Windthrow damage 2 years after partial cutting at the Date Creek silvicultural systems study in the Interior Cedar Hemlock forests of northwestern British Columbia

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NOTE

Windthrow damage 2 years after partial cutting at the Date Creek silvicultural systems study in the Interior Cedar–Hemlock forests of northwestern British Columbia

K. Dave Coates

Abstract: Partial cutting that removed either 30 or 60% of the volume as single trees or small groups up to 0.5 ha had little effect on wind damage to merchantable trees (≥17.5 cm diameter). On average, 6.7 stems per hectare of windthrow occurred across unlogged and logged units, representing approximately 1.9% of the standing trees. Over 2 years, 0.63 $m^2 \cdot ha^{-1}$ of merchantable basal area was damaged, or 1.5% of the original standing basal area. In the partial cuts, 2.2% of the trees were damaged compared with 1.1% in unlogged areas. The 1.1% increase in damage in partial cut units was well below the 10% effect size considered large enough to warrant either management intervention or to deem the partial cutting a failure. The greatest wind damage occurred in the old-growth stands. For 8 of the 9 tree species examined, no individual tree characteristics seemed to predispose them to wind damage. *Abies amabilis* (Dougl. ex Loud.) Dougl. ex J. Forbes, *Populus tremuloides* Michx., and *Abies lasiocarpa* (Hook.) Nutt. were the most susceptible species to windthrow.

Résumé : La coupe partielle, où 30 ou 60% du volume par pieds d'arbre ou par trouées ne dépassant pas 0,5 ha avait été enlevé, avait peu d'effet sur les dommages causés par le vent aux tiges marchandes (≥17,5 cm de diamètre). En moyenne, 6,7 tiges à l'hectare étaient renversées par le vent dans les unités récoltées et non récoltées; ce qui représentait approximativement 1,9% des arbres sur pied. Sur une période de 2 ans, 0,63 $m^2 \cdot ha^{-1}$ de surface terrière marchande avait été endommagée ou 1,5% de la surface terrière sur pied. Dans les coupes partielles, 2,2% des arbres avaient été endommagés comparativement à 1,1% dans les zones non coupées. L'augmentation de 1,1% des dommages dans les unités soumises à la coupe partielle était nettement inférieure à 10% qui est considérée comme une augmentation dont l'effet est suffisamment important pour nécessiter une intervention ou qualifier la coupe partielle d'échec. Les dommages dus au vent les plus importants sont survenus dans les vieux peuplements. Dans le cas de 8 des 9 espèces d'arbres examinées, aucune caractéristique individuelle des arbres semblait les prédisposer aux dommages dus au vent. *Abies amabilis* (Dougl. ex Loud.) Dougl. ex J. Forbes, *Populus tremuloides* Michx. et *Abies lasiocarpa* (Hook.) Nutt. étaient les espèces les plus sensibles au renversement par le vent. [Traduit par la Rédaction]

Introduction

In British Columbia, where clear-cutting is the dominant harvesting practice, wind damage generally occurs in uncut mature and old-growth stands and along edges of clear-cut units (Stathers et al. 1994). Partial cutting in mature and old-growth forests is increasing in response to new silvicultural, ecological, and social management objectives. In part, the success of these partial cutting systems will depend on how the logging alters wind damage risk and whether the extent of subsequent wind damage compromises management objectives.

Wind damage in forest stands is affected by internal stand characteristics (age, species composition, diameter and height distributions, presence of root rot), internal stand treatment history (time since last cutting, percent of stand removed during cutting), adjacent stand history (e.g., clear-cutting), site conditions (soil moisture and depth, local topography), and storm characteristics (season, wind direction, average and maximum gust wind speed) (see reviews by Hubert 1918; Curtis 1943; Ruth and Yoder 1953; Savill 1983; Harris 1989; Stathers et al. 1994; Navratil 1995; Coutts and Grace 1995; Ruel 1995).

