Does Variable-Density Thinning Increase Wind Damage in Conifer Stands on the Olympic Peninsula?

Scott D. Roberts, Constance A. Harrington, and Karl R. Buermeyer

ABSTRACT

Silvicultural treatments designed to enhance stand structural diversity may result in increased wind damage. The ability to avoid conditions that might lead to excessive wind damage would benefit forest managers. We analyzed wind damage following implementation of a variable-density thinning at four sites on the Olympic National Forest in northwest Washington. The prescription created small canopy gaps and retained unthinned patches within a uniformly thinned matrix, thus creating substantial amounts of internal edge. Our objective was to determine whether variable-density thinning resulted in elevated wind damage and whether the damage was spatially related to elements of the treatment, i.e., canopy gaps and uncut patches. Wind damage on the thinned plots averaged slightly more than 8.0 trees/ha. Although precise determinations of residual stem densities were not available, we estimate that total wind damage amounted to 1.3% of total stems remaining following treatment. Approximately 80% of the wind damage was blowdown, the remaining damage being stem breakage, leaning, or bowing. Nearly 54% of the damaged stems were less than 20 cm dbh. The maximum amount of damage observed was 51 trees/ha, but only 3 of 13 thinned plots had wind damage exceeding 7 trees/ha. The overall level of wind damage across all thinned plots after two growing seasons was not statistically greater than on unthinned control plots. Internal edges created by gaps, skid trails, and unthinned patches did not inherently increase wind damage risk; however, where gaps were located in topographically vulnerable positions, greater wind damage did occur. Overall wind damage was not excessive on any of the plots, and after 2 years, all residual stands remained intact and in a manageable condition. Our preliminary results suggest that variable-density thinning that includes creation of small canopy gaps does not necessarily predispose stands to greater risk of wind damage than uniform thinning. However, care must be taken in locating gaps and skid trails away from topographically vulnerable positions.

Keywords: blowdown, Douglas-fir, western hemlock, height-diameter ratio, forest edge

Evolving public attitudes and expectations are leading to changes in how forests are being managed. Particularly on public lands, there is an increasing use of silvicultural prescriptions designed to encourage accelerated development of late-successional forest characteristics (Kohm and Franklin 1997, Curtis et al. 1998, Franklin et al. 2002). The desired characteristics commonly include greater structural diversity both vertically and horizontally within the stand. This is often accomplished with variable-density thinning, which varies stem densities across the stand and encourages rapid production of larger trees (cf. Carey et al. 1999). One variant of variable-density thinning also includes the creation of canopy gaps and the retention of untreated patches (Carey and Harrington 2001). In attempting to achieve these objectives, stands are often treated at an age or stage of development when, until recently, they would have been considered for regeneration harvest. A concern over the creation of these structurally diverse stands is whether the treatments will result in increased levels of wind damage. Losses due to wind are common in many forest ecosystems, typically occurring at low endemic levels but occasionally resulting in substantial mortality. Increased knowledge about stand conditions susceptible to wind damage, and the ability to minimize wind damage following silvicultural treatments, would greatly benefit forest managers.

Susceptibility to wind damage is a function of numerous factors related to climate, topography, soils, and stand conditions (Mitchell 1995, Ruel 1995, Nowacki and Kramer 1998, Sinton et al. 2000). Climate influences the frequency and intensity of high wind events. Topography modifies wind characteristics at the local landscape level (Kramer et al. 2001). Soils affect the rooting characteristics of trees and provide the critical anchorage of trees against blowdown. Stand characteristics influence the development of individual trees, and thus, their resistance to wind damage (Lohmander and Helles 1987). Although there is typically little or nothing that can be done silviculturally to affect climate, topography, or soils, managers do have substantial control over tree and stand characteristics and can therefore influence a stand's susceptibility to wind damage.

The effects of silvicultural activities on stand structure are known to influence the risk of wind damage. The creation of edges, such as those associated with clearcut boundaries or streamside buffers, has been shown to increase wind damage, as trees once protected by neighboring trees are now exposed to greater wind forces (Gratkowski 1956, Mitchell et al. 2001, Ruel et al. 2001). Thinning also

Received April 25, 2005; accepted October 22, 2006.

Scott D. Roberts (sroberts@cfr.msstate.edu), Department of Forestry, Mississippi State University, Mississippi State, MS 39762-9681. Constance A. Harrington and Karl R. Buermeyer, USDA Forest Service, Pacific Northwest Research Station, Olympia Forestry Sciences Laboratory, Olympia, WA 98512-9193. *We thank the Olympic National Forest for implementing the treatments. We appreciate our current and former coworkers at the Olympia Forestry Sciences Laboratory for their help on this project and Miriam Rorig for assisting with the wind data. We also thank Drs. Temesgen Hailemariam, Andrew Londo, and George McFadden and two anonymous reviewers for helpful comments on earlier drafts of the manuscript. This study was funded, in part, by the Pacific Northwest Research Station's Wood Compatibility Program.*

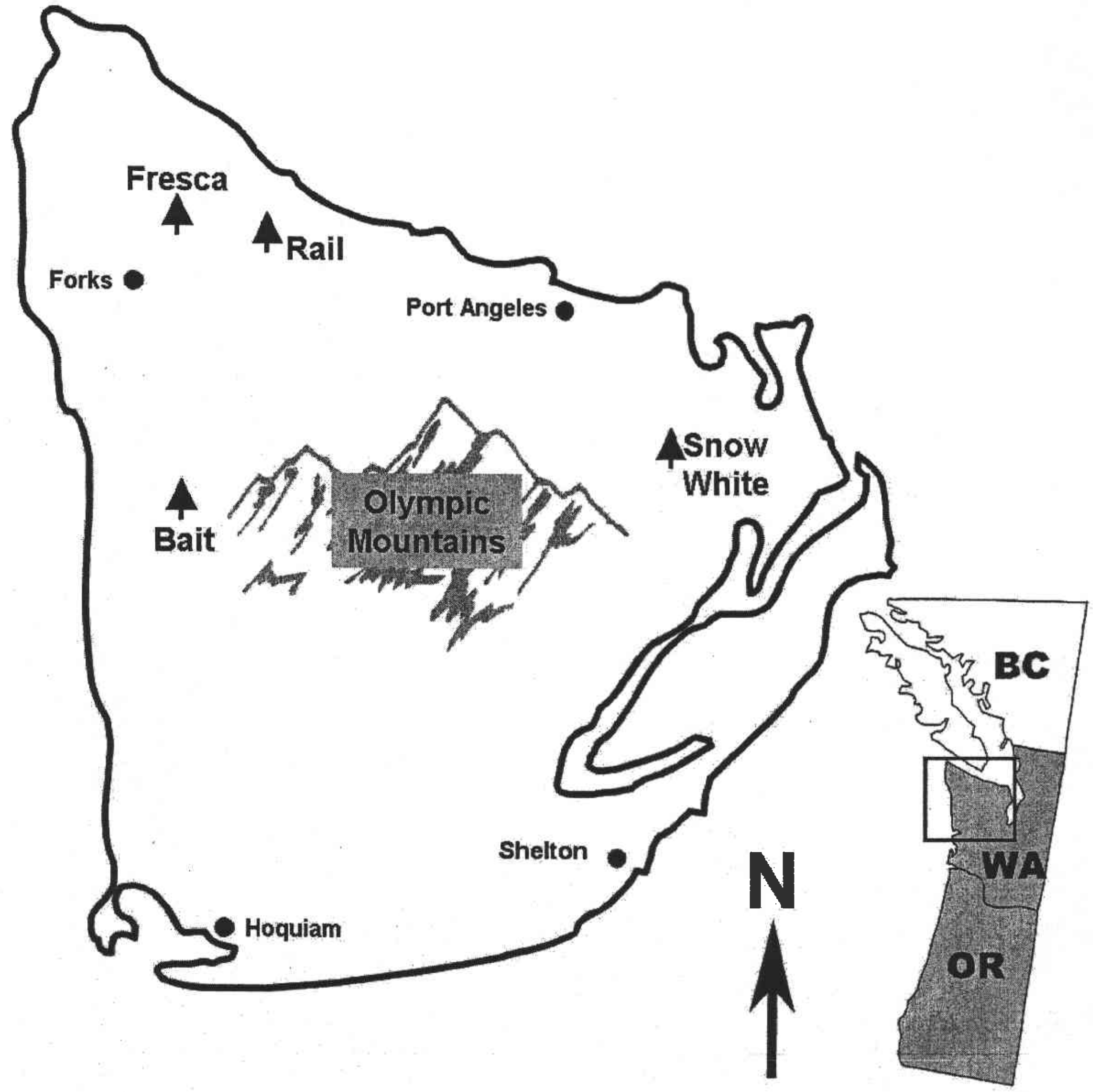

Figure 1. Area map of the Olympic Peninsula in northwestern Washington showing locations of the four study sites on the Olympic National Forest where wind damage was assessed following variable-density thinning. Circles indicate locations of major towns on the Olympic Peninsula.

increases the risk of wind damage, at least until the trees become adapted to the new wind environment. Trees eventually adjust the allocation of stem and crown growth, resulting in a more stable configuration. Over time, the risk of wind damage is greatly reduced following thinning (Cremer et al. 1982).

