Windthrow Assessment and Management in British Columbia.

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Forward

Windthrow affects the outcomes of forest level plans and stand level prescriptions in many areas of BC –especially on the coast and on the interior plateau. Recent changes in management approaches such as protection of small streams and gullies, wildlife tree patches, and partial cutting strategies such as variable retention have increased the need by managers for up-to-date knowledge of windthrow assessment and management techniques. Managers also need to understand the positive and negative impacts of windthrow on forest values, and ecosystem health and function in order to determine the acceptable levels of damage in prescriptions, and identify where salvage is appropriate.

The document most widely used by managers in BC – the Windthrow Handbook is now 6 years old. Advances in windthrow assessment and management have been made in BC and elsewhere during the past few years. This two-day workshop for windthrow researchers and managers provided a venue for exchange of and discussion of current research results and their implications for management. It also set the stage for development of collaborative research approaches to this multi-faceted problem. Results of these discussions are summarized at the end of the proceedings.

The papers in these proceedings have been compiled as provided by the authors, and have not been peer reviewed. They are grouped into four topic areas. The first section contains papers that report studies of damage associated with clearcuts or partial cuts. Studies of windthrow in natural stands, and wind regimes are in the second section. The third section contains papers that describe methods for monitoring and modelling windthrow risk. The final section contains a study on the effectiveness of edge modification techniques for reducing damage.

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The workshop organizing committee,

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TABLE OF CONTENTS

Section 1. Wind Damage Associated with Management

Windthrow Monitoring of Alternative Silvicultural Systems in Montane Coastal Forests

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Abstract

This study is one of several investigating the biological impacts of silvicultural systems at the Montane Alternative Silvicultural Systems (MASS) study, located southwest of Campbell River in Weyerhaeuser’s North Island Timberlands. The study quantifies and compares residual forest structure and wind damage under clearcut, patch cut, green tree retention and shelterwood systems for montane coastal B.C. forests.

Low levels of dispersed retention resulted in wind damage to 29% (8 sph) of the leave trees over 6 years. Greater numbers of windthrown trees (21 sph) occurred under shelterwoods that retained a quarter of the original basal area, which represented about 10% of the leave trees. Edges of patch cuts (1.5 ha) lost fewer stems to wind damage (6 sph) than any other treatment, including the 69 ha clearcut (9 sph). Trees with larger crowns were more vulnerable to wind damage. Western redcedar appears to be more windfirm than amabilis fir or western hemlock on well drained soils.

Introduction

The Montane Alternative Silvicultural Systems (MASS) study was established to develop operationally feasible and ecologically sustainable silvicultural systems in montane old-growth forests. Seventeen integrated studies are examining the biological and economic consequences of shelterwood, patch cut, green tree retention and clearcut alternatives. Windthrow and other types of wind and snow damage are potential problems for implementing partial cutting in high elevation coastal forests. The objective of this study was to quantify and characterize windthrow under four silvicultural systems in coastal montane forests. Damage from wind was monitored for six years post-harvesting.

Methods

Study Area

The study area is in the Iron River Operation of Weyerhaeuser’s North Island Timberlands Division, south of Campbell River. The site is a gently sloping, northerly aspect at 750 m to 850 m elevation within the Montane Moist Maritime Coastal Western Hemlock (CWHmm2) biogeoclimatic variant. The old-growth forest consisted of predominantly western hemlock (*Tsuga heterophylla*) and amabilis fir (*Abies amabilis*), with varying amounts of western redcedar (*Thuja plicata*) and yellow-cedar (*Chamaecyparis nootkatensis*). Overstory trees in the multi-canopied stand ranged from 200 to 800 years old. Pre-harvest characteristics of the old-growth forest were examined in detail, including: forest inventory, stand age, site series, soil physical and chemical properties, microclimate and forest birds (Beese, Sandford and Toms 1995).

Experimental Design

The experiment includes silvicultural systems representing a range of overstory removal (three replicates each): a uniform shelterwood and two variations of clearcutting—small patch cuts and green tree retention. Adjacent to these treatments is a 69 ha clearcut and a 20 ha old-growth baseline monitoring reserve (Figure 1). The three replicates of each of the three clearcut-alternative systems were allocated to a 94-ha area by dividing it into nine roughly equal blocks and three groups of three, west to east. Each replicate occupies an area ranging from 8.6 ha to 11.5 ha. Treatments were assigned randomly within each group with one constraint: two green tree retention treatments could not be adjacent, creating a larger opening. Three pseudo-replicates were established in the center of the clearcut and old-growth areas.

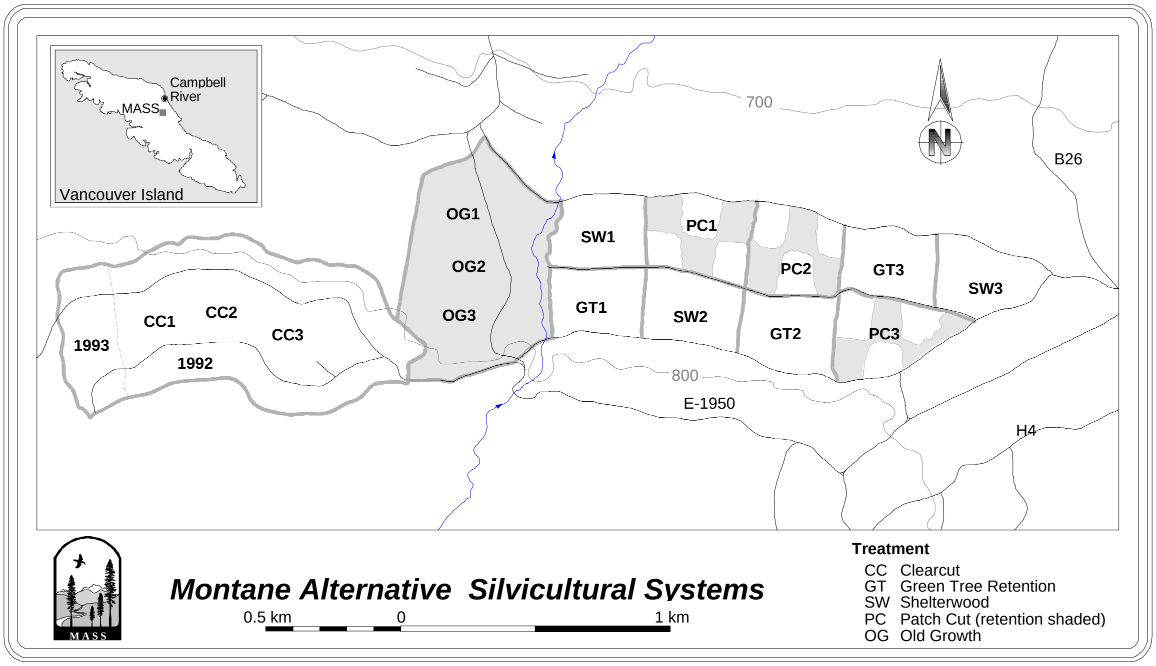

Figure 1. Study area layout**.**

Silvicultural Systems

The treatments represent a gradient of microclimatic conditions and residual forest cover for regeneration protection and wildlife habitat. Each was designed with specific goals.

Clearcut. A 69-ha area was harvested over a two-year period with two adjacent clearcuts to provide a large clearcut for comparison to alternative systems.

Patch Cut. Small cutblocks (1.5 ha to 2 ha) were designed with alternating leave-strips so that regeneration is within two tree lengths of an edge. This provides seed-fall and protects regeneration against snow, wind and temperature extremes. The remaining 50% of the stand will be harvested in 20 years.

Green Tree Retention. The goal of this treatment was to leave 25 trees/ha uniformly distributed in small cutblocks to enhance the structural diversity of future stands for wildlife and aesthetics.

Shelterwood. Trees representing the entire stand profile and 30% of the basal area (200 sph over 17.5 cm DBH) were left throughout the stand. This system provides protection for regeneration against snow, wind and temperature extremes, and enhances the structural diversity of future stands for wildlife and aesthetic values. If feasible and economical, a portion of the leave trees will be recovered when regeneration is established, leaving up to 25 wildlife trees per hectare. The second option is to leave all residual trees for the entire rotation, creating a multi-aged “irregular” shelterwood.

Harvesting

Most of the clearcut was harvested in 1992. The rest of the clearcut and all other treatments were harvested between May and November of 1993. A hydraulic log loader was used to forward or swing the logs from stump to roadside. Hoe-forwarding is the method of choice for yarding timber on gentle slopes. Although this type of logging system has been employed in partial cut treatments of second-growth stands it had not been used before for partial cutting old growth in coastal B.C. In the shelterwood, access corridors up to 20 m wide were placed perpendicular to main roads at a maximum spacing of 120 m. Trees were hand-felled and removed from corridors before felling trees toward them from the surrounding stand. Ground skidding was used in conjunction with hoe-forwarding in the shelterwood to yard wood from corridors to the main roads. A detailed description and cost analysis of the harvesting was completed by the Forest Engineering Research Institute of Canada (FERIC) and was published by FRDA (Phillips 1996).

Windthrow measurements

Wind damaged trees from the previous season were tallied annually in July within the shelterwood and green tree retention blocks, along the boundaries of the patch cut and clearcut blocks, and within the old-growth reserve. Tree canopy class, species, estimated height and diameter, direction of fall, wind damage type (windthrown, leaning or broken stems) and probable causes were recorded. Each tree was painted with the year and a sequential number to avoid duplicate tallies.

Results and Discussion

Wind and snow damage occurred to leave-trees and stand edges in all treatments. Most of the wind damage was windthrow (i.e., uprooted stems), but there were also broken and leaning stems. Snow contributed to an unknown portion of the total damage. For this discussion, windthrow refers to all categories of wind or snow damage. After six seasons (up to July 1999), the green tree (GT) treatments lost about 8 stems per ha (sph) or 29% of the leave trees to damage and the shelterwood (SW) treatments lost 21 sph (10%, Table 1). The patch cut (PC) and clearcut (CC) treatments lost the equivalent of 6 and 9 sph, respectively. Trees in the sparse GT retention treatment appeared to be the most vulnerable to wind damage; however, the shelterwood treatment resulted in a greater number of windthrown stems because of the higher density of retention.