There have been numerous post hoc studies of wind damage in partially cut stands (Smith and Weitknech 1915; Weidman 1920; Behre 1921; Gilmour 1926; Kelly and Place 1950; Ruth and Yoder 1953; Worthington 1953; McLintock 1954; Glew 1963; Elling and Verry 1978; Fleming and Grossfield 1983). The intent was usually to document the magnitude of damage, look for causal factors, and make recommendations on the acceptability of the partial cutting practices. Conclusions varied about the suitability of the various cutting methods. Unfortunately, direct comparison of wind damage in uncut stands and adjacent partially cut stands was made in only a few early studies (Smith and Weitknech 1915; Ruth and Yoder 1953; McLintock 1954; Lees 1964), of which only one was a replicated

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Table 1. The extent of wind damage in the Date Creek silvicultural systems study 2 years after logging (trees ≥ 17.5 cm).

	Treatment[a]					Power=0.70		Power=0.90	
Wind damage response variable	No removal[b]	Light removal[b]	Heavy removal[b]	Mean	SE	Min.[c]	Max.[c]	Min.[c]	Max.[c]
No of windthrown trees/ha	5.9±5.2	8.1±4.2	6.05±4.8	6.7	2.01	8.48	10.39	10.84	13.27
% windthrow	1.12±1.3	1.7±1.2	2.72±3.7	1.85	0.79	3.33	4.08	4.26	5.22
Basal area of windthrown trees/ha	0.53±0.53	0.79±0.55	0.58±0.74	0.63	0.13	0.54	0.67	0.70	0.85
% basal area	0.87±0.82	1.77±1.44	1.97±2.61	1.54	0.56	2.38	2.92	3.05	3.73

[a] No removal is the unlogged treatment; light removal had approximately 30% volume removal; heavy removal had approximately 60% volume removal.

[b] Treatment means ± SD, $n = 4$.

[c] Minimum and maximum ranges of differences between the smallest and largest means that could be detected at power 0.70 and 0.90.

experiment (Lees 1964). Ruel (1995), in a review focusing on how silvicultural practice affects wind damage, concluded that windthrow losses remain mostly unquantified.

In this study, a replicated experimental design was used to assess the hypothesis that increasing amounts of tree removal results in higher wind damage in the coast–interior transitional forests of northwestern British Columbia.

Methods

The windthrow study is a component of the Date Creek silvicultural systems study (Coates et al. 1997), established in 1992, approximately 21 km north of Hazelton, west of the Kispiox River (55°22′N, 127°50′W; 370–665 m elevation). Date Creek is within the moist cold subzone of the Interior Cedar–Hemlock biogeoclimatic zone (ICHmc; Banner et al. 1993), a transitional area between the interior and coastal forests of northwestern British Columbia (Pojar et al. 1987; Meidinger and Pojar 1991). Forests in the Date Creek area are wildfire origin stratified mixtures of coniferous and deciduous tree species. In mature stands (140 years), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) dominates; other species include western redcedar (*Thuja plicata* Donn ex D. Don), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), hybrid spruce (a complex of white spruce (*Picea glauca* (Moench) Voss), Sitka spruce (*Picea sitchensis* (Bong.) Carrière), and perhaps Engelmann spruce (*Picea engelmannii* Parry ex Engelm.)), paper birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.), and black cottonwood (*Populus balsamifera* ssp. *trichocarpa* Torr. & Gray). Old-growth forests (250–300+ years) are dominated by western hemlock with varying amounts of western redcedar and some amabilis fir (*Abies amabilis* (Dougl. ex Loud.) Dougl. ex J. Forbes). Amabilis fir abundance increases with elevation.

The mountainous nature of the study area results in climatic variation occurring over relatively short distances. Variations correspond to elevation and surrounding topography. The moderate to steep lower slopes of the Kispiox Range make up one-half of the total area. The rest of the area is a rolling morainal landscape, dissected by many glacial meltwater channels. Morainal parent materials dominate the area, ranging in texture from loamy sand to clay loam. Eluviated Dystric Brunisols, Orthic Dystric Brunisols, and Orthic Humo–Ferric Podzols are the most common soils (Agriculture Canada Expert Committee on Soil Survey 1987).

For the windthrow study, three tree removal treatments (in approximately 20-ha treatment units) were replicated four times (12 units in total), in a randomized block design, with combinations of ecological site type and forest age as the blocking factor (mesic 140 years; mesic–submesic 140 years; mesic–subhygric 140 years; mesic 350 years). The treatments were (1) no tree removal; (2) light tree removal, where approximately 30% of the stand volume was removed across all species and diameter classes in single stems and small groups; and (3) heavy tree removal, where approximately 60% of the stand volume was removed using a combination of small patch cuts (0.1–0.5 ha) and single-tree to small-group selection within the surrounding forest matrix. Again, in the forest matrix, trees were removed evenly across all species and diameter classes.