The Olympic Habitat Development Study was designed to examine responses of plant and animal communities following variable-density thinning (VDT) in 30–70-year-old stands on the Olympic Peninsula in northwest Washington (Carey and Harrington 2001, Reutebuch et al. 2002). The operational-scale treatments combined thinning from below with the creation of small canopy gaps and the retention of untreated patches. In this analysis, we examine wind damage 2–3 years following treatment on four of the study blocks. Our primary objective was to assess whether implementation of VDT increased wind damage relative to untreated stands and whether wind damage within VDT units was spatially related to canopy gaps or uncut patches. A secondary objective was to assess factors other than VDT that may have contributed to wind damage.

Methods

Study Site Description

Four blocks of the Olympic Habitat Development Study were included in this analysis. All are within the Olympic National Forest located on the Olympic Peninsula in northwestern Washington (Figure 1). Soils are generally deep, with good drainage. Average annual precipitation ranges from 1,450 mm at the lower elevations at Snow White, which is situated in the rain shadow of the Olympic Mountains, to nearly 3,200 mm at Bait (Table 1). Each block contains three or four thinned plots and one randomly assigned control plot. A total of 17 5.6-ha rectangular plots (13 thinned and 4 control) were surveyed for wind damage.

Rail (plots 101–104) and Fresca (plots 201–204) were both clearcut harvested and burned around 1930 and allowed to regenerate naturally. Both blocks are situated on terraces of the Solduc River with generally flat topography, although one of the plots at Fresca (plot 204) contains a small, flat-topped ridge. Rail received a

Table 1. Description of the blocks located on the Olympic National Forest that were examined for wind damage associated with implementation of a variable-density thinning.

Block	Elevation (m)	Annual precipitation (mm)	Soils	Primary tree species
Rail	275	2,390	Loam/sandy loam, very deep, well to somewhat excessively drained, glacial outwash (Bogachiel–Ishmael complex)	Douglas-fir, Western hemlock
Fresca	150	2,650	Silt loam, very deep, well drained, glacial outwash *or* sandy loam, gravelly/very gravelly, very deep, somewhat excessively drained, glacial outwash (Nanich–Solduc complex, Emmiott)	Western hemlock, Sitka spruce
Bait	190–335	3,175	Variable: loams to silt loams, with or without gravel/cobble, moderate deep to very deep, somewhat poorly to well drained, formed in residuum and colluvium (Sockeye, Sollecks, Snahopish, Thimblepeak–Haas complex)	Western hemlock, Douglas-fir
Snow White	430–580	1,450–1,950	Sandy loam, very gravelly, moderate deep, moderate well drained, from glacial till (Nicklund, Rockybrook)	Douglas-fir

light thinning in 1986. There are no records of any cultural treatments occurring at Fresca prior to the implementation of the VDT.

Bait (plots 401 and 403–405) was clearcut between 1951 and 1954 and was likely burned prior to planting Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco]. Substantial amounts of western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] established naturally. Slopes range from 0% to 35%, with all plots containing both sideslopes and hilltops. The site was precommercially thinned in the late 1960s and early 1970s. There are no records of any other cultural treatments occurring.

Snow White (plots 801–805) is the only block located on the east side of the Olympic Peninsula. The site was clearcut around 1928, burned, and planted with Douglas-fir in the early 1930s. The area was commercially thinned between 1971 and 1973. Slopes at Snow White are generally less than 25%.

Treatment Description

A VDT was applied to each of the treatment plots as part of an operational thinning. The control plots received no manipulation. The VDT prescription called for a series of small gaps and unthinned patches to be embedded within a thinned matrix. Creation of 0.04–0.05-ha gaps over 15% of the treatment area involved removal of all merchantable stems (>20 cm dbh), with the exception of species of low local abundance (e.g., hardwoods, *Thuja plicata*, and *Abies amabilis*). Gap width (~20 m) was chosen to be less than the mean height of upper canopy trees. Where existing gaps occurred within the treatment plots, they were counted as part of the 15% gap area. Unthinned patches covered 10% of the treatment area. These patches were 0.09–0.3 ha in size, with approximately one unthinned patch per every 1.5–2.0 ha. No harvest or entry of equipment was allowed in the unthinned areas. The prescription for the thinned matrix, covering the remaining 75% of the treatment area, called for a uniform thinning removing 25% of the basal area. Removals were primarily from the lower crown classes, although species of low local abundance were not removed. The VDT treatment was designed such that all three components of the treatment (gaps, unthinned areas, and matrix) were in close proximity. This fine-scale mixing makes it difficult to partition treatment response into individual stand components, as opposed to evaluating the entire thinned unit.

At Fresca, the VDT was implemented during the summer and fall of 1997. Rail was thinned during the winter of 1997/1998. Thinning treatments on Snow White plots 801 and 802 occurred in the winter of 1998/1999, and plots 804 and 805 were thinned in the fall of 1999. Bait plots 403 and 404 were thinned in the winter of 1998/1999. Thinning of plot 405 was completed in December 1999.

Data and Analysis

A pretreatment inventory involving 6–8 sample points per plot provided a description of each plot prior to treatment implementation (Table 2). The variable-radius sample points, containing an average of 8–10 trees per point, were established on a regular grid throughout the plots. Average breast-height age ranged from 33 to 63 years. Stem density ranged from 300 to more than 1,500 trees ha^{-1} (tph). Basal area stocking ranged from 37 to 75 $m^2\ ha^{-1}$. An estimate of the height:diameter (H:D) ratio of each plot was based on 6–10 dominant trees per plot. These estimates of plot H:D ratios are considered conservative, as they are based only on dominant trees, which generally have lower ratios than smaller trees within a stand. As part of the larger Olympic Habitat Development Study, a single 1.44-ha stem-mapped subplot was established in one of the thinned plots in each of the four blocks and measured before and after the thinning operations. These plots, which were established to examine the effect of the VDT on tree growth, each contained one unthinned patch and at least two gaps. Because only one stem-mapped plot per block was installed, and its location was not random, the plots do not provide a statistically precise characterization of posttreatment stand conditions. They do provide a general picture of the stand conditions in each block following thinning. However, caution must be exercised when interpreting the severity of wind damage reported throughout our analysis, because a complete postthinning inventory of undamaged trees was not taken.

In the summer/fall of 2000, all 17 plots were surveyed for wind damage. Three of the plots that had not been thinned prior to the fall/winter of 1999/2000 (plots 405, 804, and 805) were resurveyed in fall 2001, so that all plots had experienced at least two winters posttreatment. One additional thinned plot (plot 402 at Bait) was not included in this analysis, as it was thinned later than the other plots. A complete survey of the plots recorded wind damage on all trees greater than 2 m in height over an area 180 m × 280 m. The treated area extended beyond the survey area by a minimum of 40 m. The survey recorded all blowdown (defined as uprooted trees), trees leaning more than 30° from vertical, bowed trees, and trees with stem breakage below the live crown. A determination was

Table 2. Preharvest stand conditions for 17 plots located on the Olympic National Forest that were examined for wind damage associated with implementation of a variable-density thinning.