The pattern and direction of windthrow was consistent with wind patterns observed during the six assessment years (Figure 2). The most prevalent direction of windthrow over the six seasons was to the northwest, which is consistent with prevailing winds from the southeast. The northwest corner of the clearcut had the greatest fetch for southeasterly winds, resulting in the worst damage of any edge. Virtually no windthrow occurred along the north-facing edge of the clearcut. Wind speed was recorded at the eight weather stations located at MASS; a typical season is given in Table 2. Average winds were from the south to southeast. The highest average wind speed and maximum wind speed were recorded at the two stations in the clearcut. While the lowest wind speeds were recorded in the shelterwood blocks, the patch cuts also appear to provide considerable protection from high winds.

Windthrow decreased for the first three seasons after harvesting, particularly in the shelterwood where 84% of the windthrow occurred in the first year and windthrow in the third year was negligible. In the adjacent old growth (OG), only two recent windfalls were observed in the entire 20 ha area. At the start of the fourth season, a 25-year storm on October 17, 1996 blew down 325 trees. Winds were from the southeast and remained strong from 9 a.m. to 5 p.m., reaching nearly 9 m/sec (32 km/hr) at 3 m height in the clearcut. Speeds would be much greater at the top of the tree canopy than those recorded by the 9 weather stations. Sensors stalled on 5 of the stations during peak winds. Of the functional stations, wind speeds at 3 m were greatest in the clearcut, considerably lower in the shelterwood (SW2), and remained light in the old growth. This storm doubled the cumulative windthrow in the shelterwood (9.5 sph damaged in the storm) and increased windthrow in the green tree blocks by 36% (2.4 sph). Surprisingly, there was no significant windthrow on the edges of the patch cuts (0.1 sph) and clearcut from this storm. Windthrow in the old growth was not assessed immediately after the storm, but was found to be minimal during the annual summer measurement.

Table 1. Total wind-damaged trees after six seasons.

			Wind damage (stems/ha)							Reserves	
Block	Treatment	Area (ha)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Total	stems/ha	% damage
92 (1)	CC	58.5	-	4.6	0.1	0.0	0.0	0.0	4.8	-	-
93 (2)	CC	10.6	-	11.9	0.0	1.1	0.0	0.4	13.4	-	-
Mean	**Clearcut**		**n/a**	**8.3**	**0.0**	**0.6**	**0.0**	**0.2**	**9.1 a**	**n/a**	**n/a**
SE				**3.6**	**0.0**	**0.5**	**0.0**	**0.2**	**4.3**		
1	GT	8.6	3.8	1.6	0.2	1.6	0.1	0.1	7.6	17	34
2	GT	9.7	3.4	2.1	0.7	0.2	0.0	0.2	6.6	20	23
3	GT	9.0	3.9	2.7	0.4	3.1	0.2	0.0	10.3	28	31
Mean	**Green Tree**		**3.7**	**2.1**	**0.5**	**1.6**	**0.1**	**0.1**	**8.2 a**	**21.7**	**29.4**
SE			**0.2**	**0.3**	**0.1**	**0.8**	**0.1**	**0.1**	**1.1**		
1	PC	5.9	-	2.2	0.3	0.2	0.2	0.8	3.7	-	-
2	PC	5.4	-	7.4	0.7	1.7	0.0	1.1	10.9	-	-
3	PC	5.7	-	1.4	0.9	0.9	0.5	0.4	4.0	-	-
Mean	**Patch Cut**		**n/a**	**3.7**	**0.7**	**0.9**	**0.2**	**0.8**	**6.2 a**	**n/a**	**n/a**
SE				**1.9**	**0.2**	**0.4**	**0.2**	**0.2**	**2.3**		
1	SW	9.4	12.0	1.2	0.1	6.9	0.7	0.3	21.3	207	10
2	SW	9.5	9.5	1.6	0.4	6.5	1.2	0.4	19.6	232	8
3	SW	8.7	9.3	1.8	0.0	9.5	0.3	0.8	21.8	178	12
Mean	**Shelterwood**		**10.3**	**1.5**	**0.2**	**7.7**	**0.7**	**0.5**	**20.9 b**	**205.7**	**10.3**
SE			**0.9**	**0.2**	**0.1**	**0.9**	**0.2**	**0.1**	**0.7**		
	Old growth	20.0	-	-	-	1.1	0.0	0.3	1.4	-	-

Notes: Year 1 = Nov 93 - Aug 94, Year 2 = Sep 94 - Jun 95, Year 3 = Jul 95 - Jun 96, Year 4 = Jul 96 - Jun 97, Year 5 = Jul 97 -Jun 98, Year 6 = Jul 98 - Jun 99. Wind damage was primarily windthrow, but also included trees that were broken or had excessive (>45 degree) lean. Data for Clearcuts in Year 2 includes all post-harvest damage; the 1992 block has an extra season. Windthrow assessments in the Old Growth for the first three years were done on sample plots; no windthrow was recorded within plots but some was observed outside of plots. The entire Old Growth area was surveyed beginning in Year 4; data reflects current season windthrow and is not cumulative.

Total windthrow treatment means not followed by the same letter are different at $\underline{P} < 0.05$ using a Tukey-Kramer test.

Figure 2. Direction of windthrow at MASS study area. Red arrows in diagrams are proportional to the percent windthrow by orientation.

Table 2: Wind data recorded for Year 5 (July 1, 1997 to June 31, 1998).

Treatment block	Avg. wind speed (m/sec)	Avg. Max. wind speed (m/sec)	Avg. wind direction (°)
CC1	1.7	3.7	not available
CC3	1.8	4.4	176
GT2	1.0	2.9	165
GT3	0.9	3.2	156
PC1	0.7	2.4	186
PC2	0.6	2.1	198
SW2	0.5	1.9	170
SW3	0.4	1.6	159

Source: R. Benton, Canadian Forest Service

Table 3. Summary of wind damage attributes by treatment.

Attribute	**Clearcut**		**Green Tree**		**Patch Cut**		**Shelterwood**	
	%	SE	%	SE	%	SE	%	SE
Windthrow Damage Type (% of wind damaged trees)								
Uprooted	89	2.2	90	1.0	83	6.3	85	3.1
Broken	9	2.4	8	0.5	16	6.2	11	1.8
Leaning	2	0.2	2	0.6	1	0.6	4	1.3
Contributing Factors (% of wind damaged trees)								
Wet soil	20	0.4	14	2.6	13	5.6	10	1.3
Shallow roots	6	4.8	2	2.6	10	1.4	3	0.1
Small root mass	15	5.9	14	4.2	20	8.6	7	2.9
Rooting in woody	4	1.6	6	1.5	8	1.5	3	1.9
Damaged roots	0	0	5	4.0	0	0	6	1.2
Hit by another tree	45	1.4	5	2.8	24	8.0	28	0.5
Decayed wood (stem)	3	0.7	12	3.4	4	3.0	12	4.0
Unknown	24	1.6	43	3.3	37	1.9	33	2.6
Crown Class (% of leave-trees in Crown Class damaged)								
Dominant	n/a		47	18.8	n/a		17	3.4
Codominant			44	0.0			10	1.1
Intermediate			33	4.2			9	1.9
Suppressed			10	2.9			9	0.8
Species (% of leave-trees by species)								
Ba	n/a		35	4.8	n/a		12	1.5
Hw			28	2.2			9	1.5
Cw			16	8.1			4	1.5
Cy			21	7.1			13	4.6

Table 4. Summary of wind damage by height and diameter classes for the Green Tree retention blocks

	Classes	n	%	SE
Diameter	0<=17.5 (cm)	88	7	6.6
	>17.5–35	316	29	2.4
	>35–52.5	213	36	2.8
	>52.5–70	85	38	6.4
	>70–87.5	41	29	6.3
	>87.5–105	27	15	6.4
Height	<= 15 (m)	257	11	2
	>15–20	96	31	6.1
	>20–25	104	48	6.4
	>25–30	120	44	6.1
	>30–35	115	38	3.3
	>35	78	21	8.2

Note: n = number of reserves; SE = Standard Error

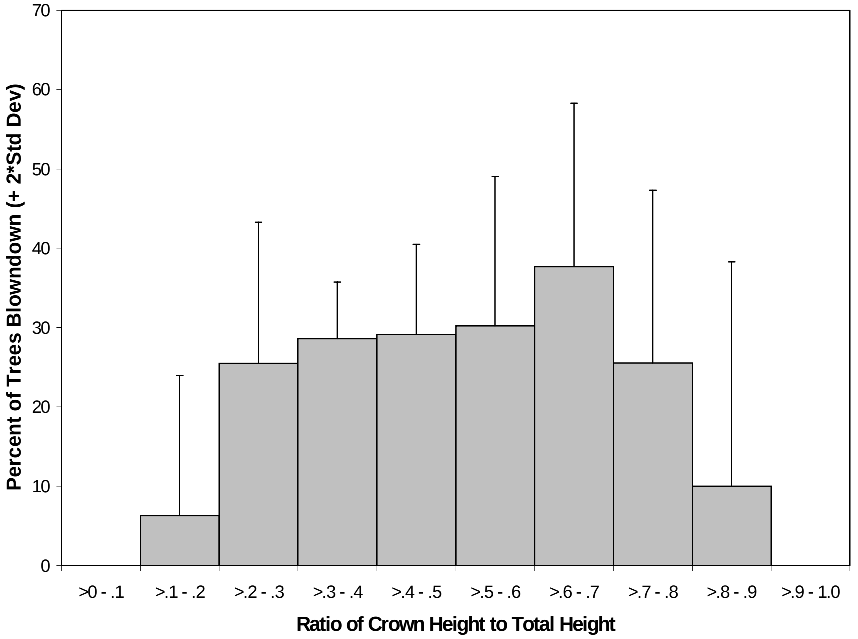

Figure 3. Windthrow in green tree retention areas by crown height to total height ratio.

