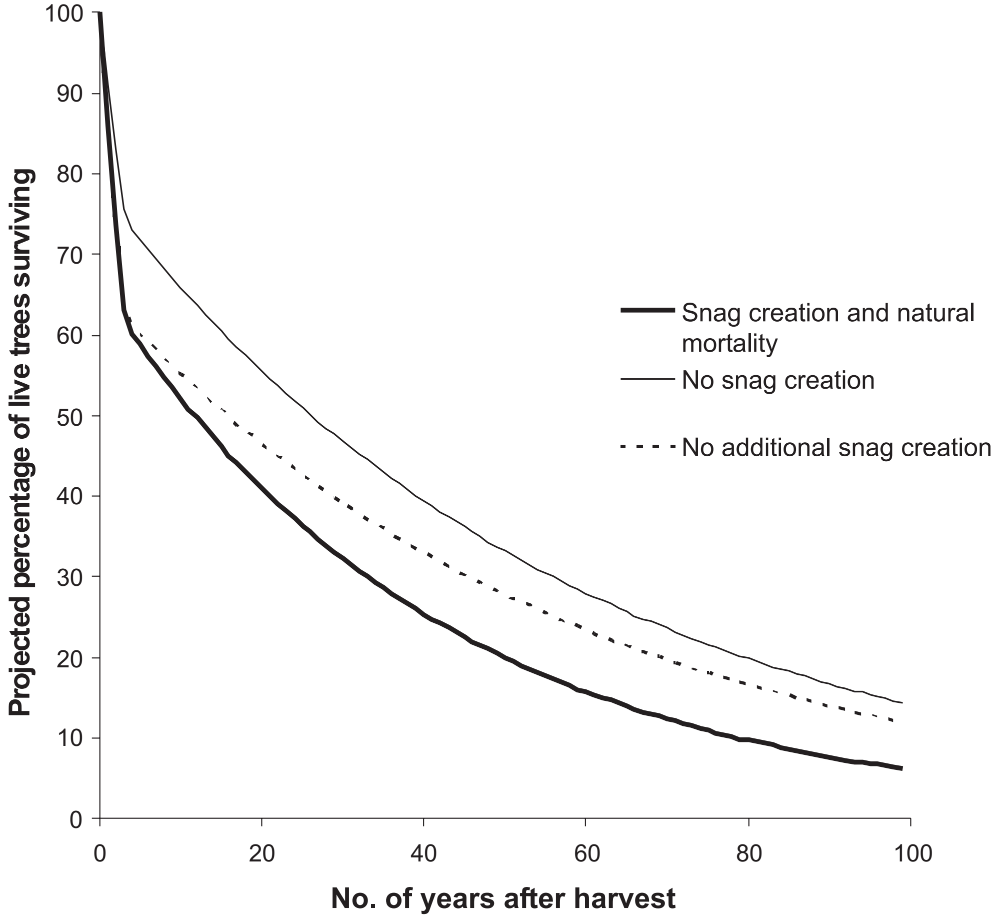
While no general pattern of topographic controls on tree mortality was discernible over the entire sample, some individual sites exhibited high or low levels of mortality that appeared to be related to local conditions, including exposure to wind and time of cutting of adjacent stands. The weak influence of topography likely reflects variability in wind direction and velocity, especially under the influence of the steep topography characteristic of the study area.

Wind damage

Substantial conversion of live trees to standing and downed dead occurred over the one- to two-decade period of this study. Rates of processes affecting live trees in partial cutting units appear to shift over time. Several lines of evidence point to decreased windthrow of retained live trees over time, which agrees with published observations from other study locations (Wiedman 1920; Savill 1983; Moore et al. 2003). This "windfirming" process can be a direct effect of wind pruning of the crowns of individual trees, making them less vulnerable to windthrow, and buttressing of root systems to increase windfirmness. Windfirming at the stand scale occurs when the least stable trees are blown down, leaving a residuum of trees that are more windfirm.

An alternative explanation for the apparent decline in windthrow is that major wind events may have occurred shortly after harvest, followed by a period without significant wind events. However, the record of wind speeds from

Fig. 4. Projected future populations of live trees retained at harvest, based on three possible scenarios: (1) snag creation and natural mortality, (2) no snag creation, and (3) no additional snag creation.



the Vanmet station does not support this explanation. Any interpretation of the wind records should be tempered by the weak relationship between observed windthrow and the wind-speed records. For example, two events of conspicuous windthrow in the area were not reported as windy days (>15 m/s) in the meteorological records. The disparity may reflect geographic variability in wind velocity in the complex terrain of the study area, although the Vanmet station is well suited to record general wind direction and speed in the area. Additionally, other unobserved processes, such as canopy loading by wet snow, common in this area, can topple trees of all age classes, in combination or irrespective of wind conditions (Acker et al. 2003). However, we believe that windthrow was the main cause of toppling in the study area, based on alignment of fallen trees, patterns of windthrow along stand edges, and other observations.