Block and plot	Stem density (tph)[b]	Dq (cm)[c]	Basal area ($m^2\ ha^{-1}$)	Site tree characteristics[a] Height (m)	Height:diameter ratio (m:m)	BH age (years)
Rail						
101	300	42	42	34	60	44
103	361	41	48	35	68	43
104	356	41	47	35	60	48
Control (102)	424	38	48	35	72	44
Fresca						
201	571	30	41	27	57	33
202	509	41	66	37	69	50
204	775	35	73	34	73	49
Control (203)	498	43	73	38	70	51
Bait						
403	840	27	49	29	81	34
404	1,574	26	70	31	80	35
405	849	31	65	33	80	38
Control (401)	1,076	30	75	28	65	33
Snow White						
801	593	30	42	43	68	63
802	1,077	24	47	43	64	63
804	841	29	55	40	65	63
805	429	36	44	40	67	63
Control (803)	605	28	37	39	70	59

[a] Site tree information is based on 6–10 dominant trees per plot; depending on stand conditions, site trees may be of one species or represent a mixture of the primary species occurring on the plot.
[b] Data include only trees greater than 10 cm dbh, as large numbers of very small trees on some plots result in misleading density estimates. tph, trees per hectare.
[c] Quadratic mean diameter.

made in the field as to whether the observed damage was likely due to wind rather than direct logging damage or some other cause. Trees with direct logging damage generally exhibited stem or crown damage from equipment passage or damaged crowns from harvested trees being felled into them. The root systems of all uprooted trees were examined for obvious signs of root disease (primarily *Phellinus weirii*). The location of each wind-damaged tree was mapped, and the direction of stem fall or lean or breakage was noted. This information was entered into a GIS database that also included the location of gaps, unthinned patches, and skid trails and the topography of the plot. Stem diameter at 1.3 m from the tree base was recorded for each wind-damaged tree.

The level of wind damage on each plot was calculated as both number of trees/ha and basal area/ha. A general linear models approach (SAS 9.1; SAS Institute, Inc., Cary, NC) was used to examine whether the variable-density thinning treatment or stand characteristics before, or immediately after, thinning significantly affected the amount of wind damage observed on the plots. Stand characteristics tested included pretreatment H:D ratio, pre- and posttreatment basal area, and pre- and posttreatment stem density (tph). We also tested for differences in the amount of damage among the four blocks. A critical value of $\alpha = 0.05$ was used to determine significance.

This study did not offer the opportunity to rigorously test the susceptibility of individual species to windthrow, as the experimental design did not control for species and we did not have detailed information on the number of undamaged trees per species on each plot. We were able to examine whether the number of wind-damaged trees per species was roughly similar to what would have been expected based on the number of trees per species present in the four 1.44-ha stem-mapped subplots (one in each block). Although these subplots do not represent a complete sample all of the thinned plots, they do include nearly 3,700 trees postthinning; thus, the estimated species compositions are based on a reasonably large sample size. The postthinning species composition on the stem-mapped plots was used to establish a hypothesized estimate of the number of trees by species (western hemlock, Douglas-fir, and other) and size class (<20 or ≥20 cm or combined) across the four study blocks to compare against the actual count of wind-damaged trees by species and size class. The expected proportion of wind-damaged trees per species, based on the hypothesized number of trees of each species estimated from the stem-mapped plots, and the actual proportion of wind-damaged trees per species were compared using a chi-square test to determine whether the observed damage for a species was greater than or less than would expected due to chance (Freese 1967).

Maps showing the distribution of wind-damaged trees were visually assessed for spatial patterning of the wind damage. A subjective determination was made as to whether the wind damage on each plot appeared to be associated with elements of the variable-density thinning (gaps, unthinned patches, and skid trails) or with topographic features. Overall wind damage was quite low with most of the damage occurring in portions of three thinned plots; thus, the data did not lend themselves to a rigorous spatial analysis. On the three plots with the greatest damage, however, we quantified the wind damage relative to the components of the thinning treatment by determining the number of trees ≥20 cm in diameter that were wind-damaged in 3 categories: within 10 m of a gap, within 10 m of an unthinned patch, and in the rest of the thinned matrix (excluding landings). We compared the number of damaged trees with the number that would be expected based on the relative area in each category using a chi-square test. A critical value of $\alpha = 0.05$ was used in all chi-square tests to determine significance.

Site-specific information on the timing and intensity of high wind events was not available for our study areas. In lieu of on-site observations, information on winds occurring on the Olympic Peninsula between 1997 and 2001 was obtained from the National Climatic Data Center archives (2006). This site reports the date and

Table 3. Breakdown of wind-damaged trees by size, species, and damage class on 17 plots located on the Olympic National Forest that were examined for wind damage associated with implementation of a variable-density thinning.

Size and Species	Total damage: Stems	Total damage: Trees/ha	Blowdown: Relative damage ratio[a]	Blowdown: Stems (no.)	Blowdown: Average dbh (cm)	Stem breakage: Stems (no.)	Stem breakage: Average dbh (cm)	Bowed: Stems (no.)	Bowed: Average dbh (cm)	Lean: Stems (no.)	Lean: Average dbh (cm)
Trees >20 cm dbh											
Western hemlock	306	3.2	2.63	270	31	28	32	2	31	6	29
Douglas-fir	40	0.4	0.20	34	41	5	43	–	–	1	53
Other[b]	17	<0.1	0.30	13	26	3	28	–	–	1	20
Total	363			317		36		2		8	
Trees <20 cm dbh											
Western hemlock	382	4.0	1.03	285	12	44	15	32	10	21	10
Douglas-fir	6	0.1	0.26	6	13	–	–	–	–	–	–
Other[b]	33	0.3	1.53	20	11	4	12	1	12	8	11
Total	421			311		48		33		29	
All trees											
Western hemlock	688	7.2	1.39	555	22	72	21	34	12	27	15
Douglas-fir	46	0.5	0.24	40	37	5	43	–	–	1	53
Other[b]	50	0.5	0.58	33	17	7	19	1	12	9	12
Total	784			628		84		35		37	

[a] Relative damage ratio is calculated as the percentage of the blown-down stems occurring in a species/size class divided by the percentage of all stems occurring in that class over the entire study area. Estimates of the total number of stems are based on one 1.44-ha stem-mapped subplot per block. A relative damage ratio of 1.0 indicates that blowdown damage in that class was equal to the relative representation of that class. – indicates no wind damage.
[b] Other species include *Abies amabilis, Alnus rubra, Frangula purshiana, Thuja plicata*, and *Picea sitchensis*.

magnitude of winds associated with high wind events, defined as winds exceeding 74 km hour^{-1}. Clearly, each wind event did not affect all of the sites equally; however, the information provides a general picture of the timing and magnitude of wind events in this part of northwest Washington. Additional information on the timing of wind damage was obtained from on-site visits following thinning operations.

Data on prevailing wind directions during the months when high wind events occurred were obtained for the National Oceanic and Atmospheric Administration weather station at Hoquiam, WA (National Climatic Data Center 2002). The Hoquiam station provided the best indication of wind directions and wind speeds associated with storms coming from the Pacific Ocean, the direction from which most winter weather systems occur. We calculated a mean wind direction ($\bar{a}$, corrected for the bias associated with grouped data). We also calculated a mean angle of windthrow (blowdown/breakage/lean) for each block and a 95% confidence interval around the mean based on methods for circular distributions (Zar 1999). The null hypothesis, tested individually for each block, was that the mean angle of windthrow was equal to the mean direction of wind gusts (i.e., the direction of wind gusts measured at Hoquiam plus 180°). The null hypothesis would not be rejected if the mean wind direction was within the 95% confidence interval for the mean angle of windthrow.

Results and Discussion

Individual Tree Factors: Size and Species

A total of 784 trees were recorded as having wind damage (Table 3). This amounted to a studywide average of approximately 8 trees per ha. Based on our limited sampling of undamaged trees, the amount of wind damage represented approximately 1.3% of all trees. Eighty percent of wind-damaged trees were blowdown (i.e., had been uprooted), 11% experienced stem breakage below the live crown, and 9% were either leaning or bowed. Just over 46% of the damaged trees were 20 cm dbh or larger. Very few (<3%) of these larger trees were bowed or leaning. Of the nearly 54% of the damaged trees less than 20 cm dbh, 15% were either bowed or leaning. Thus, although the type of damage varied somewhat by stem diameter, tree size did not appear to significantly influence the overall occurrence of wind damage. This is counter to the contention of some other studies (Peterson and Pickett 1991, Canham et al. 2001, Peterson 2004) that suggest that larger trees within a stand tend to be more vulnerable to direct wind damage. One explanation for this apparent contradiction could be that much of the damage to smaller trees was secondary damage caused by larger trees falling and knocking them over.

Root rot is generally considered to be a contributing factor to wind damage in forests. Less than 2% of uprooted trees in this study showed obvious signs of root rot, suggesting that root rot incidence was not high in these stands and thus was not a major contributing factor to the wind damage that we observed. Given that root rot fungi can develop or expand on the root systems of harvested trees, it is possible that root rot levels in these stands could increase through time.