Wind damage was analyzed by type, contributing factors, crown class and species for all treatments (Table 3). Uprooted and leaning trees accounted for 84 to 92 % of the damage in all treatments. The remaining trees were broken at various contributing factors. A "domino effect" was particularly evident for windthrow at the edge of the clearcut where nearly half of the trees were recorded as being hit by other trees. Although trees in the intermediate crown class had the greatest total number of windthrown stems, the proportion of windthrow was greatest among dominants in both the green tree and shelterwood treatments. Western redcedar appeared to be more windfirm than either amabilis fir or western hemlock on well-drained soils. Only 7% of cedar leave trees were lost to wind damage over six seasons, compared to 13% for hemlock and amabilis fir combined in the SW and GT treatments. There was no apparent difference in windfirmness between western hemlock and amabilis fir. Windthrow was fairly evenly distributed across diameter classes, except for the smallest (< 17.5 cm) and largest (>87.5 to 105 cm) classes. The extremes appeared to have less windthrow. Trees less than 15 m tall had a smaller percentage of windthrow than all other height classes. The amount of live crown was not a significant factor contributing to windthrow at this site.

The proportion of damaged trees by height, diameter and the ratio of crown length to total height was compared for the GT retention treatment where a complete tree inventory was done (Table 5). Windthrow was fairly evenly distributed across diameter classes, except for the smallest (< 17.5 cm) and largest (>87.5 to 105 cm) classes. The extremes appeared to have less windthrow. Trees less than 15 m tall had a smaller percentage of windthrow than all other height classes. The amount of live crown did not appear to be an important factor contributing to windthrow (Figure 3).

Conclusions

Windthrow remains a key concern for retaining various levels of forest canopy in coastal B.C. The MASS site was not considered a high risk site for windthrow, yet losses were substantial after six years. Windthrow was lower than anticipated along the edges of the patch cuts. This result suggests that group retention can reduce windthrow losses compared to dispersed, single-tree retention.

Setting stand-level goals for maintaining forest structure must be done in the context of landscape-level objectives. No single silvicultural system will meet all objectives; consequently, results from MASS are not meant to select a single "best" practice, but to improve our ability to predict the consequences of alternatives so that systems can be chosen to meet specific goals. Retention of relatively intact old-growth forest patches appears to be a more viable strategy for conservation of structural elements than uniform distribution of leave-trees to avoid losses to windthrow. This approach also appears to have cost and safety advantages. Nevertheless, each silvicultural approach will likely have site specific applications. Challenges to those designing silvicultural systems include: ensuring that regeneration and product objectives are met; minimizing windthrow and protecting regeneration during multiple entries; meeting wildlife needs without compromising worker safety and forest health; and thinking beyond traditional silvicultural systems to create innovative approaches.

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Wind Damage and Related Risk Factors for Interior Douglas-fir Leave Trees in Central BC

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The following is an extended abstract of a research paper currently being prepared for submission to a peer-reviewed journal in early- to mid-2001. For more information, please contact the author.

Interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) plays a unique ecological role in the fire-dominated sub-boreal forests of central British Columbia. Douglas-fir in the BC central interior typically occurs as a secondary or minor component in mixed-species, even-aged or two-aged fire-origin stands of lodgepole pine (*Pinus contorta* var. *latifolia*), hybrid white spruce (*Picea glauca*), and other species such as aspen and birch. However, the thick-barked Douglas-fir is the only sub-boreal tree species capable of surviving many of the high-intensity wildfires that kill other tree species in this forest type. Fire-scarred veteran Douglas-fir are common in many younger fire-origin stands; these Douglas-fir "vets" frequently have many valuable features for wildlife habitat, and are important seed sources for Douglas-fir in the surrounding area. Interior Douglas-fir is capable of growing to large sizes and great ages (300 to 500 years or more), and therefore is an important and distinctive element of stand structure, composition, wildlife habitat, and biodiversity in sub-boreal forests.

The unique ecological role of Douglas-fir (particularly larger, older trees) in these fire-dominated sub-boreal forests is increasingly being recognized by forest managers, both in stand- and landscape-level management objectives (BC Ministry of Forests and Ministry of Environment, 1995; Lousier and Kessler, 1999). In central interior BC, forest managers are increasing prescribing post-harvest retention of Douglas-fir leave trees for areas proposed for timber harvesting, to meet a wide range of non-timber management objectives, including visual quality, structural biodiversity, and wildlife habitat. Douglas-fir leave-trees are incorporated into a range of silvicultural systems, including clearcuts with reserves, variable retention, and occasionally, seed-tree system systems.

However, Douglas-fir retention practices have been controversial. Forest managers have concerns about the risk of wind damage to leave trees and expected stability of the residual stand. Operational experience has included numerous anecdotal reports of heavy wind damage to Douglas-fir leave trees in operational cutblocks in the BC central interior in recent years, sparking additional concerns about potential subsequent bark beetle risks and costs of timber salvage. Conversely, proponents of Douglas-fir retention tend to defend this practice, and there is dispute over the purported severity and extent of wind damage to these leave trees. Lacking throughout this vigorous debate has been any rigorous study or well-documented data on actual rates of wind damage in these Douglas-fir retention cutblocks.

This study was designed to address these diverse concerns through systematic post-harvest monitoring of wind damage incidence for Douglas-fir leave trees in range of operational cutblocks, and to identify possible future measures for windthrow mitigation. The following is a summary of these research findings.

Objectives

The two main objectives of this study are:

1. To better understand and quantify the effects of wind damage on Interior Douglas-fir in SBS retention silvicultural systems;
2. To develop windthrow management practices customized for Douglas-fir leave trees in the Central Interior.

The study examines several questions regarding high winds and wind damage incidence in the SBS zone. These are:

- How much wind damage to Douglas-fir leave trees is observed following harvesting in these SBS stands?
- Are certain types of Douglas-fir leave trees more or less resistant to wind damage?
- What prescriptive measures are most likely to reduce wind damage in future treatments?

Study Areas

The Sub-boreal Spruce (SBS) biogeoclimatic zone (Meidinger *et al*, 1991) occurs in the Nechako and Fraser plateaus and Fraser Basin from about 600 to 1100 metres elevation. This study includes the drier central and southeastern portions of the SBS zone between 53 and 55^{o} latitude. The climate of the SBS is continental: annual precipitation is 400 to 990 mm, while mean annual temperature ranges from 1.7 to 5^{o} C.

The study focussed on three specific study areas in the dry warm SBSdw2 and SBSdw3 subzones in the Prince George and Fort St. James Forest Districts (Table 1). Elevations range from 800 to 1050 metres, and encompass a wide range of slopes and aspects. In total 8 cutblocks logged between 1994 and early 1997 were monitored. These cutblocks examined range in size from 10 to 100 hectares. Douglas-fir leave trees were dispersed individually on these cutblocks, and leave-tree densities ranged from <5 sph to 70 sph (typically 20-40 sph).

Estimated wind exposure on these study sites ranged from moderate (Tako Creek) to high / very high (Pinchi Mountain, Mt. Baldy Hughes). Baldy Hughes site is an isolated large hill, rising well above the surrounding rolling plateau. The Pinchi site is located at mid- to upper slope on a south to west-facing high ridge. The Tako site is located on gently rolling terrain similar to the surrounding plateau. Wind station data for all these locations are summarized by Sagar and Jull (2001, this volume).

Soils of the study areas are generally typical of the range of conditions found on Douglas-fir sites in the SBS zone, including morainal veneers with silty-clay to silty loam textures, usually with compact basal till or dense Bt horizons at 30-45 cm depth. The soils of the Tako site are glaciofluvial sands, with low coarse fragment content. All sites are reasonably mesic and well drained with no perched water tables.

Methods

This study used the analytical sampling survey approach described by Schwarz (1998), following a two-stage sampling design. The first stage of sampling described the original post-harvest population of leave-trees following the initial harvest treatment, and initial levels of wind damage (if any). The second stage (monitoring) consisted of annual repeated examinations of the same permanent transects over time to examine potential changes in the rate and pattern of wind damage to Douglas-fir leave trees since harvest.

Monitoring commenced within a year (or less) of harvest in each cutblock, and any post-harvest wind damage prior to that date was recorded at that time. In each block, permanent 20-metre-wide belt transects were established at 100 metre intervals across the contour, and trees tagged. Annual assessments were carried out in the late summer or fall. Initial data collections on each transect recorded for each individual tree: species, diameter at breast height, height, live crown length, and presence of logging injuries or defects. All trees on the transect were tagged for future reference. For wind damage encountered on annual revisits of each transects, we recorded the type of wind damage (windthrow or wind snap as per Stathers et al, 1994), height of wind snap, direction of tree fall (from top to roots), live-crown length, and comments if any.

Sample sizes (number of cutblocks and leave trees sampled by study area) are summarized in Table 2.

For initial data analyses, wind damage data was combined for each cutblock and summarized by individual cutblock and study area. Rates of wind damage to Douglas-fir leave trees for all study areas were combined and summarized by tree size (dbh class and height class), and percent live crown to allow comparison of the wind-damaged cohort with the undamaged cohorts. Wind damage rates (in stems-per-hectare) were expressed as percent of the original post-harvest cohort; for example, if 150 trees in a given tree class formed the original leave tree population immediately following harvest, but subsequent surveys indicated 15 trees became wind damaged, wind damage rates would be expressed as 15/150 = 10.%.

Results

Based on our results to October 2000, post-harvest wind damage rates for Douglas-fir leave trees in the cutblocks studied ranged from 4 % to a high of 32%; the mean rate for all cutblocks and study areas was 10-11%. Of this wind damage, about 90% was windthrow (uprooting), with the remainder being windsnap.

Wind damage incidence for the Douglas-fir leave trees was not significantly correlated with either tree height or percent live crown. However, the data did indicate that that rates of Douglas-fir wind damage on these upland SBS sites are negatively correlated to tree diameter and positively correlated to height-to-diameter ratio (HDR).

For all study areas, wind damage rates decrease with increasing tree diameter. Wind damage rates to date generally have been highest in diameter classes less than 45 cm dbh, probably because these size classes tend to be lower-canopy trees with little taper and limited history of wind exposure. Wind damage rates are lowest (<5%) for diameter classes > 65 cm dbh, corresponding with dominant or "emergent" Douglas-firs with crowns well above the main canopy in the pre-harvest stand. The relationship of tree diameter to leave-tree survival and wind damage may also be related to the fact that tree HDR tends to decrease as diameter increases.