Wind damage was sampled in late August 1994, 2 years after logging was completed. Two major wind events occurred, one in mid-October 1993 and another in mid-August 1994 just prior to sampling. Both storms caused considerable windthrow over a much wider geographic area than the study sites and were considered 1 in 5 or 1 in 10 year events by local foresters. Unfortunately, no wind or gust speed data were recorded for either event.

To assess wind damage, transect lines were established 50 m apart (approximately 3600 m of line) on maps of each treatment unit. From these lines, approximately 2000 m of transect line was randomly selected. Windthrow originally rooted within 5 m of either side of the transect line was tallied. The total amount of transect line in an individual treatment unit was considered one plot (i.e., 1950 × 10 m wide transect line = 1.95 ha). To be tallied, a windthrown tree had to have a diameter of 17.5 cm or greater and have been either snapped or uprooted (uprooted included trees leaning at greater than a 45° angle from the vertical). Data recorded for each tree included species, stem diameter (at 1.3 m), height, height to live crown, crown class (overstory, intermediate, or suppressed), direction of fall, and type of windfall (uprooted or snapped).

The extent of windthrow was calculated both as basal area ($m^2 \cdot ha^{-1}$) and stems per hectare on the ground. In addition, damage was calculated as a percent of the standing basal area and stem density using stand structure data collected immediately after logging (Coates et al. 1997).

Individual tree data (mean diameter, height, height:diameter ratio, crown class) of the windthrown trees were compared with data from prism cruise plots established after logging was completed. In each cruise plot all “in” trees were recorded by species and diameter and two trees were randomly selected for height measurement. To compare the two populations (except for crown class), I used a folded form F statistic to test the hypothesis of equal variances and found only western hemlock diameter significant at $P < 0.05$. I then performed a classic two- sample t-test on all the data; thus all P-values in Table 5, except for hemlock diameter, assume equal variances.

In applied experiments of this type, it is important to examine the power the experiment had to detect differences among the treatment means (effect size). Based on an informal survey of local professional foresters, I selected an effect size of greater than 10% as large enough to be operationally significant. In northwestern British Columbia, 10 to 20% of a stand would have to be wind damaged before either management intervention would be considered, or the treatment would be written off as a failure.

Finally, all statistical analysis was done with SAS version 6.11 (SAS Institute Inc. 1989).

Table 2. ANOVA table for the wind damage response variables in a randomized block design.

	df	SS	MS	*F*-value	*P*-value
Experimental block					
No of windthrown trees/ha	3	109.2	36.4	2.3	0.18
% windthrow	3	35.0	11.7	4.7	0.05
Basal area of windthrown trees/ha	3	2.99	0.99	15.1	0.003
% basal area	3	18.8	6.3	4.9	0.05
Tree removal level (treatment)					
No of windthrown trees/ha	2	12.6	6.3	0.39	0.69
% windthrow	2	5.2	2.5	1.06	0.4
Basal area of windthrown trees/ha	2	0.15	0.08	1.14	0.38
% basal area	2	2.8	1.4	1.09	0.39
Error (block×treatment)					
No of windthrown trees/ha	6	96.1	16		
% windthrow	6	14.9	2.5		
Basal area of windthrown trees/ha	6	0.4	0.07		
% basal area	6	7.6	1.3		
Total					
No of windthrown trees/ha	11	217.9			
% windthrow	11	55.1			
Basal area of windthrown trees/ha	11	3.5			
% basal area	11	29.2			

Results

On average, 6.7 stems per hectare of windthrow occurred across all treatment units, representing approximately 1.9% of the standing trees (Table 1). Over the 2 years, 0.63 $m^2 \cdot ha^{-1}$ of merchantable basal area was damaged, or 1.54% of the original standing basal area (Table 1). There was little evidence that wind damage to merchantable trees (those ≥17.5 cm diameter) was greater in the light or heavy removal treatments (Table 2). This result is true for measures of both basal area and stems per hectare on the ground and for damage expressed as either percent of original basal area or original number of standing stems (Table 2; all *P*-values >0.37).