The proportion of wind-damaged trees varied by species (Table 3) in all size categories (chi-square tests were significant). Differences among species were especially large in the 20 cm and larger size class. Based on our posttreatment inventory of one large stem-mapped plot per block, we estimate that western hemlock made up only approximately 32% of residual stems 20 cm dbh or larger across all plots, but it accounted for 85% of wind-damaged trees. Conversely, following treatment, we estimated that 54% of stems 20 cm dbh or greater were Douglas-fir; however, it accounted for only 11% of the wind-damaged stems. Damage to western hemlock <20 cm dbh was not much different from what was expected, but Douglas-fir blowdown damage was only 26% of the expected level for that size class. Thus, although our study design did not allow for a rigorous test, our results appear to support the common belief that Douglas-fir is more windfirm than western hemlock (Boyce 1929, Burns and Honkala 1990). Although Sitka spruce [*Picea sitchensis* (Bong.) Carr.] is generally considered to be susceptible to blowdown (Burns and Honkala 1990), only one Sitka spruce tree was blown down at Fresca, even though the species made up a significant component in the block (39%).

Table 4. Basal area and number of stems per hectare suffering wind damage on 17 plots located on the Olympic National Forest that were examined for wind damage associated with implementation of a variable-density thinning.

Block and Plot	dbh <20 cm		dbh ≥20 cm		Total	
	Stems (tph)[a]	Basal area (m^2 ha^{-1})	Stems (tph)	Basal area (m^2 ha^{-1})	Stems (tph)	Basal area (m^2 ha^{-1})
Rail						
101	2.3	0.03	0.7	0.08	3.0	0.11
103	2.0	0.04	3.4	0.31	5.4	0.34
104	2.5	0.03	0.7	0.07	3.2	0.10
Average of thinned plots	2.3	0.03	1.6	0.15	3.9	0.18
Control (102)	1.1	0.02	2.1	0.20	3.2	0.22
Fresca						
201	2.9	0.02	0.4	0.02	3.2	0.04
202	0.5	0.01	0.7	0.05	1.3	0.06
204	3.9	0.06	15.7	1.60	19.6	1.66
Average of thinned plots	2.4	0.03	5.6	0.56	8.0	0.59
Control (203)	2.5	0.04	2.7	0.28	5.2	0.33
Bait						
403	26.3	0.38	24.8	1.76	51.1	2.14
404	14.3	0.17	8.2	0.51	22.5	0.68
405	4.5	0.07	1.4	0.15	5.9	0.21
Average of thinned plots	11.6	0.16	8.9	0.63	20.5	0.79
Control (401)	1.3	0.01	0.0	0.0	1.3	0.01
Snow White						
801	2.3	0.03	2.3	0.53	4.6	0.56
802	0.4	0.01	0.0	0.0	0.4	0.01
804	6.4	0.04	0.5	0.11	7.0	0.15
805	2.1	0.03	1.1	0.11	3.2	0.15
Average of thinned plots	2.8	0.03	1.0	0.19	3.8	0.21
Control (803)	0.0	0.0	0.0	0.0	0.0	0.0

[a] tph, trees per hectare.

Treatment and Site Effects on Wind Damage

There was no statistically significant VDT treatment effect on the average amount of wind damage, measured as a percentage of posttreatment basal area ($P = 0.27$) or percentage of trees ($P = 0.25$), across all treatment blocks. Based on our posttreatment sample, we estimate that on average, 1.9% of trees (1.2% of basal area) on the thinned plots were wind-damaged, compared with 0.5% of trees (0.2% of basal area) on control plots (Table 4). The amount of wind damage occurring on the thinned plots varied considerably, ranging from an average of 3.8 tph [0.2 m^2 ha^{-1} basal area (BA)] at Snow White to 20.5 tph (0.8 m^2 ha^{-1} BA) at Bait (Table 4). Wind damage on the control plots ranged from no damage at Snow White to 5.2 tph (0.3 m^2 ha^{-1} BA) at Fresca. Despite the variation, however, there was no significant block effect for either percentage basal area damaged ($P = 0.53$) or percentage of trees damaged ($P = 0.36$).

Neither basal area nor number of stems/ha prior to or immediately following thinning significantly affected the amount of wind damage on the treatment plots. The H:D ratio of the stands prior to thinning was the only factor evaluated that significantly affected the amount of basal area ($P = 0.01$) or the number of trees ($P = 0.006$) suffering wind damage. The importance of H:D ratios on tree stability and incidence of wind damage has often been noted in other studies (Cremer et al. 1982, Lohmander and Helles 1987, Wonn and O'Hara 2001).

The lack of statistically significant treatment or block effects was due largely to the high variability in wind damage observed on the thinned plots. Only 4 of the 13 thinned plots, one at Fresca and all three at Bait, had substantially greater wind damage than the control plots. The remaining plots received only slightly greater or, in the case of four plots, slightly less damage than recorded on the control plots (Table 4).

The higher wind damage at Bait, particularly on plots 403 and 404, was likely due to a variety of factors. Bait had the greatest topographic relief among the blocks, thus creating more locations vulnerable to wind damage. Topographic features potentially funneling winds or causing greater eddying were associated with the heaviest damage. Bait is also located in the southwest corner of the Olympic Peninsula in the first major set of hills encountering storm-damaging winds off the Pacific Ocean and receives higher precipitation than the other blocks, which may facilitate the uprooting of trees. Wet, poorly drained soils, commonly occurring on small benches or in shallow depressions, can significantly increase the risk of wind damage (Gratkowski 1956, Cremer et al. 1982) and may have been a factor in the greater wind damage observed at Bait. Finally, for operational reasons, the unthinned patches at Bait were located on the edges of the treatment plots rather than dispersed throughout the unit as they were at the other sites and therefore could not serve as stabilizing features, as they may have at the other locations.

Although the above-mentioned site factors probably influenced the amount of observed wind damage at Bait, we suspect that the most important reason for greater damage at this site relates to the condition of the stands prior to treatment. Stem densities were generally higher at Bait than at the other sites (Table 2). Plots 403 and 404, which sustained the greatest wind damage, had the highest H:D ratios among all plots in the study. Plot 405 also had a high H:D ratio but did not suffer as much damage, possibly due to a higher component of Douglas-fir. Plot 405 was also treated later than plots 403 and 404 and did not experience the high wind events of late 1998 and early 1999 (Table 5). Since extremely high wind events do not occur every year, some thinned areas may not experience events during the time period when they are most vulnerable.

Fresca plot 204 suffered the second highest wind damage in terms of basal area and the third highest in terms of numbers of trees (Table 4). Although the terrain on the plot is generally flat, a small

Table 5. Storm events with winds exceeding 74 km $hour^{-1}$ (40 knots) recorded at weather stations near the study plots in northwestern Washington from January 1997 through December 2001. Blocks or plots are considered affected if the storm event occurred between the date that the thinning treatment was initiated and the time of the wind damage assessment in summer/fall 2000.

Date	Wind speed (km $hour^{-1}$)	Blocks (plots) affected after treatment
Jan. 1, 1997[a]	128	
Mar. 30, 1997	131	
Oct. 9, 1997	93	Fresca
Dec. 15, 1997	74	Fresca
Jan. 16, 1998	87	Fresca
Nov. 12, 1998	107	Fresca, Rail
Nov. 23, 1998	122	Fresca, Rail
Jan. 15, 1999	96	Fresca, Rail
Jan. 28, 1999	120	Fresca, Rail
Feb. 2, 1999	109	Fresca, Rail
Mar. 2, 1999	113	Fresca, Rail, Bait (403, 404), Snow White (801, 802)
Oct. 23, 1999	89	Fresca, Rail, Bait (403, 404), Snow White
Nov. 3, 1999	80	Fresca, Rail, Bait (403, 404), Snow White
Jan. 10, 2000	119	Fresca, Rail, Bait, Snow White
Jan. 16, 2000	122	Fresca, Rail, Bait, Snow White
Feb. 4, 2000	85	Fresca, Rail, Bait, Snow White
Dec. 14, 2000	143	Fresca, Rail, Bait, Snow White
Dec. 16, 2000	117	Fresca, Rail, Bait, Snow White
Nov. 19, 2001[a]	96	
Nov. 28, 2001	96	
Dec. 13, 2001	111	
Dec. 15, 2001	96	

[a] Storms prior to fall 1997 occurred prior to treatments, and storms after fall 2001 occurred after damage surveys had been completed. They are included here to illustrate the frequency of winter storm occurrence for the years shown.

ridge is located in the northern third of the plot, which is where the wind damage was largely concentrated (Figure 2). The Fresca site sits in an area where funneling of winds up the Solduc River Valley can occur; this funneling effect, combined with the small ridge on plot 204, probably resulted in higher local wind velocities and thus greater wind damage. A high H:D ratio may have also contributed to the relatively high wind damage observed on plot 204. Although not as high as the thinned plots at Bait, the H:D ratio on plot 204 was higher than that of the other plots at Fresca or any of the plots at Rail or Snow White.