HDR appears to be a very useful predictor of expected Douglas-fir leave-tree stability. Leave trees with HDR's < 50 have loss rates of 3.9% overall, while leave trees with HDR's of 50-70 have loss rates of 10.7-11.4% over all sites. Slender leave trees are increasingly vulnerable to post-harvest wind damage, with wind damage incidence increasing to approximately 15% for HDR 70-90, and to >20% for trees with HDR >90.

Conclusions

1. Height-to-diameter ratio (HDR) of leave-trees appears to be a useful and robust indicator of potential post-harvest windfirmness for Douglas-fir leave-trees in drier subzones of the SBS. Douglas-fir with HDR <50 have low rates of post-harvest wind damage, while leave tree classes with increasing HDR have progressively increasing levels of wind damage. For forest managers, HDR is recommended as a useful tool and key criterion for identifying windfirm leave trees on sites to be harvested, and can potentially be used in combination with other criteria such as tree diameter.

2. Tree height and percent live crown are poorly correlated with wind damage incidence, and therefore not recommended as primary criteria for selection of windfirm Douglas-fir leave-trees.

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TABLE 1: Summary of Site and Stand Attributes of Douglas-fir retention cutblocks monitored.

STUDY AREAS	BEC Subzone	Elevation (m)	Aspect	Forest District	Density of Fd Leave Trees > 20 cm dbh
Tako Creek	SBSdw2	780	Neutral	Pr. George	35-71 sph
Pinchi Mtn.	SBSdw3	900-1000	SW-W	Ft. St. James	5–63 sph
Mt. Baldy Hughes	SBSdw3	910-1050	NE-SE	Pr. George	14-48 sph

TABLE 2: Sample sizes by study areas and number of leave trees monitored.

STUDY AREAS	# of Cutblocks	# of Fd Leave Trees
Tako Creek	1	203
Pinchi Mtn.	4	429
Mt. Baldy Hughes	3	385

Windthrow Patterns on Cutblock Edges and in Retention Patches in the SBSmc

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Abstract

Twenty-five transects across 9- to 21-year old cutblock edges in fir-spruce-pine forests of the SBSmc subzone were sampled for windthrow, mensuration, and vegetation attributes. Sampling was conducted in 129 200 m^2 rectangular plots arranged with their long axis parallel to the stand edge, and results are expressed relative to conditions found in the forest interior (>106 m from the nearest edge). Background levels of recently fallen trees averaged 6.5% of all stems. These rates increased to 11.1% at north-facing edges and to 24.0% at south-facing edges. Elevated levels of windthrow (expressed as a percentage of all stems) extended 84 m into the standing timber north of south-facing cutblock edges. Fallen trees had average height-to-DBH ratios greater than 69:1, a threshold lowered at stand edges. Selective thinning (of stems with large height-to-DBH ratios) and salvage could minimize timber losses at stand edges.

Wildlife tree patches have been prescribed in the SBSmc since the early 1990's, but such small reserves of green trees may be dominated by edge effects. We sampled 31 4- to 9-year old wildlife tree patches using 77 plots. Windthrow in the centre of patches ranged from 0% to 58%, averaging 13% in small (<33m across) patches, 6% in medium (34 to 60 m across) patches, and 5% in large (>60m across) patches, compared to 10% at nearby stand edges and 3% in the forest interior. There was a marked concentration of windthrow on the south or southwest side of patches, reflecting the direction of prevailing winds. This pattern suggests laying out elliptical- or teardrop-shaped retention patches, with the long axis in the direction of prevailing winds, in order to minimize total windthrow losses.

Introduction

Clearcut harvesting of timber creates a severe contrast in environmental conditions at the new boundary between open and forested terrain. Such newly created transition zones are characterized by a suite of biophysical conditions broadly described as "edge effects" (Murcia 1995, Voller 1998). Edge effects become an increasingly important set of phenomena wherever logging is dispersed and outstrips the rate of forest recovery, resulting in a fragmented landscape. Because trees which grew up in the middle of a stand are now exposed to open conditions, their allometry and rooting patterns are usually poorly adapted to the newly created stand edge, and this typically results in levels of wind-induced treefall (windthrow) much greater than background (forest interior) conditions. Indeed, windthrow is one of the most pronounced effects of forest edge creation in boreal, temperate and tropical biomes (Chen et al. 1992, Laurence et al. 1997, Esseen & Renhorn 1998). In addition, wind-induced canopy thinning is one of the principal mechanisms by which edge contrasts are softened over time.

Green-tree patch retention has recently become a widespread method for providing structural diversity and coarse-filter biodiversity conservation within large clear-cuts (Coates & Steventon 1995, Franklin et al. 1997). But there is concern that these small islands of mature trees (often called wildlife tree patches) are dominated by edge effects. By the same mechanisms explained above for stand edges, it is widely observed that a large proportion of the reserved trees blow over within a few years (Esseen 1994).

This analysis of edge-associated windthrow in mature and old forests of the moist cold subzone of the Sub-Boreal Spruce biogeoclimatic zone (SBSmc) of northwest-central British Columbia was undertaken as part of a larger project documenting edge effects on a wide suite of vegetation attributes (Burton 1999, Burton *submitted*). The objectives of this component of the study were to: (1) document the significance, magnitude and extent (distance) of windthrow losses in stands adjacent to clearcuts; (2) identify thresholds of size or allometry that might denote windthrow susceptibility for different tree species; (3) determine the degree to which windthrow within retention patches are related to patch size and distance from uncut forest; and (4) recommend management practices that could minimize harvesting-associated windthrow in SBSmc forests.

Methods

A full description of the study area and details of the sampling design and statistical analysis are provided in Burton (*in review*). Sampling was restricted to mature and old forests dominated by subalpine fir or hybrid white spruce in the SBSmc subzone of the Morice and Bulkley Forest Districts. Over the last several decades, the disturbance regime of these forests has been dominated by clearcut logging, with cutblocks artificially regenerated to promote second-growth stands of conifers.

Sampling for cutblock edge effects was limited to those habitats most likely to exhibit strong responses to edge creation: straight forest-cutblock boundaries running east and west ($\pm 30^o$ azimuth), on level terrain (<15 % slope), with apparently identical ecosystems and forest cover types on either side of the boundary prior to logging which took place approximately 10 to 20 years previously. We rejected forest stands <80 years or >250 years of age, and sites for which reasonable access by road and foot was not possible. Twelve edges, at elevations from 810 to 1031 m, were chosen for sampling from a total of 114 suitable candidates, screened from a pool of 535 cutblock boundaries of the desired age.

Blocks with retention patches were evaluated in a similar manner, with consideration given to patch size and patch distance from intact forest. Green-tree retention prescriptions only started in the early 1990's, so all sampled patch retention blocks were only 4 to 9 years old since logging. The total population of more than 180 patches in 66 cutblocks logged during the desired time interval was inspected to identify three classes of patch size (small = 20 to 33 m across their north-south axis, medium = 34 to 60 m across, or large >60 m across) and three classes of distance from the nearest intact forest edge (near = 30 to 60 m, medium = 61 to 120 m, or far, >120 m). Our goal was to sample at least three patches of each combination of size class and distance class. Some patches that did not meet all orientation criteria for the sampling of north-south gradients within them were sampled with a single plot in their centre. A total of 31 patches were sampled in 18 cutblocks, ranging in elevation from 808 to 1200 m.

Twelve stand edges (six south-facing and six north facing) were sampled with 25 transects running from the centre of each clearcut, perpendicular to the stand edge, deep into the forest interior (Burton *in review*). Each transect was anchored by a plot in the forest interior located 105 to 290 m from the nearest opening. The inner edge of south-facing edges was intensively sampled with an array of adjacent plots, while north-facing edges were usually sampled with one plot at the cutblock boundary and an interior plot. Rectangular sample plots were 200 m^2 in area, with their long axes laid out parallel to the stand edge. Plots measured 20 m x 10 m during the first year of sampling (1996), and 30 m x 6.67 m in the second and third years. Five to nine contiguous plots were located in the first 50 to 90 m north of the edge.

In blocks sampled for green-tree retention patches, a plot was situated in the centre of the patch, several adjacent plots south (and sometimes north) of the centre plot within the patch, in a nearby forest interior, and sometimes at the edge of nearby forest. Very small patches or those with a curved boundary sometimes required plots less than 30 m long, for which density estimates were adjusted accordingly. Over three years of sampling, 34 plots sampled deep forest interiors, 95 plots sampled various positions along the inner edge of forest stands, and another 77 plots were situated within retention patches.

All trees >7.5 cm DBH in each plot were recorded by species and DBH. Tree height and height to the base of the live crown were determined (using a clinometer) for three representative trees per plot. Dead and fallen trees were recorded as well, limited to those stems originating within the sample plot. The directional orientation and mode of falling (uprooting or "tip-up", butt rot or "rot," and stem breakage or "snap") were also recorded for recently fallen trees. “Recent” treefalls are defined as those estimated to have fallen since logging occurred nearby. Wood volume of both standing and fallen stems were estimated using allometric equations reported in Burton (*in review*).

A wide range of tree-related response variables were tested for measurable edge effects in Burton (*in review*). Windthrow responses are expanded upon in this paper, with a search for correlative environmental factors, and evaluations made within and among retention patches. Furthermore, the cutblock edges dataset reported here includes forest edge and interior plots sampled near some of the retention blocks (and hence includes some younger edges), which were not included in the Burton (*in review*) analysis. Following Chen et al. (1995), edge analysis was designed to both measure the significance of edge effect (SEE) and the depth of edge effect (DEE). Analysis of variance using SAS procedure GLM (SAS Institute 1988), with transects nested within edges as a blocking factor, was first used to determine if a response variable in plots immediately adjacent to the forest-clearcut boundary (<10 m from the edge) was significantly different from its value in the forest interior (>106 m from the cutblock). The contrast between edge and interior conditions is described in terms of the magnitude of edge effect (MEE), which is simply the ratio of the larger value to the smaller value. In all cases, separate analyses were conducted for south-facing and north-facing edges.