Power analysis found the experiment had a 90% reliability (at $\alpha = 0.05$) to detect an effect size (difference between means) of 5.2% windthrow or more and may have had sufficient power for differences between 4.3 and 5.2% windthrow, but would not have detected differences smaller than 4.3% windthrow among the treatments (Table 1). The same detection limits exist for windthrow stems per hectare, basal area of windthrow per hectare, and percent basal area damage using numbers presented in Table 1. The experiment had nearly 100% reliability for detecting differences among treatment means (effect size) of 8% or greater windthrow (6% for basal area damage), well below the effect size considered operationally significant (10%).

Among the individual treatment units, windthrow varied from a low of 1.3 stems per hectare (0.3%, in a heavy removal unit) to a high of 12.8 stems per hectare (8.2%, also in a heavy removal unit) (Table 3). Basal area damage among individual treatment units varied from a low of 0.06 $m^2 \cdot ha^{-1}$ to a high of 1.68 $m^2 \cdot ha^{-1}$, or between 0.2 and 5.9% of the original basal area, with both extremes again found in heavy removal units (Table 3). One clear trend in the data was a higher incidence of wind damage in the old-growth experimental block (block 1 in Table 3). Statistically, it is not possible to conclude whether this trend was due to forest age or to some other factor, such as the physical location of the experimental block, since blocks were not replicated in the experiment. Among the mature forest experimental blocks there were no consistent trends; for example, there was no indication that the wettest sites (block 4) were least windfirm.

There was no evidence to suggest that species susceptibility to wind damage varied at different levels of tree removal (interaction among species and treatment: windthrown stems per hectare, $P = 0.98$; percent windthrow, $P = 0.61$; basal area damaged, $P = 0.97$; percent basal area, $P = 0.53$). There were, however, differences in susceptibility among species when data were pooled across all treatments and the observed distribution of windthrow was compared with the predicted distribution (χ^2 df = 6; value = 58.1; $P < 0.001$). Although western hemlock was by far the most common tree species and had the greatest number of wind-damaged stems (Table 4), hemlock was not the most wind-damage-prone species. The rank order of species susceptibility (percent of the original standing population damaged by wind) from most to least damaged was amabilis fir (5.3%) > trembling aspen (4%) > subalpine fir (2%) > western hemlock (1.3%) > hybrid spruce (0.8%) > paper birch (0.6%) > western redcedar (0.3%) > lodgepole pine (0.2%) > black cottonwood (0%) (Table 4).

The majority of wind damage was uprooting of trees (84.4%) rather than stem snapping (15.6%), and this trend was consistent for all species except trembling aspen; however, sample sizes for two of the species, lodgepole pine and black cottonwood, were too small to draw reliable conclusions (Table 4). Of the wind-damaged trees, 72.4% were from the overstory (top third of canopy), 24.5% were intermediate (middle third of canopy), and 3.1% were suppressed (bottom third of canopy). This was very similar to the distribution of merchantable trees immediately after logging: 74.8% overstory, 22.2% intermediate, and 3.0% suppressed. Except for western hemlock, there was no evidence (all *P*-values >0.05) to suggest that wind-damaged individual species were different in terms of

Table 3. Number of stems and basal area per hectare before (1991) and after (1992) partial cutting and the extent of wind damage 2 years after cutting (1994) for trees ≥17.5 cm diameter.

	Treatment[a]											
	No removal				Light removal				Heavy removal			
	1	2	3	4	1	2	3	4	1	2	3	4
Before cutting (1991)												
No. of stems/ha	414.5	841.7	957.4	677.2	458.6	881.3	687.5	731.7	389.4	701.9	819.9	814.9
Basal area/ha	63.6	55.5	64.1	55.4	69.1	65.6	63.5	69.1	56.7	55.7	71.2	70.3
After cutting (1992)												
No. of stems/ha	414.5	841.7	957.4	677.2	285.1	683.3	596.4	616.2	156.1	448.5	406.6	417.5
Basal area/ha	63.6	55.5	64.1	55.4	47.6	39.9	40.6	46.4	28.7	28.1	34.3	30.6
Wind damage (1994)												
No. of windthrown trees/ha	12.2	1.5	1.7	8.03	9.2	13.1	2.9	7.3	12.8	5.4	4.6	1.3
% windthrow	2.94	0.18	0.18	1.19	3.22	1.92	0.48	1.19	8.21	1.21	1.14	0.32
Basal area of windthrown trees/ha	1.26	0.12	0.17	0.55	1.54	0.84	0.31	0.46	1.68	0.23	0.34	0.06
% basal area	1.98	0.21	0.27	1.01	3.23	2.1	0.75	0.99	5.85	0.82	0.99	0.21