Previous thinning on two of the blocks—Rail and Snow White—appears to have contributed to greater wind resistance. Thinning promotes diameter growth more than height growth, so thinned stands develop lower H:D ratios over time. Thinning also reduces variability in tree sizes. More homogeneous stands tend to display greater wind resistance (Cucchi and Bert 2003). The number of trees damaged at Rail and Snow White was less than half that observed at Fresca, and only approximately 20% of the average damage occurring at Bait. The apparent influence of previous thinning in reducing subsequent wind damage observed in this study is consistent with observations from other studies showing that reducing stand density leads to greater long-term wind-firmness (Cremer et al. 1982, Wonn and O'Hara 2001).

Spatial Distribution of Wind Damage

Visual analysis of the mapped stem damage suggests that the small-scale patterns associated with this type of variable-density thinning (gaps and unthinned patches) may influence wind damage under some conditions. The wind damage observed in this study was generally dispersed, but on some plots, the majority of wind damage did occur in proximity to gap edges or skid trails. Most of this damage, however, did not appear to have been caused solely by the presence of these features. Damage adjacent to gaps located on or near ridges was often greater than damage within the thinned matrix. However, wind damage adjacent to vulnerably positioned gaps was also greater than damage adjacent to gaps in more protected locations (e.g., lower slope positions). In fact, wind damage adjacent to gaps in more protected positions was typically not substantially greater than the damage observed in the thinned matrix.

Although very little wind damage occurred at either Rail or Snow White, it appeared that approximately half of the damaged trees on the thinned plots were in proximity to the edge of a gap or a skid trail. Fresca was a little more variable, with the damage on one of the thinned plots not associated with gaps or skid trails, whereas most of the wind damage on the other two thinned plots occurred close to gap edges. Most of the wind damage on plot 204, the only plot at Fresca experiencing more than minor damage, was concentrated near gap boundaries, with the exception of a small cluster of damage on the edge of an unthinned patch located at the top of the small ridge (Figure 2). The chi-square test for plot 204 was significant, with more damage occurring within 10 m of a gap than expected based on the area involved.

All three thinned plots at Bait experienced more wind damage than the control plot. The heaviest damage, located on Bait plot 403, occurred adjacent to a gap located on a hilltop in the southeast corner of plot and along a low ridge that runs north from the hilltop (Figure 3). Over the entire plot, however, the chi-square test was not significant, indicating that the number of wind-damaged trees ≥20 cm in diameter and within 10 m of a gap was not significantly different from would be expected. Wind damage on plot 404 was largely associated with gaps located on top of a ridge or just below a skid trail where the terrain becomes much steeper and exposed to winds funneling down a small valley (Figure 3). The remaining damage on the plot was scattered, and it did not appear to be strongly associated with gaps or skid trails. However, the chi-square test was significant for plot 404, indicating that more trees within 10 m of a gap experienced wind-damaged than would be expected based on area. This was likely confounded, however, by the presence of the ridge.

Timing and Direction of Winds and Wind Damage

In the western portions of the Pacific Northwest, most high wind events occur during the fall and winter months (Meteorology Committee Pacific Northwest River Basins Commission 1968). This general pattern of high wind events during the fall and winter was consistent with what was observed at weather stations close to the study sites from 1997 though 2001. During that time period, 22 separate storm events with wind speeds exceeding 74 km $hour^{-1}$ (40 knots) were recorded (Table 5). All of these events occurred between October 1 and March 31. Both the average number of wind events greater than 74 km $hour^{-1}$ and the average reported magnitude of the wind events were slightly higher during the 1997–2001 period than they were in the 2 years before and 3 years after this period. No

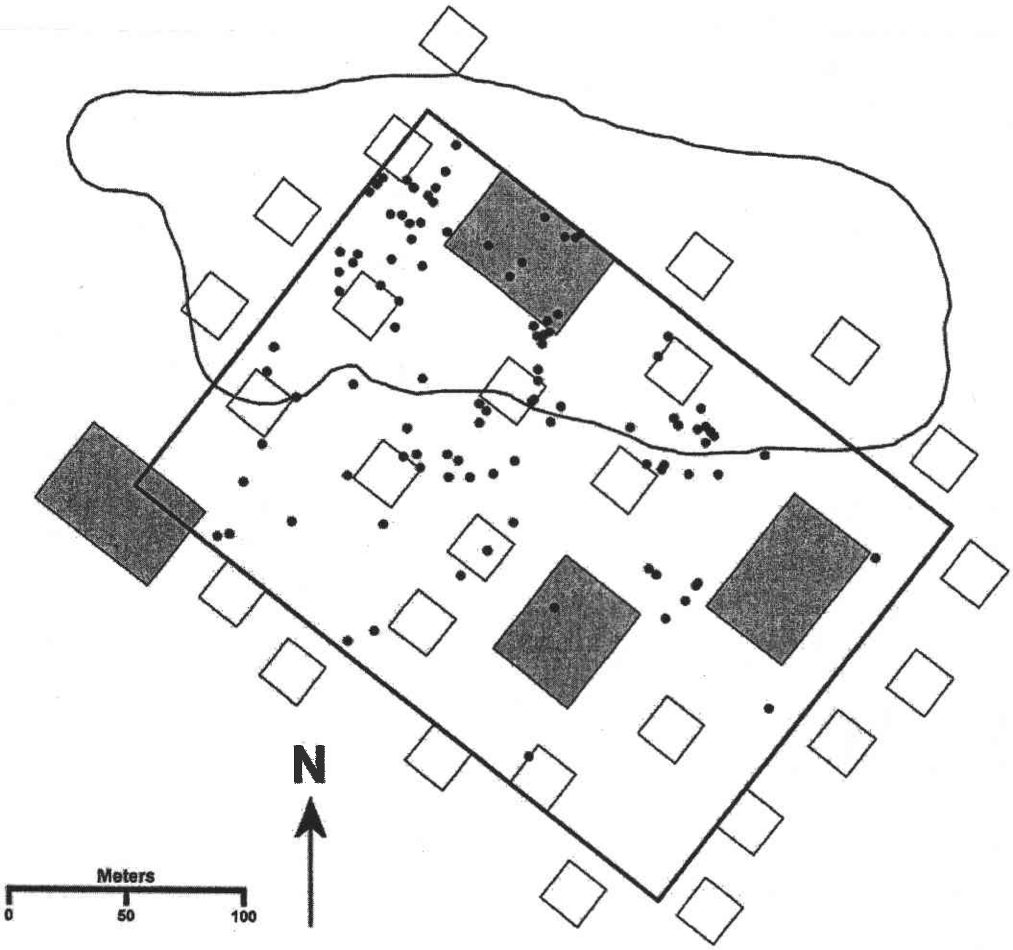

Figure 2. Location of wind-damaged trees in relation to gaps (open squares), unthinned patches (shaded rectangles), and topography at Fresca plot 204. The irregular oval overlapping the northern corner of the plot indicates the position of a small ridge.

unusually powerful wind events occurred during the period of observation, with the strongest event being recorded at 143 km hour^{-1} in December of 2000.

Winter storms in northwestern Washington are generally out of the southwest. As indicated in Figure 4A, over 90% of the high wind events at Hoquiam, Washington, in the southwest corner of the Olympic Peninsula, blow toward the northeast quadrant (mean angle of wind direction, 37°). In the absence of any other influences, we would expect windthrow to be predominantly toward the northeast. However, the measured azimuth of stem fall/lean/breakage at each of the sites was much more variable. The percentage of tree fall or stem breakage occurring to the northeast ranged from approximately 35% to just over 60% in the four study areas (Figure 4B), suggesting, as others have reported, that factors other than prevailing wind direction influence the direction of treefall (Hennon and McClellan 2003). One of these factors is likely the swirling of winds associated with ridges and hilltops in terrain with topographic relief (Kramer et al. 2001). The mean angle of windfall differed from 37° at Bait and Rail (i.e., the confidence interval for the mean angle of wind-damaged trees did not include 37° for these two sites). Bait is located just to the west of the first major ridge that winds would encounter coming from the ocean. This ridge apparently redirects winds toward the northwest. Rail is located in a portion of the Solduc River valley where the deep but broad valley is oriented in an east/west direction, and this apparently causes the major winds to blow in a more easterly direction during winter storm events.