Regression analysis was used to infer the distance at which response attributes could not be distinguished from background (interior) levels. As a first approximation of the edge response function, linear regression was used to describe the relationship between each attribute and distance north of the edge, excluding any interior plots from the analysis. To determine DEE (in m from the stand edge), y in the equation for a straight line, $y = a + bx$, was set to the mean background level of a given attribute, and the equation was then solved for x (where a is the y-intercept and b is the slope).

Analysis of data collected in retention patches consisted of both hypothesis-testing and descriptive methods. Two-way analysis of variance (SAS procedure GLM) tested for the effects of patch size and patch isolation and the interaction of these two factors on windthrow density. Following the criteria for patch selection, this analysis tested three classes of patch size (small, medium and large) and three classes of distance from the nearest intact forest (near, mid and far) on the windthrow levels observed at patch centres. A third statistical evaluation of retention patch attributes included only those patches sampled by more than one plot, arrayed in a north-south transect through the centre of the patch. These transects of plots were assessed using the same methods employed at cutblock edges, in order to estimate SEE, MEE, and DEE within patches, in order to compare these patterns with those found on the edges of intact forest.

Results

Windthrow at Cutblock Edges

Sampling of the most interior forest plots revealed mean densities of 1409 canopy stems per ha (sph), with trees averaging 19.8 cm DBH and 23.8 m in height, for a mean basal area of 56.7 m^2/ha and mean stand volume of 498 m^3/ha. Interior trees had an average height-to-dbh ratio of 69.5 to 1, with mean live crown ratios of 59.5%. Stand interiors were dominated by subalpine fir (averaging 66% of the stems), with lower densities (19%) of hybrid white spruce and lodgepole pine (14%). Background levels of recently fallen trees averaged 6.5% of all stems, while dead and dying trees constituted an average of 12.0% of all upright stems. In forest interiors, 7.0% of all fir stems are likely to have fallen recently, as are 9.5% of spruce and 1.4% of pine stems. Approximately equal numbers of recently fallen trees had snapped off above the ground (49.2%) or tipped up with a full root plate (44.9%), while relatively few (5.9%) originated from butt rot. The height-to-DBH ratio of fallen trees in forest interiors averaged 78.1 to 1, significantly higher than that of standing trees (F=5.35, p=0.0224).

Many of these stand attributes were altered in edge plots, though not significantly so at north-facing edges. In general, fewer stems (and consequently lower basal areas and wood volumes) were left in the canopy at edge plots, primarily because of increased numbers of recently fallen trees. Fallen trees typically had height-to-DBH ratios greater than 69:1, while most standing trees (except pine) had height-to-DBH ratios of less than 69:1. Fallen trees in edge plots included more individuals with lower ratios (Figure 1). Most remarkable is the trend observed for hybrid white spruce, generally considered prone to windthrow: fallen spruce trees in the forest interior tend to have height-to-DBH ratios greater than 88:1, or ratios greater than approximately 71:1 at stand edges (Figure 1). Fallen subalpine fir height-to-DBH ratios averaged 76.5:1 in stand interiors and 73.5:1 at stand edges (Figure 1). Fewer lodgepole pine trees were encountered, and hence their height-to-DBH ratios were more variable and are difficult to interpret.

Larger numbers of standing dead trees were typically observed in edge plots, though the live crown ratio of living trees was often greater than in the forest interior. These trends resulted in statistically detectable (at p=0.05) edge effects only for direct windthrow and canopy stem attributes on south-facing edges (Table 1). The magnitude of edge effect (MEE) was over 3.3 for the amount of windthrow, and over 1.4 for residual stand attributes (density, basal area and stem volume). Very high (>3.0) MEE values were also noted for increased proportions of sick and dying trees, decreased proportions of windthrow originating as snapped boles, and higher proportions of spruce trees having fallen on south-facing edges.

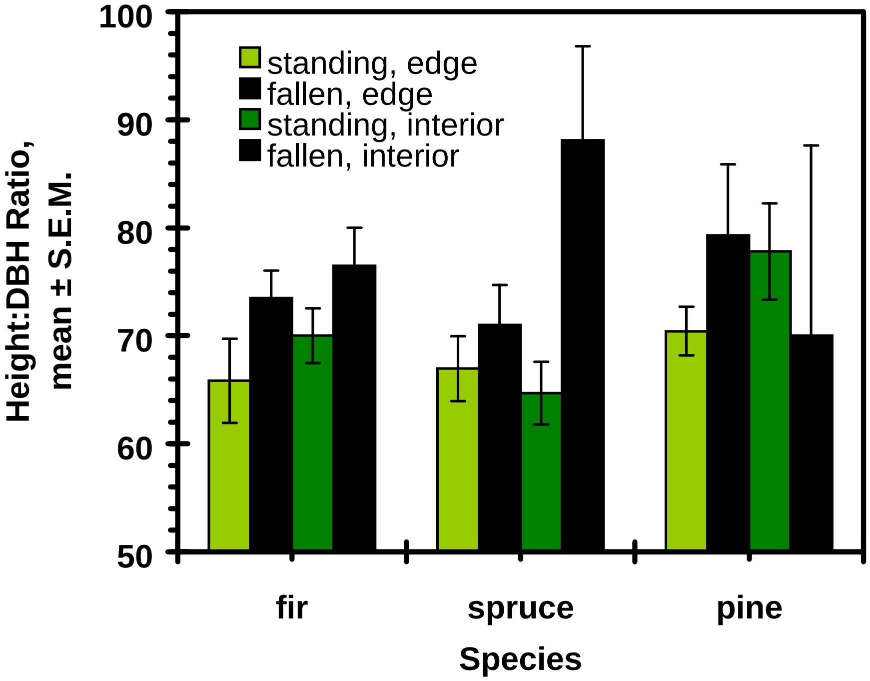

Figure 1. Height-to-DBH ratios of standing and fallen trees sampled at all edge plots (<10 m from clearcut) and at all forest interior plots (>106 m from the nearest clearcut).

Significant linear regressions were obtained for several measures of windthrow, with estimates of the distance of edge effect (DEE) ranging from 76 to 85 m at south-facing edges (Table 1). Regression analysis further suggests that some stand attributes, such as the mean DBH of fallen trees and the proportion of spruce stems to collapse, are altered for more than 115 m into the uncut forest at south-facing edges.

Windthrow at the Centre of Retention Patches

Windthrow in the centre of retention patches ranged from 0% to 57.7%, averaging 13.1% in small patches, 6.3% in medium patches, and 5.1% in large patches, compared to 10.1% at nearby stand edges and 3.1% at comparable forest interior sites (Figure 2). Patch distance from the nearest forest edge had a less pronounced effect on windthrow: far patches had 6.8% of their stems toppled, mid-distance patches 9.3%, and near patches 9.2%. Two-way analysis of variance failed to detect a significant effect of size, distance from the cutblock boundary, or their interaction.

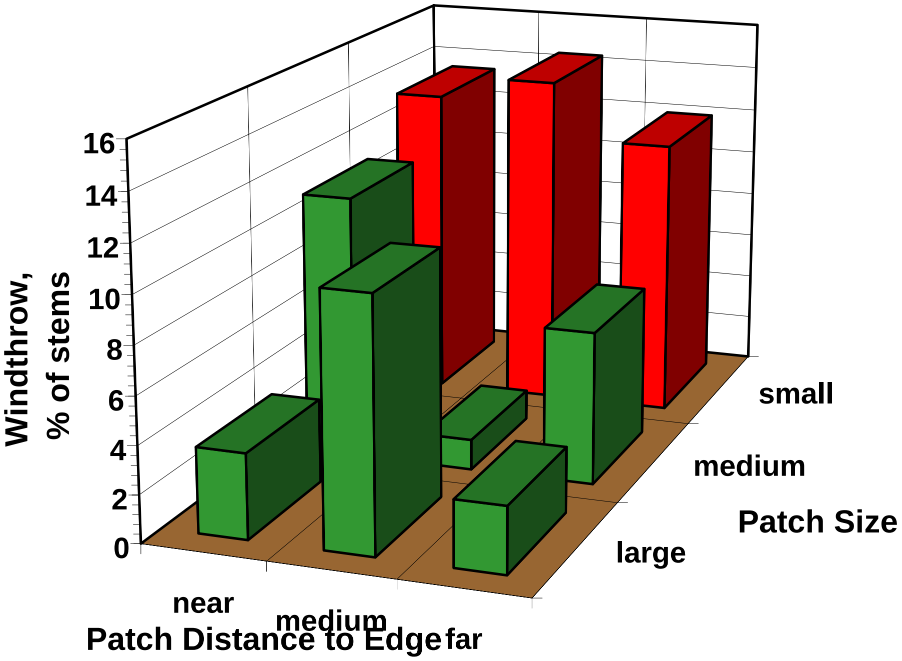

Figure 2. Mean windthrow in the centre of green-tree retention patches, expressed as a function of patch size and patch distance to the nearest forest edge; small patches showed marginally greater windthrow when tested by one-way analysis of variance (F=2.92, p=0.0702), but no significant effects were detected by two-way analysis of variance.

The only features significantly correlated with windthrow in the middle of retention patches were the maximum width of the patch and the width of the patch in the direction of prevailing winds. One-way analysis of variance detected no significant differences in percent windthrow among patch, edge and forest interior plots, but revealed much greater original (pre-windthrow) densities in patches, because most of those trees were smaller than found in undisturbed forest. That is, most green-tree patches left in the mid-1990's were dominated by smaller than average trees and cannot be considered representative islands of mature forest.

Windthrow Patterns Within Retention Patches

Transects of plots through 11 retention patches revealed patterns of windthrow similar to that found on cutblock edges: a concentration of losses at south-facing edges, with reduced windthrow further into the patch, though some treefall was observed on all sides of the perimeter. On average, small patches (averaging 25.5 m across) exhibited 18% to 25% windthrow throughout; medium-sized patches (averaging 45.3 m across) experienced windthrow as high as 32% on south-facing edges, but also had a sheltered zone with average windthrow under 10%. This sheltered area dominated large patches (averaging 83 m across), and included a zone in which windthrow averaged 3%, the same as in nearby forest interiors (Figure 3). Windthrow patterns within patches differing in their distance from intact forest exhibited no consistent trends and are not presented here.