Natural and intentional snag creation

The rate of tree mortality in uncut natural forest offers a reference measure of the background rate of tree death. Franklin et al. (1987) examined mortality in natural, mature, and old-growth Douglas-fir – western hemlock forests in the H.J. Andrews Experimental Forest within the study area and elsewhere in the Pacific Northwest, using observations in long-term plots. They estimated annual mortality to be 0.7%, which is significantly lower than the natural-process average annual mortality rate of 1.7% for the 1993-to-2001 period in our study. This observation raises a question concerning the long-term mortality rate of trees in the partial-cut units — will it eventually approximate that in unmanaged mature and old forests in the area? If average annual mortality rates at the study sites continue to decline, survival of retained trees may be greater than our model predictions.

Our analysis is somewhat complicated by management activities to create snags, which increased over the study period, affecting 55% of the cutting units by 2001. It is common practice to wait a few years after cutting to let natural tree mortality processes operate before determining whether additional snag creation is desirable. Also, criteria for selecting trees for snag creation may affect the vulnerability of the remaining live trees. For example, in some cases snag-creation techniques may target less windfirm trees for topping, but trees with multiple tops, stem decay, and other defects may be excluded from topping for safety reasons. Therefore, snag creation can significantly alter effects of subsequent major windstorms in ways that are difficult to predict.

Projection of future live-tree populations

Our projections of the fate of live trees suggest that much of the initial live-tree component at these sites may become standing or downed dead over the first century after cutting, with possibly fewer than 50% of retained live trees surviving for 50 years (Fig. 4). Our projections assume a low initial survival rate and a higher survival rate thereafter. However, if trees continue to become more windfirm, our projections underestimate survival. In addition, the establishment of a new stand beneath the retained trees could eventually provide shelter. On the other hand, increases in storm severity due to climate change (Karl and Knight 1998; Salinger 2005) or other unknown factors could have the opposite effect. This high degree of uncertainty emphasizes the need for long-term monitoring to determine mortality trends over time.

Management activities further complicate long-term projections. Intentional snag creation, affecting 55% of inventoried sites, has been and may continue to be an important determinant of forest structure in managed units in the study area. Under current practice, snag creation occurs in the first 5 years after initial cutting. If snag creation continues into the future, it could alter natural patterns of mortality.

Management implications

Our projections of long-term survival indicate substantial conversion of retained live trees to standing and downed dead status over the century time scale, but uncertainty is high. Reducing this uncertainty will require further monitoring, especially of mortality rates of retained trees as new stands grow. It is also important for managers to consider the entire residual tree resource on such sites, including the standing live and dead and downed dead trees, and how these components will be distributed over time and space at the cutting-unit and landscape scales.

The diversity of inventory approaches used to date (e.g., Coates 1997; Halpern et al. 1999; Huggard et al. 1999; Moore et al. 2003) reveals strengths and weaknesses of different monitoring systems. Some studies used one-time sampling and others used repeat surveys at a variety of sampling intervals. We suggest that an integrated analysis of this dynamic system would benefit future planning and management at the stand and landscape scales. Such an analysis would be based on an inventory system with (*i*) data linking change in the status of retained live and dead stems with management history, including documentation of criteria for selecting trees to retain, remove, or convert to snags and locations and methods of snag creation; (*ii*) permanently marked trees to improve tracking over time; (*iii*) careful measurement and documentation of wind and other stressors at multiple locations over the study period and study area; and (*iv*) the use of cohorts of trees retained at different dates to evaluate effects of different sequences of weather conditions. Tree-toppling wind does not occur every year in most regions, so results of an inventory study may be sensitive to the specific timing of cutting and windstorms. This issue can be addressed when the surveyed sites span a range of years of cutting so that different storm sequences can be examined.

We recommend scheduling inventories to detect and quantify any early pulse of windthrow. In our study, some sites cut within a year or two before the 1993 inventory may have experienced initial windthrow in the second inventory period. If the initial inventory comes 5–10 years after cutting, the estimated annual mortality may include both the initial period of high susceptibility to windthrow and other processes causing mortality and the subsequent period of low mortality, thus obscuring temporal variation in mortality. Therefore, it is useful to monitor annually in the first 3–5 years, which the Demonstration of Ecosystem Management Options study is doing (Halpern and Halaj 2005), and less frequently thereafter.

Our results provide a general indication of the fates of dispersed live trees retained in cutting units for approximately the first one to two decades after cutting in the central western Cascade Range in Oregon. The practice of retaining live trees in cutting units in this region and of attending to the many ecological functions of live and dead trees in multicohort stands are rather new, and this practice and the study of its effects are continuing to evolve.

Acknowledgements

This work was supported in part through National Science Foundation (NSF) grants to the H.J. Andrews Experimental Forest Long-Term Ecological Research (LTER) Program and by USDA Forest Service funding to the Central Cascades Adaptive Management Area. Work was conducted under the NSF-sponsored Research Experiences for Undergraduates program associated with the H.J. Andrews Experimental Forest LTER program. We thank J. Cissel, A. McKee, and J. Mayo for helpful guidance during the study, and the Blue River Ranger District (now part of the McKenzie River Ranger District) of the Willamette National Forest for providing data on forest-cutting and snag-creation histories and other information. We thank J. Franklin, C. Friesen, T. Hailemariam, C. Halpern, P. Harris, K. Mellen, J. Mayo, R. Seitz, and two anonymous reviewers for helpful comments on earlier drafts of the paper.

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