Recommendations and Conclusions

The variable-density thinning imposed in this study removed a small percentage of pretreatment basal area, and the gaps created were relatively small (gap diameter was less than dominant tree height). This likely contributed to the low amount of overall wind damage observed. Few of the plots experienced substantial levels of wind damage, and none of the plots incurred what we considered to be severe damage. Even on the most heavily affected plots, the damage tended to be concentrated in relatively small pockets (Figure 5). If silvicultural objectives include restoration of late-successional stand characteristics, as is commonly the intent of variable-density thinning prescriptions, then some level of wind damage may actually help achieve these objectives by enhancing spatial diversity, increasing coarse woody debris, and creating snags through stem breakage.

This study represents a short-term view of wind damage following one approach to variable density thinning. The study was limited to the Olympic Peninsula; however, the sites were located across a broad range of topographic and climatic conditions. Although we recognize these limitations, the results of our study, along with field observations and results from other studies, allow some general recommendations for management that may be helpful in minimizing the potential for wind

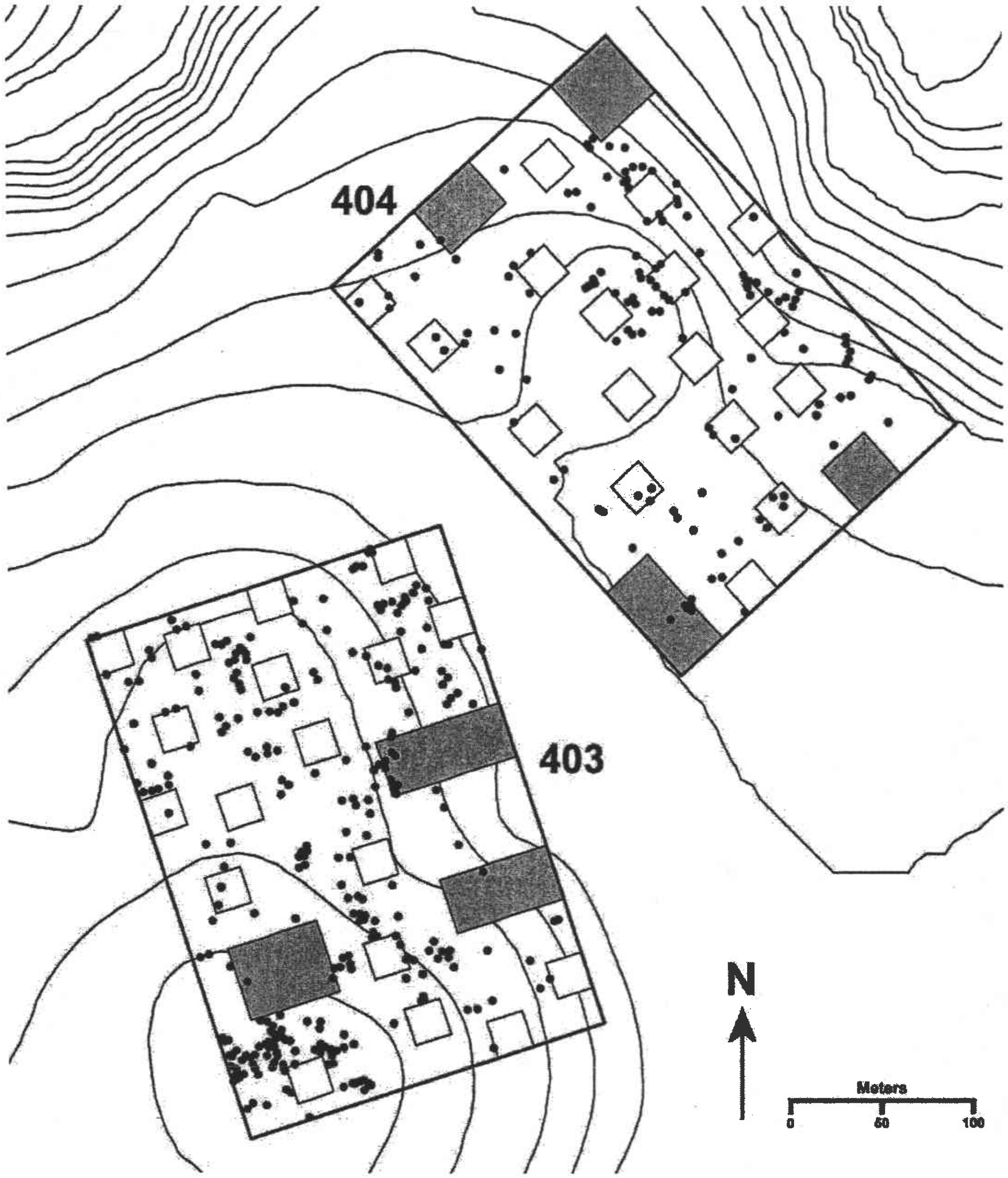

Figure 3. Location of wind-damaged trees in relation to gaps (open squares), unthinned patches (shaded rectangles), and topography at Bait plots 403 and 404.

damage following thinning. These recommendations are not necessarily new to practicing foresters or even unique to variable-density thinning, but they do deserve mention here as part of this discussion on the relationships between wind damage and thinning.

Stands with high stem densities should be thinned early to lower future H:D ratios and increase overall wind firmness. Priority for thinning should be given to stands, or portions of stands, on exposed sites, as these locations will be at the highest risk of future wind damage. If H:D ratios in the stand are already high, indicating a current risk of wind damage, then the first entry into the stand should concentrate on enhancing wind firmness by implementing a light uniform thinning. If a nonuniform thinning prescription, such as a VDT, is desired, then managers might consider girdling trees in vulnerable locations to minimize the creation of hard edges along gaps, skid trails, or landings. Finally, to the extent possible, gaps, skid trails, and landings should be located away from hilltops, ridges, and other locations susceptible to high wind velocities and thus greater wind damage.

We found that trees in the thinned matrix but away from the influence of vulnerable topographic positions or gap edges experienced low levels of wind damage. Unthinned patches within the variable-density thinning acted much like the unthinned control plots. Little wind damage occurred inside these patches, and only occasionally was damage observed that appeared to be related to the "soft edge" boundary between the unthinned patch and the thinned matrix. Even edges caused by the creation of gaps did not result in greatly elevated levels of wind damage unless the gaps were associated with hilltops or ridges. The fact that the gaps in this study were small and thinning intensity low was probably important in keeping damage levels low.