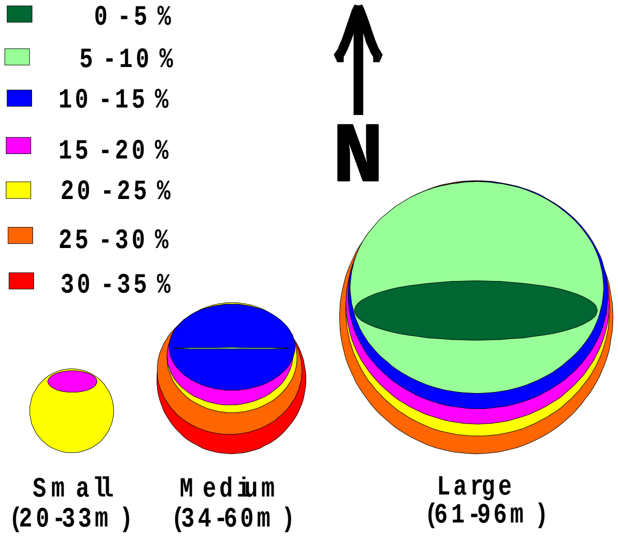

Figure 3. Average patterns of windthrow (% of stems >7.5 cm DBH) observed within 31 4- to 9-year old wildlife tree patches sampled in the SBSmc of the Morice and Bulkley Forest Districts; schematic patches are drawn to scale for the average north-south dimension in each size class.

Discussion

Managing Windthrow at Cutblock Edges

Since the forest-cutblock edges were 4 to 21 years old at the time of sampling, most of them can be considered stabilized. Windthrow in edge plots showed some correlation with opening age at north-facing edges (especially for spruce, r=0.50, p=0.01, n=14), but not at south-facing edges. On south-facing edges, it appears that a brief period of elevated windthrow quickly removed the most susceptible stems. In the SBSmc of northwest-central British Columbia, prevailing winds are from the southwest (Figure 4), so no significant differences in residual tree density, basal area or fallen trees were detected in the inner edge of protected north-facing forest stands (Table 1). In contrast, highly significant canopy differences were detected at south-facing edges, ranging in magnitude from 1.4 to 1.7 times the background levels prevailing in forest interiors.

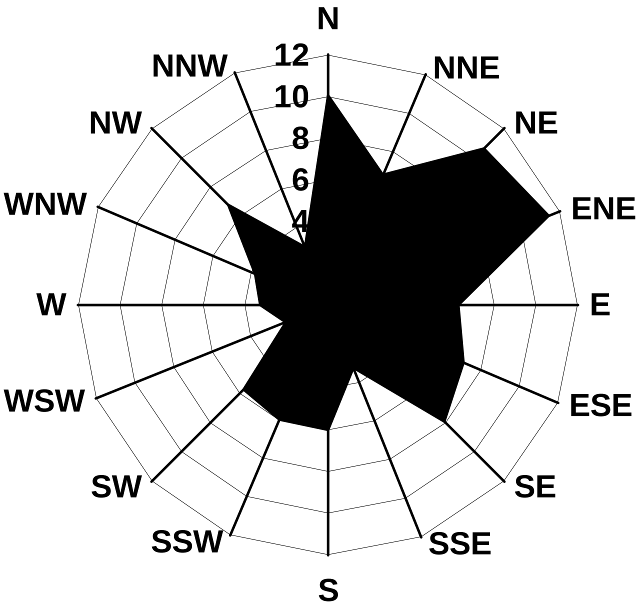

Figure 4. Frequency of windthrow (% of 368 fallen stems, >7.5 cm DBH) in 16 compass directions, SBSmc forest interior and patch centre plots only.

Though elevated densities of recently fallen trees were found 77 m into south-facing edges, some altered stand features (e.g., the height-to-DBH ratio of fallen trees) are predicted to extend up to 119 m north of cutblock boundaries. Since the upper quartile (25%) of trees in each interior plot averaged more than 25.9 m in height, elevated windthrow can be said to extend 3.0 to 4.6 tree heights into the uncut timber. With 42% of spruce trees having fallen in south-facing edge plots (compared to 16% of fir trees and 10% of pine trees), elevated windthrow has acted selectively to alter forest canopy composition up to 116 m (4.5 tree heights) from the edge (Burton *in review*).

Another aspect of the selective effects of wind is expressed in the height-to-DBH ratio of trees which have fallen compared to those which remained standing (Figure 1). Trees which had ratios greater than approximately 69:1 were likely to have been blown over in the first few years after logging, while those with stouter proportions were likely to remain standing. It is well accepted that taller trees, in general, are more susceptible to windthrow (Stathers et al. 1994, Quine 1995, Mitchell 1995), as are trees with proportionally slender stems (Ruel 1995). Given the incentive in British Columbia to prevent windthrow of commercially valuable timber or to salvage windthrown boles even after normal clearcut logging is completed, it might be worthwhile to selectively remove susceptible trees at south-facing edges when the cutblock is logged. For the purposes of discussion, I propose selectively harvesting edge trees (those within 10 to 20 m of south-facing edges) with height-to-DBH ratios greater than species-specific thresholds.

Trees should be 'marked-to-cut' by technical staff, and cutting must extend only to the approved cutblock boundary or have suitable administrative approval to avoid charges of trespass. Some of this pre-emptive salvage (often referred to as "edge feathering," Stathers et al. 1994) could be done with a feller-buncher reaching in from the cutblock edge, while the deeper trees may have to be hand-felled and yarded out by cable skidder or horse team. If one employed threshold height-to-DBH values midway between the mean values for standing and fallen trees in the SBSmc (69.7 for fir, 69.0 for spruce, and 74.9 for pine, as per Figure 1), one could effectively utilize the wood from most of the trees that would eventually fall (57% of the fir, 54% of the spruce, and 58% of the pine) while unnecessarily taking less than 42% of the trees that would likely remain standing (fir 42%, spruce 41%, and pine 33%). In order to prevent further windthrow, it is important to leave the remaining (or likely to remain) windfirm trees standing and undamaged so they can buffer the less robust trees in their lee (Stathers et al. 1994).

To minimize the problems of edge-associated windthrow in the SBSmc in the first place, it would also be a good idea for cutblock layout to avoid the creation of great lengths of uniform timber facing the south- through west-facing quadrants. Instead, natural breaks in topography and forest cover should be employed to feather and ramp cutblock boundaries so that naturally windfirm boundaries prevail (Stathers et al. 1994). My data also suggest that more windthrow occurs next to large cutblocks: for fir trees only, r=0.57 (p=0.02, n=16) for windthrow density as related to wind fetch (uninterrupted distance across the cutblock). Overall windthrow also showed a negative correlation with original stand density: r=-0.62 (p=0.01, n=16). So limiting the size of the cutblock and situating boundaries so a stand of high density (often younger than the stand being harvested) is left to form a windfirm edge should help minimize windthrow losses.

Managing Windthrow in Retention Patches

Green-tree retention patches larger than 33 m across were found to be intermediate in character between forest interiors and forest-cutblock edges. Retention patches suffered an overall average of less than 15% windthrow, in marked contrast to popular perceptions that newly exposed patches of mature conifers are inherently unstable and doomed to loose most standing trees. Patch size was found to be the single most important factor in determining the amount of windthrow within isolated patches of green trees left within SBSmc clearcuts. This interpretation is based on patches between 20 m and 125 m across (200 m^2 to 11,500 m^2 in area), and identified more windthrow in patches less than 900 m^2 (Figure 3). The primary importance of patch size was also concluded by DeLong et al. (*these proceedings*) in their analysis of a larger dataset, in which they distinguish patches greater or less than 1 ha in area. It is safe to conclude, therefore, that greater patch size generally helps reduce windthrow. Other features associated with lower windthrow in retention patches are reported in DeLong et al. (*these proceedings*).

Results from this study also demonstrate that edge effect gradients exist within green-tree retention patches as well as at cutblock edges. As at cutblock edges, the greatest losses were detected at south- or southwest-facing patch edges, while losses were minimal at the north- or northeast facing patch edges (Figure 3). The zone of elevated (>10%) windthrow appears to extend an average of 18 m to 32 m into the windward edge of these green-tree reserves. That windward edge quickly becomes a bit tattered and feathered, but after a few years it consists of stable trees which then protect the rest of the patch. It would be useful, therefore, to lay out wildlife tree patches with the long axis oriented in the direction of prevailing winds, and with the narrow axis at least 60 m across. Whether elliptical or teardrop-shaped (with the wide end facing into prevailing winds), patches laid out in this manner (Figure 5) would have the greatest chance of protecting the most trees with a windward edge consisting of relatively few trees that would be lost to windthrow. While other site factors (such as the presence of deciduous and other desirable wildlife trees, site exposure, likely difficulty in regenerating the spot if logged, etc.) must be considered too, this simple guideline for the shaping and orientation of new retention patches should help improve their stability and effectiveness.

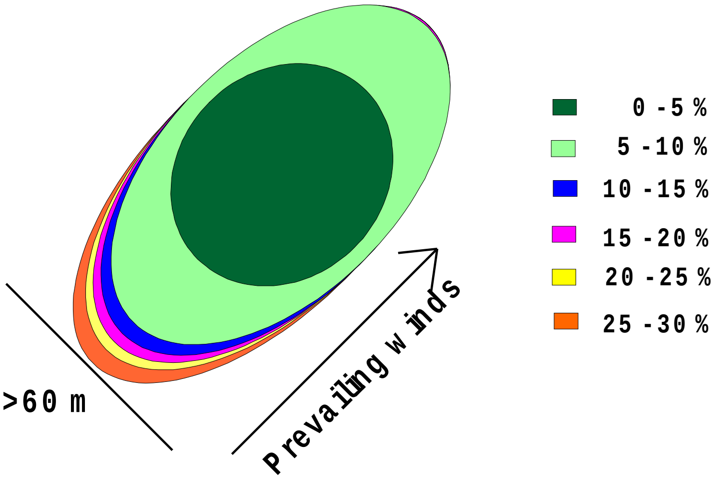

Figure 5. Recommended layout and expected windthrow (% of stems >7.5 cm DBH) for retention patches in the SBSmc. Optimal shape (elliptical vs. teardrop, etc.) remains to be determined, but the long axis should run in the direction of prevailing winds.