[a] No removal is the unlogged treatment; light removal had approximately 30% volume removal; heavy removal had approximately 60% volume removal. The experimental blocks are shown by the numbers 1 to 4: 1, old growth (350 years) mesic; 2, mature (140 years) mesic to submesic; 3, mature (140 years) mesic; 4, mature (140 years) mesic to subhygric.

Table 4. Windthrow distributed by tree species, combined across all experimental blocks and treatment units.

	Windthrown stems tallied	Original stand density[a] (stems/ha)	Windthrow density[b] (stems/ha)	Original stand density[c] (%)	Windthrow (% of windthrown trees)	Windthrow (% of standing trees)	Uprooted (%)	Snapped (%)
Amabilis fir	5	2.8±8.7	0.18±0.43	0.5	2.7	5.28	75	25
Trembling aspen	6	7.0±13.7	0.28±0.48	1.3	4.2	4.00	50	50
Subalpine fir	5	10.6±10.7	0.20±0.38	2.0	3.0	1.98	100	0
Western hemlock	129	349.6±149.5	5.37±4.34	64.6	80.5	1.31	85	15
Hybrid spruce	4	17.3±14.6	0.14±0.27	3.2	2.1	0.80	75	25
Paper birch	6	32.9±36.4	0.22±0.49	6.1	3.3	0.55	86	14
Western redcedar	7	101.6±58.6	0.25±0.49	18.8	3.7	0.25	90	11
Lodgepole pine	1	15.8±26.0	0.03±0.12	2.9	0.5	0.22	0	100
Black cottonwood	0	4.1±5.3	0.00±0.00	0.8	0.0	0.00	0	0
Total	163	541.7±230.2	6.67±4.45	100.0	100.0			

[a] Stand density (mean ± SD, $n = 12$) data are from immediately after removal treatments were applied (Coates et al. 1997).

[b] Windthrow density (mean ± SD, $n = 12$) data are for uprooted (>45°) and snapped trees recorded 2 years after removal treatments were applied.

[c] For example, 1.3% of the original stand density comprised trembling aspen.

mean diameter, height, or height:diameter ratio from the population of trees sampled in the cruise plots established right after logging (Table 5). Wind-damaged hemlock trees appear to be smaller in diameter, but still fairly tall, resulting in a high height:diameter ratio compared with the general hemlock population. Wind damaged paper birch, although not significant ($P = 0.06$), tended to have high height:diameter ratios (Table 5). The crown class distribution of wind-damaged trees by species was also quite similar to that of the population right after logging was completed (Table 5).

Finally, there was a very consistent trend in the direction of fall of all wind-damaged trees (Fig. 1). The vast majority of trees fell to the north, suggesting winds from the south caused most of the damage. This is reasonable given that the Kispiox River valley is orientated north–south and the major winds coming from the Pacific Coast (up the Skeena River from Prince Rupert) would enter the Kispiox valley from the south.

Discussion

The results demonstrate that partial cutting rates of up to 60% removal can be undertaken in previously unmanaged mixed-species forests with little resulting short-term increase in wind damage. A certain amount of wind damage is acceptable, or even desirable, from an ecosystem perspective, but at some point damage can compromise management objectives. Choosing a threshold level of damage depends on management values. After 2 years, 2.2% of the trees had been damaged in partially cut units compared with 1.1% in unlogged areas. This experiment does not have the power to detect whether a 1.1% difference was due to the partial cutting. However, the 1.1% increase in damage was well below the 10% effect size (the difference between treatment means) considered large enough to warrant either management intervention or to deem the partial cutting a failure.