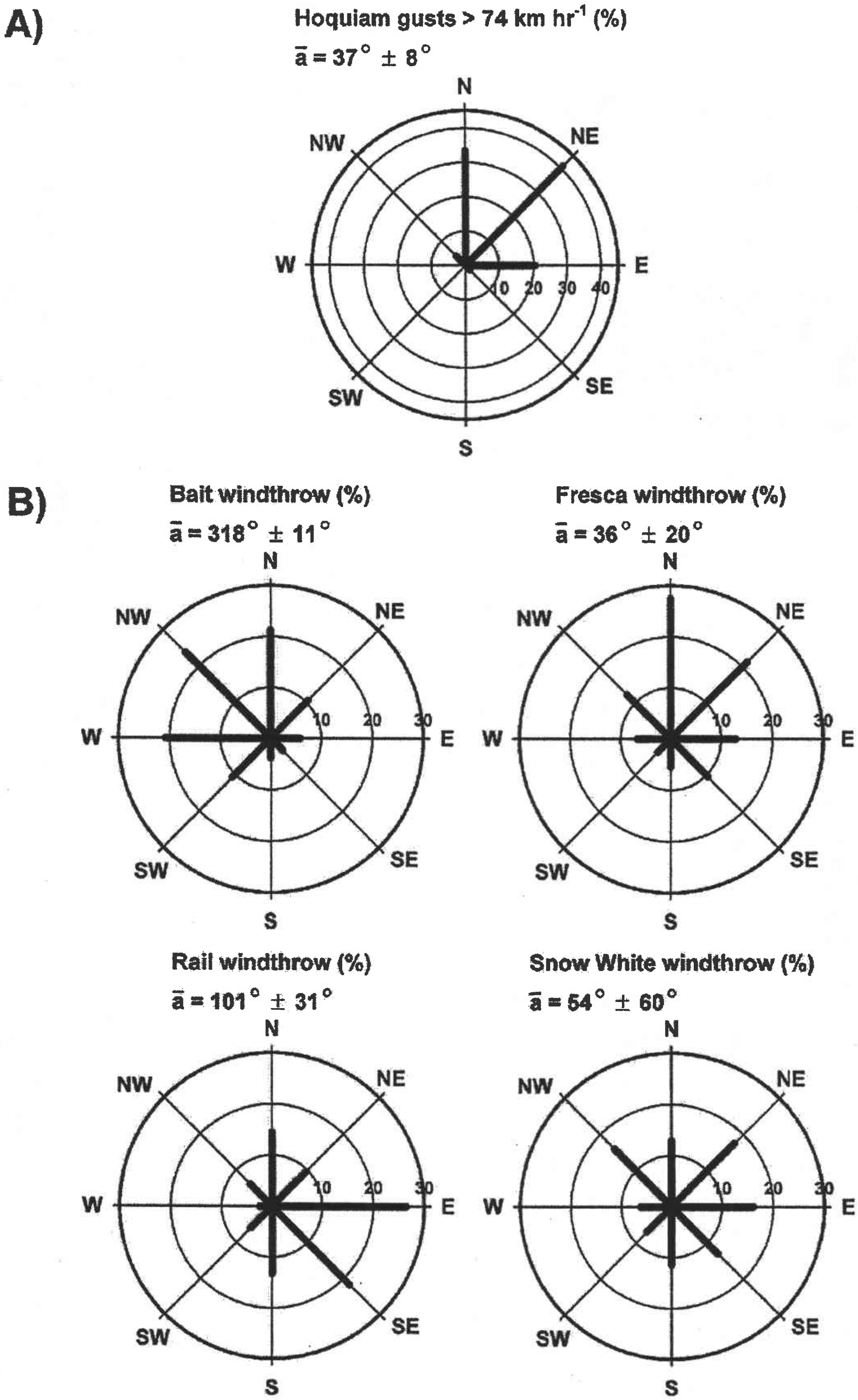

Figure 4. Direction of wind and windfall on the Olympic Peninsula. (A): Frequency of wind gusts >74 km hour^{-1} between Jan. 1, 1997, and Dec. 31, 2001, at the National Oceanographic and Atmospheric administration weather station in Hoquiam, WA. The numbers on the circles indicate the percentage of time the wind gusts blew toward the indicated direction (i.e., standard wind direction plus 180°). (B): Frequency of direction of wind damage at the four study sites on the Olympic Peninsula. The numbers on the circles indicate the percentage of the total number of wind-damaged trees that fell, broke, or leaned in that direction. The mean angle (ā) and the 95% confidence interval are shown for each set of circular data.

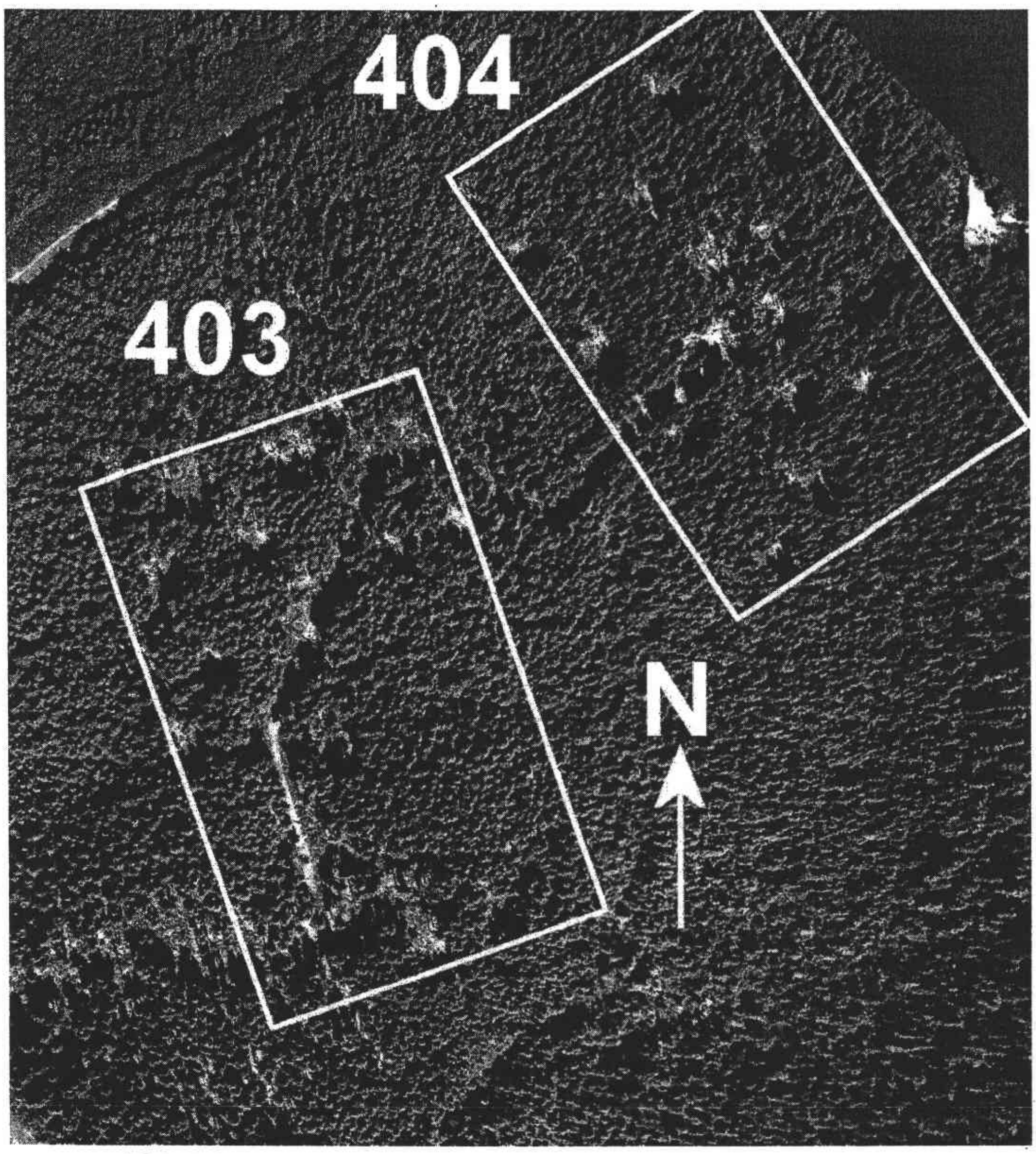

Figure 5. Aerial image of Bait plots 403 and 404, the two plots experiencing the greatest wind damage, 3½ years after being treated with a variable density thinning. On both plots, an intact and manageable stand remains. Plot boundaries are approximate; plot sizes appear different because of parallax in the photo.

Site visits in 2004 and 2005 revealed that a small amount of additional wind damage has occurred since the plots were first assessed. However, the great majority of wind-related damage occurred within the first 2 years of thinning, which is consistent with the findings of others (Rowan et al. 2003). Where additional damage has occurred, it has tended to be concentrated in vulnerable topographic positions, often close to, or in association with, locations where much of the original wind damage had occurred. It should be noted, however, that these results are based on surveys 2–3 years following thinning, and longer-term surveys or thinning operations performed in different stand conditions or followed by different wind conditions may yield different results. Harcombe et al. (2004) documented that forest gaps created in areas without anthropogenic factors did continue to expand in topographically susceptible areas, and Ott and Juday (2002), examining finer-scale features involved in windthrow in southeast Alaska, documented that approximately half of their naturally formed small gaps continued to expand over time.

The most important factors related to wind damage in this study appeared to be topographic position and the condition of the stand prior to thinning. Although some wind damage was spatially related to the gaps and skid trails associated with the variable-density thinning, these components of the VDT did not automatically predispose the stands to wind damage as trees around gaps and near skid trails in flat or protected topographic settings were rarely damaged. Based on our observations from this study, the following conclusions are offered. However, given the limitations of this study and the lack of experience with VDT approaches throughout the Pacific Northwest region, these conclusions should be considered tentative.