Conclusions

Clearcuts in the SBSmc had a much more pronounced effect on windthrow at south-facing forest edges than at north-facing edges, due to winds which blow predominantly from the southwest in the study area. Elevated windthrow densities (3.4 times that of background levels in the forest interior) extended 77 m (3.0 tree heights) into adjacent stands, though attributes such as the height-to-DBH ratio of fallen trees appear to have been altered up to 119 m (4.6 tree heights) into south-facing edges. Spruce showed a greater susceptibility to windthrow at edges than fir or pine, so windthrow has acted as an agent of selective mortality. Fallen trees typically had greater height-to-DBH ratios than standing trees of the same species, suggesting that species-specific taper thresholds can be used to selectively thin new stand edges for the purpose of windproofing them.

Elevated levels of windthrow at patch centres were found in patches less than 34 m across, but no effect of patch isolation from intact forest was detected. Patterns of windthrow within green-tree retention patches were similar to those observed on cutblock perimeters. Because windthrow decreases with increasing distance from the south-facing edge of these patches, reserves typically have to be more than 60 m across (in the north-south direction) in order to be dominated by conditions that result in less than 10% windthrow. Laying out patches with a long axis in the direction of prevailing winds should further minimize the overall proportion of stems to collapse as a result of windthrow.

These results indicate that the ecological footprint of cutblocks in the SBSmc can extend up to 119 m into the uncut forest north of clearcuts as a result of wind-induced treefall. While windthrow does not necessarily compromise the ecological integrity (productivity, diversity, resilience) of the affected zone, it must be recognized that the affected portions of remaining stands represent an altered set of habitat conditions. Foresters, forest planners and biologists must consider how the significance, magnitude and distance of edge effects affect the development and habitat values of adjacent stands and wildlife tree patches. Along with regional factors such as prevailing winds and site factors such as topography and soil moisture regime, these findings should help one design more appropriate sizes, orientations and configurations of cutblocks and reserves in order to leave stable cutblock boundaries, retention patches and forested ecosystem networks.

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Factors Affecting Windthrow in Reserves in Northern British Columbia

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Abstract

As part of a commitment to conserve biological diversity and better approximate natural disturbance regimes, reserves are being left in clearcut areas. A concern expressed by forest managers is that these reserves will experience unacceptable levels of windthrow leading to timber volume loss and an increase in bark beetle hazard. This talk summarizes 4 studies whose objectives included an assessment of factors affecting windthrow in wildlife tree patches and/or riparian reserves in an effort to develop guidelines for reserve design to reduce windthrow. Key factors that affected estimated windthrow were: time since harvest, reserve size, length to width ratio of reserve, total tree density in reserve, median diameter of trees in reserve, average moisture regime of patch, and mesoslope position. Reserves greater than 5 hectares had windthrow levels similar to those recorded in large contiguous areas of forest. Maximum level of recorded windthrow decreased from 100% to 25% for reserves less than and greater than 1 hectare, respectively. If it is necessary to design reserves less than 1 hectare, windthrow may be reduced by choosing stands that have any of the following characteristics: high tree density, small diameter stems, situated in gullies that are opposite to the direction of the wind, and/or whose thickness of the organic layer is less than 7 cm.

Background

Legacies of natural disturbance such as old large diameter trees, snags and woody debris play a fundamental role in maintaining the long term ecological functioning of the ecosystem (Ammaranthus 1994; Franklin 1994; Maser 1992;

Hansen *et. al.* 1991). It is now becoming common practice to leave patches of the pre-disturbance forest behind during clearcut harvesting in order to emulate legacies left by natural disturbance. Within British Columbia, the Biodiversity Guidebook (British Columbia Ministry of Forests 1995), a supporting document for the Forest Practices Code Act of British Columbia (Province of British Columbia 1994), recommends leaving up to 15% of the total cutblock area in mature forest reserves.

A concern expressed by forest managers is that unacceptable levels of windthrow will occur within these reserves leading to a loss in timber volume and increased risk of bark beetle outbreaks. Some basic principles for reducing windthrow are outlined in Stathers et al.. (1994) but it is felt that more specific information for managing windthrow is required, especially relating to reserves left within clearcuts.

This paper summarizes findings of four independent studies that examined reserves left in recent openings to determine if there were certain spatial or biophysical characteristics associated with the presence/absence and level of windthrow. Data for all projects was collected in different manners (see Burton 1999, DeLong 1998, Mahon et al. 1999, Steventon 1995) but common independent factors were assessed and downed stems could be expressed as percent of total standing stems for each dataset. Windthrow estimates for Burton (1999) were based on adjusted values since sampling was restricted within the reserve whereas estimates for other projects were based on samples distributed throughout the whole reserve. Table 1 lists the common set of variables assessed in all projects. A common objective of all projects was to provide guidance for the layout of reserves within clearcuts that would reduce the risk of windthrow to leave trees.

Results and Discussion

For continuous variables the strongest relationships were with time since harvest ($p = 0.002$), size of reserve ($p < 0.0001$, length to width ratio of reserve ($p = 0.044$), perimeter to area ratio ($p < 0.0001$), total stand density of trees in reserve ($p = 0.0410$), and median dbh of trees in reserve ($p = 0.002$). Windthrow appeared to increase up until about 3 years after harvest. Windthrow dropped off rapidly with size of reserve (Figure 1 & 2). The level of windthrow detected in reserves large than 5 ha (i.e., < 15%) is near the levels of recent windthrow being detected within large patches of contiguous forest (P. Burton, *these proceedings*) (Figure 2). Maximum level of recorded windthrow decreased from 100% to 25% for reserves less than and greater than 1 hectare, respectively (Figure 1 & 3). Since size of reserve had such a large effect on windthrow the remaining relationships will be discussed in the context of smaller reserves (< 1 ha) only.

Once the dataset was reduced to reserves < 1ha there was no longer a strong relationship between perimeter to area ratio and windthrow. As the average stand density of the reserve increased, windthrow decreased (Figure 3). Also, windthrow decreased as median dbh of stems within the reserve decreased (Figure 4). Although there is often a correlation between stand density and median dbh of stems (i.e., as density goes down median dbh goes up), there was a wide range in density of stands with low median dbh.

Table 1. Description of variables common to all data sets.

Variable Name and Type[1]	Description
Windthrow proportion – D	Number of downed stems > 10cm dbh as proportion of estimated total number of stems > 10 cm dbh in reserve including downed stems
Experimenter – IN	Person conducting study (4 levels)
Study location– IN	General location (7 levels)
Mesoslope position– IN	Estimated slope position (crest, upper, middle, lower, depression, level)
Moisture regime– IN	Estimated relative moisture regime (dry, mesic, moist)
Elevation (m) – IC	Estimated elevation from map or GPS
Latitude and Longitude (^{0}) – IC	Estimated to 6 significant digits using map or GPS
Time since harvest (months) - IC	Time since last recorded date of harvest operations
Proportion of block in reserve (%)	Total area of reserves divided by total harvested area
Reserve area (ha) – IC	Estimated area of reserve
Perimeter to area ratio – IC	Estimated perimeter (m) divided by estimated area (ha)
Length to width ratio – IC	Estimated length (m) divided by average width (m) estimated from 3 locations along reserve
Direction of windthrow (^{0}) - IC	Mean direction of windthrown trees from base to tip of tree using formula for circular mean
Azimuth (^{0}) – IC	Orientation of longest axis of reserve using numbers 1 to 180
Angle to wind(^{0}) – IC	Smallest angle between mean wind direction and longest axis of reserve
Width in wind direction (m) - IC	Average distance across reserve in direction of mean windthrow estimated from 3 locations along reserve
Fetch (m) – IC	Distance to cutblock boundary in direction opposite to direction of windthrow
Stand density – IC	Estimated stems per ha > 10 cm dbh
Median dbh – IC	Median dbh of standing and downed stems

[1] Variable type (D = dependant, IN = Independent nominal, IC = Independent continuous).

Mesoslope position and relative moisture regime also impacted windthrow. Since mesoslope position and moisture regime are correlated (i.e., wetter moisture regimes in lower, toe, and depression positions and drier moisture regimes in upper and crest positions) we will discuss these effects together. The combined effect of moisture regime and mesoslope position on the level of windthrow was as follows: mesic crest>mesic slope>mesic level>moist draw>moist slope (Figure 5). The location of the reserve with respect to the edge of the block also influenced windthrow. Reserves which were < 70 m from the edge of the opening in a direction opposite to that of the mean direction of winthrown trees (i.e., opposite to direction of major winds affecting each reserve) had less windthrow than ones where this ‘fetch distance’ was greater than 70 m (Figure 6).