Amabilis fir, trembling aspen, and subalpine fir were the most windthrown species in the study. This corresponds well with other studies that have reported true firs among the most susceptible tree species (e.g., Ruel 1995). However, it is possible that our amabilis fir results may be biased by the fact that amabilis fir occurred only in the old-growth experimental block, which experienced the highest levels of wind damage. Hardwoods are generally considered to be quite windfirm, and

Table 5. Tree characteristics from prism cruise plots established immediately after logging and from the windthrown trees, combined across all experimental blocks and treatment units.

	Sample size (n)	Diameter (mean±SE, cm)	Height (mean±SE, m)	Height: diameter ratio	Crown class[a] Overstory (%)	Intermediate (%)	Suppressed (%)
Amabilis fir							
Original stand	29, 8[b]	37.9±2.0	32.9±1.6	78.7±2.9	85	11	4
Windthrown stems	5	33.1±4.5	28.0±3.4	85.4±2.1	80	20	0
P-value		0.37	0.17	0.13			
Trembling aspen							
Original stand	24, 8	30.0±1.6	26.3±1.0	92.5±5.7	100	0	0
Windthrown stems	6	30.8±3.2	26.2±0.9	87.9±5.8	100	0	0
P-value		0.84	0.93	0.59			
Subalpine fir							
Original stand	26, 5	38.4±2.7	27.1±2.4	86.5±3.3	88	12	0
Windthrown stems	5	37.2±3.8	31.4±1.9	86.3±4.7	100	0	0
P-value		0.85	0.19	0.97			
Western hemlock							
Original stand	1258, 334	40.3±0.5	26.9±0.3	74.1±1.1	75	22	3
Windthrown stems	129	32.1±1.1	24.6±0.5	83.0±2.1	67	30	3
P-value		0.0001	0.0001	0.0001			
Hybrid spruce							
Original stand	99, 28	46.7±1.4	33.7±1.1	73.8±2.4	94	6	0
Windthrown stems	4	44.6±4.1	34.5±1.7	78.9±6.9	100	0	0
P-value		0.78	0.78	0.46			
Paper birch							
Original stand	87, 28	28.4±1.0	22.7±1.2	80.5±4.7	64	35	1
Windthrown stems	6	24.8±2.4	24.5±1.6	103.0±12.3	100	0	0
P-value		0.34	0.51	0.06			
Western redcedar							
Original stand	342, 89	48.2±1.4	25.9±0.8	68.0±2.4	64	32	4
Windthrown stems	7	42.4±6.1	24.7±2.8	61.2±7.4	72	14	14
P-value		0.56	0.68	0.45			
Lodgepole pine							
Original stand	47, 14	32.6±1.0	28.2±1.2	90.7±3.5	98	2	0
Windthrown stems	1	21.0	27.0	128.6	100	0	0
Black cottonwood							
Original stand	44, 10	72.3±5.1	34.9±1.3	92.5±5.9	100	0	0
Windthrown stems	0	—	—	—	0	0	0

Note: *P*-values are from a two sample *t*-test.

[a] Overstory, intermediate, and suppressed indicate that crowns occupy top, middle, and bottom thirds of the canopy, respectively.

[b] 29, 8 are sample sizes for diameter, and height and height:diameter ratio, respectively.

except for aspen this was the case in the mixed-species stands. The high incidence of aspen windthrow might be due to their tendency to have high levels of decay when old (Peterson and Peterson 1995). Unlike other studies (e.g., Curtis 1943; Ruth and Yoder 1953), the trees wind damaged in the Date Creek study were simply a subsample of the population of trees found in the forest. Except for western hemlock (and possibly paper birch), where trees with a high height:diameter ratio were most damage prone, there were no individual tree characteristics that seemed to predispose trees to damage. Nor was the susceptibility of individual trees affected by the levels of tree removal tested in the study.

The highest levels of damage occurred in the old-growth stands, generally 2 to 3 times greater for each wind damage variable (Table 2) than in the mature stands. The heavy removal old-growth stand was by far the most wind-damaged stand in the experiment. The overall high level of damage in old-growth stands is more likely due to the trees being old and often decayed than to the location of the units. Advanced age, large size, and presence of pathogens are frequently associated with higher windthrow risk (Hubert 1918; Behre 1921; Curtis 1943; Lohmander and Helles 1987). Wind damage in the heavy removal treatment may have been a topographic effect or due to the level of tree removal. The stand was adjacent to the unlogged unit, which suffered little damage. This suggests that old-growth stands may be more susceptible to wind damage as logging removal rates increase.