- Extreme weather events that generate high winds are important in producing wind damage in stands that do not have preexisting problems with root rot or other root damage. Wind events alone, however, are not necessarily sufficient to cause significant wind damage, as evidenced by the low levels of damage experienced in the control plots, as well as some of the thinned plots, of this study.

- The internal edges associated with the gaps and reserve patches created in the variable-density thinning do not greatly increase the risk of wind damage. However, care should be taken in locating gaps and in determining gap size. Locating gaps in vulnerable topographic positions can exacerbate potential wind damage problems and should be avoided when possible. Keeping gap sizes small should also help minimize wind damage. The soft edges occurring between reserve patches and the thinned matrix do not present an increased risk of wind damage.
- Trees adjacent to skid trails and landings can be vulnerable to wind damage. When possible, trails and landings should be located in topographic positions that are not vulnerable to excessive wind.

This study provides no short-term evidence that variable-density thinning per se results in unacceptable losses from wind damage. Some of our thinned stands did experience elevated levels of wind damage, and some of this damage appeared to be spatially correlated with the gaps created as part of the thinning treatment. However, our results suggest that as long as gaps are positioned to avoid exposed topographic positions, short-term losses from wind damage will be minimal.

Literature Cited

BOYCE, J.S. 1929. *Deterioration of wind-thrown timber on the Olympic Peninsula, Washington.* US For. Serv. Tech. Bull. No. 104. Portland, OR. 28 p.

BURNS, R.M., AND B.H. HONKALA (TECH. COORDS.). 1990. *Silvics of North America: Vol. 1, Conifers.* US For. Serv. Agric. Handbook 654. Washington, DC. 675 p.

CANHAM, C.D., M.J. PAPAIK, AND E.F. LATTY. 2001. Interspecific variation in susceptibility to windthrow as a function of tree size and storm severity for northern temperate tree species. *Can. J. For. Res.* 31:1–10.

CAREY, A.B., AND C.A. HARRINGTON. 2001. Small mammals in young forests: Implications for management and sustainability. *For. Ecol. Manag.* 154:289–309.

CAREY, A.B., D.R. THYSELL, AND A.W. BRODIE. 1999. *The Forest Ecosystem Study: Background, rationale, implementation, baseline conditions, and silvicultural assessment.* US For. Serv. Gen. Tech Rep. PNW-GTR-457. Portland, OR. 129 p.

CREMER, K.W., C.J. BOROUGH, F.H. MCKINNELL, AND P.R. CARTER. 1982. Effects of stocking and thinning on wind damage in plantations. *N.Z. J. For. Sci.* 12:244–268.

CUCCHI, V., AND D. BERT. 2003. Wind-firmness in *Pinus pinaster* Ait. stands in southwest France: Influence of stand density, fertilization and breeding in two experimental stands damaged during the 1999 storm. *Ann. For. Sci.* 60:209–226.

CURTIS, R.O., D.S. DEBELL, C.A. HARRINGTON, D.P. LAVENDER, J.B. ST. CLAIR, J.C. TAPPEINER, AND J.D. WALSTAD. 1998. *Silviculture for multiple objectives in the Douglas-fir region.* US For. Serv. Gen. Tech Rep. PNW-GTR-435. Portland, OR. 123 p.

FRANKLIN, J.F., T.A. SPIES, R. VAN PELT, A.B. CAREY, D.A. THORNBURGH, D.R. BERG, D.B. LINDENMAYER, M.E. HARMON, W.S. KEETON, D.C. SHAW, K. BIBLE, AND J. CHEN. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. *For. Ecol. Manag.* 155:399–423.

FREESE, F. 1967. *Elementary statistical methods for foresters.* US For. Serv. Agric. Handbook 317. Washington, DC. 87 p.

GRATKOWSKI, H.J. 1956. Windthrow around staggered settings in old-growth Douglas-fir. *For. Sci.* 2:60–74.

HARCOMBE, P.A., S.E. GREENE, M.G. KRAMER, S.A. ACKER, T.A. SPIES, AND T. VALENTINE. 2004. The influence of fire and windthrow dynamics on a coastal spruce-hemlock forest in Oregon, USA, based on aerial photographs spanning 40 years. *For. Ecol. Manag.* 194:71–84.

HENNON, P.E., AND M.H. MCCLELLAN. 2003. Tree mortality and forest structure in the temperate rain forests of southeast Alaska. *Can. J. For. Res.* 33:1621–1634.

KOHM, K.A., AND J.F. FRANKLIN (EDS.). 1997. *Creating a forestry for the 21st century.* Island Press, Washington, DC. 475 p.

KRAMER, M.G., A.J. HANSEN, M.L. TAPER, AND E.J. KISSINGER. 2001. Abiotic controls on long-term windthrow disturbance and temperate rain forest dynamics in southeast Alaska. *Ecology* 82:2749–2768.

LOHMANDER, P., AND F. HELLES. 1987. Windthrow probability as a function of stand characteristics and shelter. *Scand. J. For. Res.* 2:227–238.

METEOROLOGY COMMITTEE, PACIFIC NORTHWEST RIVER BASINS COMMISSION. 1968. *Climatological handbook: Columbia Basin states, hourly data, volume 3, Part A.* Pacific Northwest River Basins Commission, Vancouver, WA. 341 p.

MITCHELL, S.J. 1995. The windthrow triangle: A relative windthrow hazard assessment procedure for forest managers. *For. Chron.* 71:446–450.

MITCHELL, S.J., T. HAILEMARIAM, AND Y. KULIS. 2001. Empirical modeling of cutblock edge windthrow risk on Vancouver Island, Canada, using stand level information. *For. Ecol. Manag.* 154:117–130.

NATIONAL CLIMATIC DATA CENTER. 2002. *Federal climate complex data documentation for integrated surface hourly data.* Air Force Combat Climatology Center, Fleet Numerical Meteorology and Oceanography Detachment, Asheville, NC. 49 p.

NATIONAL CLIMATIC DATA CENTER. Climatic extremes and weather events. Available online at www.ncdc.noaa.gov/oa/climate/severeweather/extremes.html; last accessed Jan. 5, 2006.

NOWACKI, G.J., AND M.G. KRAMER. 1998. *The effects of wind disturbance on temperate rain forest structure and dynamics of southeast Alaska.* US For. Serv. Gen. Tech Rep. PNW-GTR-421. Portland, OR. 25 p.

OTT, R.A., AND G.P. JUDAY. 2002. Canopy gap characteristics and their implications for management in the temperate rainforests of southeast Alaska. *For. Ecol. Manag.* 159:271–291.

PETERSON, C.J. 2004. Within-stand variation in windthrow in southern boreal forests of Minnesota: Is it predictable? *Can. J. For. Res.* 34:365–375.

PETERSON, C.J., AND S.T.A. PICKETT. 1991. Treefall and resprouting following catastrophic windthrow in an old-growth hemlock-hardwoods forest. *For. Ecol. Manag.* 42:205–217.

REUTEBUCH, S.E., C.A. HARRINGTON, D.S. DEBELL, D.D. MARSHALL, AND R.O. CURTIS. 2002. Silvicultural options for multipurpose management of west-side Pacific Northwest forests. P. 38–46 in *Proc. of the 2001 National Silviculture Workshop. Beyond 2001: A silvicultural odyssey to sustaining terrestrial and aquatic ecosystems*, Parker, S., and S.S. Hummel (compilers). US For. Serv. Gen. Tech Rep. PNW-GTR-546. Portland, OR.

ROWAN, C.A., S.J. MITCHELL, AND T. HAILEMARIAM. 2003. Effectiveness of clearcut edge windfirming treatments in coastal British Columbia: Short-term results. *J. For.* 76:55–65.

RUEL, J.-C. 1995. Understanding windthrow: Silvicultural implication. *For. Chron.* 71:434–445.

RUEL, J.-C., D. PIN, AND K. COOPER. 2001. Windthrow in riparian buffer strips: Effect of wind exposure, thinning and strip width. *For. Ecol. Manag.* 143:105–113.

SINTON, D.S., J.A. JONES, J.L. OHMANN, AND F.J. SWANSON. 2000. Windthrow disturbance, forest composition, and structure in the Bull Run Basin, Oregon. *Ecology* 81:2539–2556.

WONN, H.T., AND K.L. O'HARA. 2001. Height:diameter ratios and stability relationships for four northern Rocky Mountain tree species. *West. J. Appl. For.* 16:87–94.

ZAR, J.H. 1999. *Biostatistical analysis*, 4th Ed. Prentice Hall, Englewood Cliffs, NJ. 663 p.