The mature stands (140 years), although old by industrial forest management standards, were quite windfirm. In these stands, losses to wind damage were 0.17 $m^2 \cdot ha^{-1} \cdot year^{-1}$ over the 2-year study. To put this in perspective, growth in the mature stands has averaged 0.39 $m^2 \cdot ha^{-1} \cdot year^{-1}$ over 140 years (Coates et al. 1997), and thus windthrow losses have been less than half of 1 year's average growth. These losses are similar

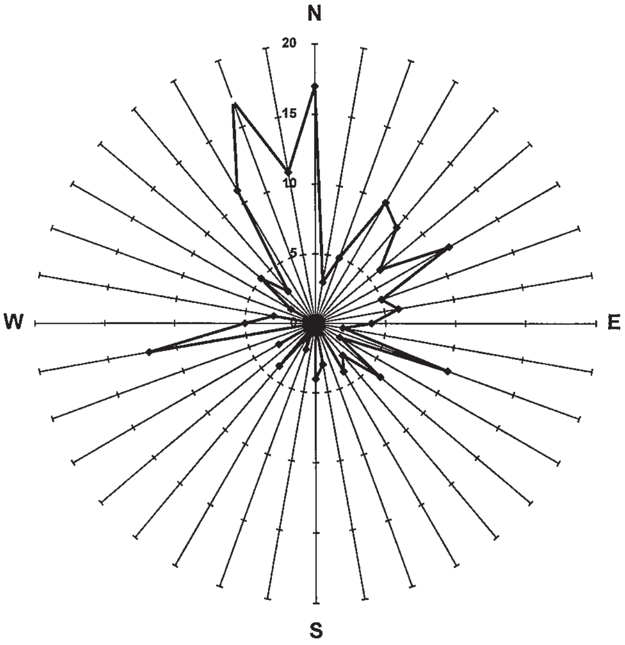

Fig. 1. Frequency distribution of the direction in which windthrown trees fell.

in magnitude to those found with other partial cutting studies in mixed eastern U.S. forests (Behre 1921; McLintock 1954), in New Brunswick upland spruce–fir (Kelly and Place 1950), after single-tree selection in northern interior B.C. forests (Glew 1963), in mixed spruce–aspen forests of northern Alberta (Lees 1964), and in selection cuttings of overmature spruce–fir stands in Quebec (Weetman and Algar 1976). Like Date Creek, all of these studies were in unmanaged stands of natural origin.

Windthrow studies that have reported low levels of damage in partially cut stands appear to have certain elements in common. Some sort of dispersed cutting pattern has been used and maximum canopy opening size is relatively small. In my study, trees were removed individually or in groups with a maximum opening size of 0.5 ha. The six studies cited above (Behre 1921; Kelly and Place 1950; McLintock 1954; Glew 1963; Lees 1964; Weetman and Algar 1976) had similar levels and patterns of tree removal.

A western U.S. study (Worthington 1953), which contrasted small and large opening sizes, found negligible damage around 0.5- to 1.6-ha openings, but severe damage around large clear-cut boundaries. Similarly, Glew (1963) reported little damage with single-tree selection but high damage in strip-cut areas. Other strip-cutting studies have also reported high levels of damage (Fleming and Grossfield 1983). In general, wind damage increases when tree removal rates are high (Lohmander and Helles 1987).

Windthrow research has shown that damage is greatest in the first few years following logging (Weidman 1920; Fleming and Grossfield 1983; Laiho 1987). Valid long-term comparisons of partially cut and unlogged stands should measure net growth, balancing losses due to windthrow (and other factors such as competition-induced mortality, insects, and pathogens) against growth gains in released trees.

Wind damage is a natural liability in forest management. The cutting pattern employed in partial cuts appears to be a critical element in windthrow susceptibility. As with any cutting method, careful attention to topographic features and prevailing wind directions is required to mitigate windthrow risk. Although this study presents results from only 2 years after logging, the area has been subject to two major storms. These early results suggest that fear of wind damage should not prevent forest managers from implementing partial cutting prescriptions.

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