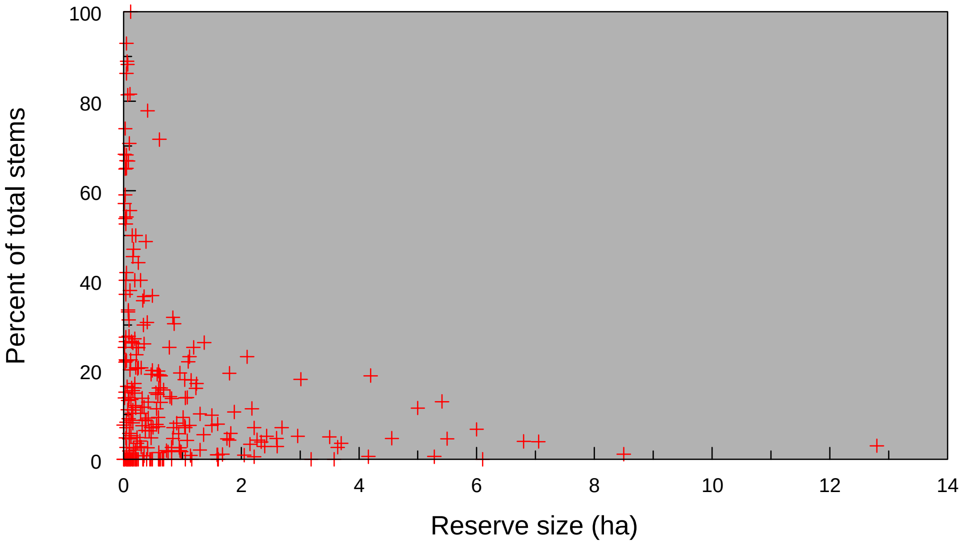

Figure 1. Percent of total trees in reserve affected by windthrow as a function of reserve

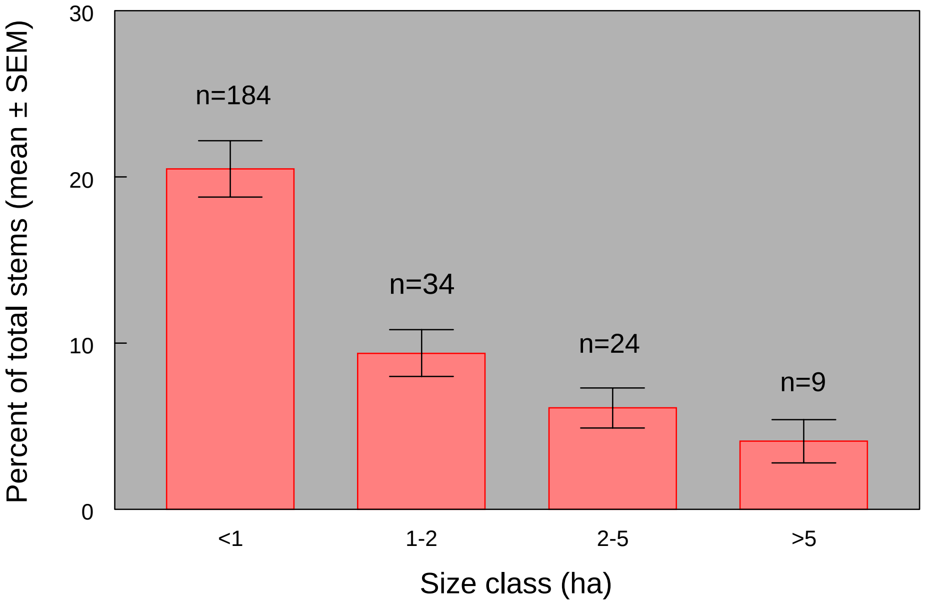

Figure 2. Percent of total stems > 15cm dbh in reserve affected by windthrow as a function of reserve size class

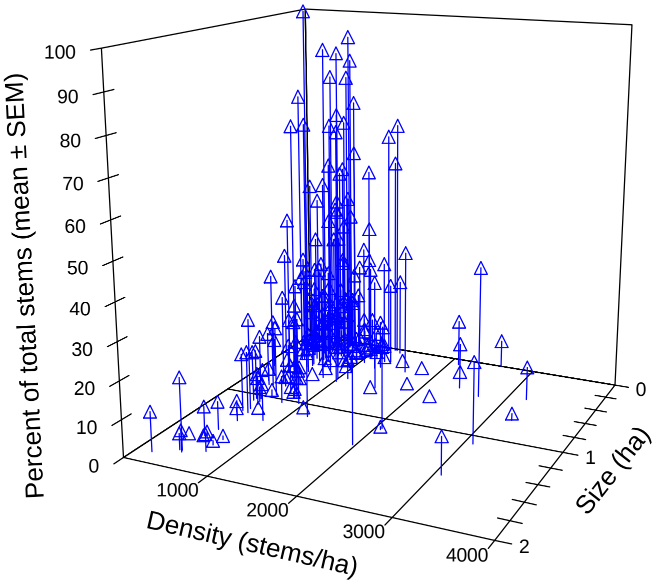

Figure 3. Percent of total stems > 15cm dbh in reserve affected by windthrow as a function of reserve size and stand density for reserves less than 2 ha.

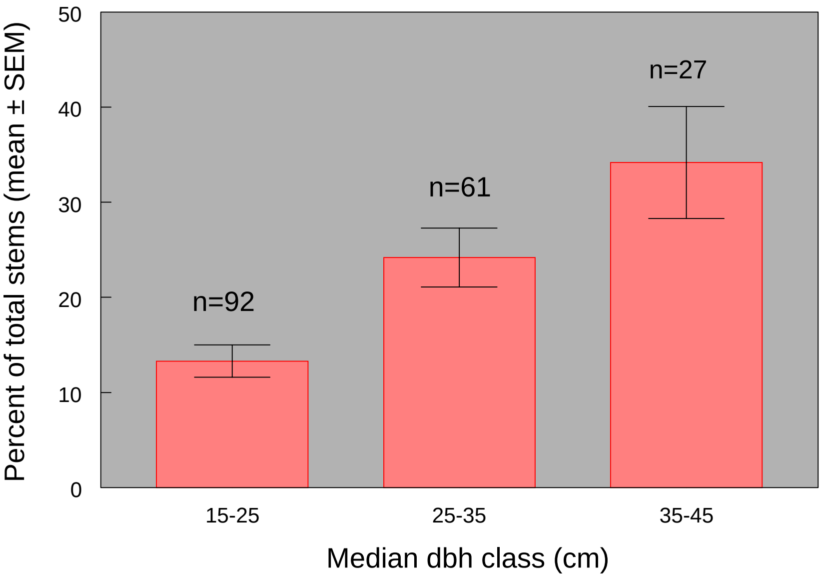

Figure 4. Percent of total stems > 15cm dbh in reserve affected by windthrow as a function of median dbh class of stems within the reserve.

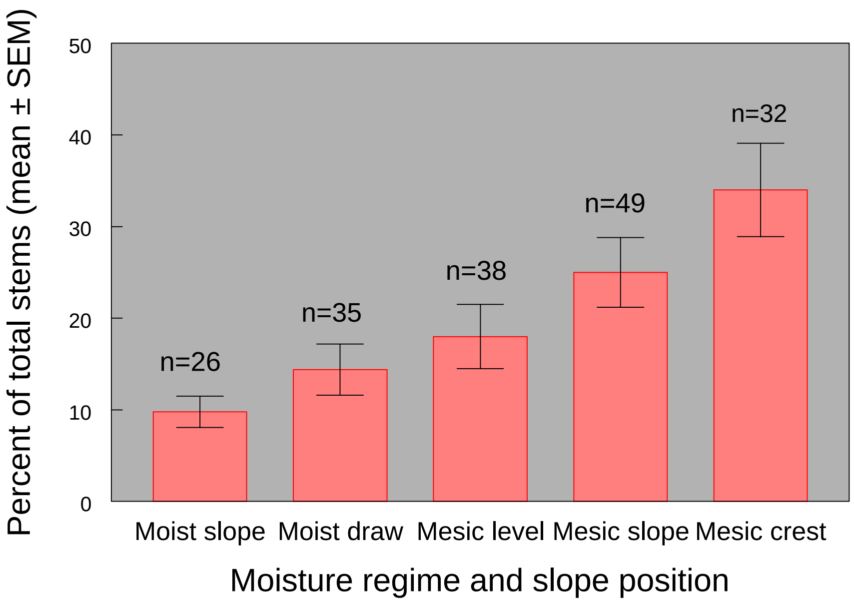

Figure 5. Percent of total stems > 15cm dbh in reserve affected by windthrow as a function of moisture regime and slope position.

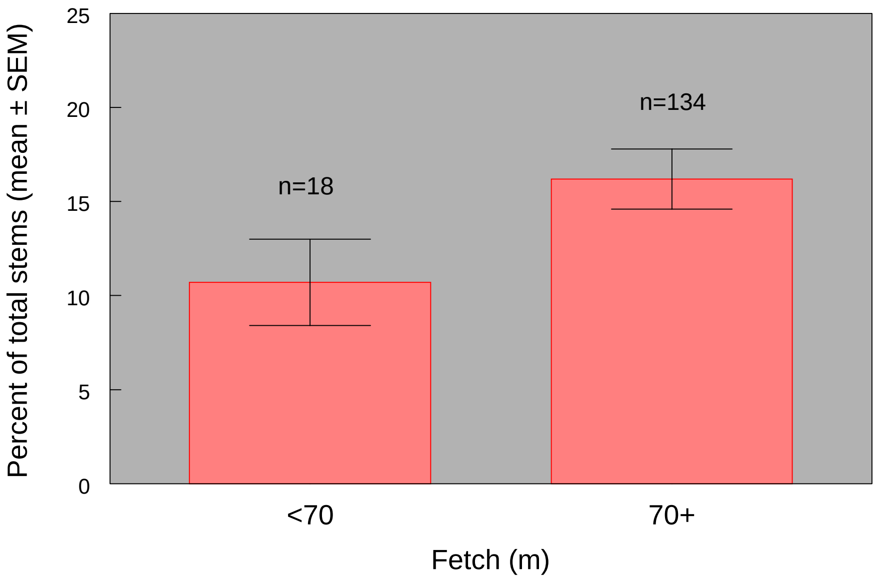

Figure 6. Percent of total stems > 15cm dbh in reserves affected by windthrow as a function of fetch distance (distance from reserve to cutblock edge in direction opposite to mean direction of trees impacted by wind).

Other factors that appear to affect windthrow in reserves but for which there was not data available for all studies were tree species and organic matter depth. Data from Mahon et al. (1999) indicated the following tree species susceptibility to windthrow in reserves Ep>Sx>Hw>At>Ba> Pl>Bl>Ac >Cw (Figure 7). It should be noted that the sample of aspen (At) trees (8 trees) was likely inadequate to gauge a response as these trees may have been distributed in portions of reserves that were generally less susceptible to windthrow. For all other species the total number of stems was greater than 150, which would provide reasonable likelihood that they would be distributed in a reserves with varying susceptibility to windthrow. Reserves with organic matter depth (i.e., humus depth plus any organic soil horizons) less than 7cm had substantially less windthrow associated with them than reserves where organic matter depth was greater than 7 cm, based on data from DeLong (1998) (Figure 8).

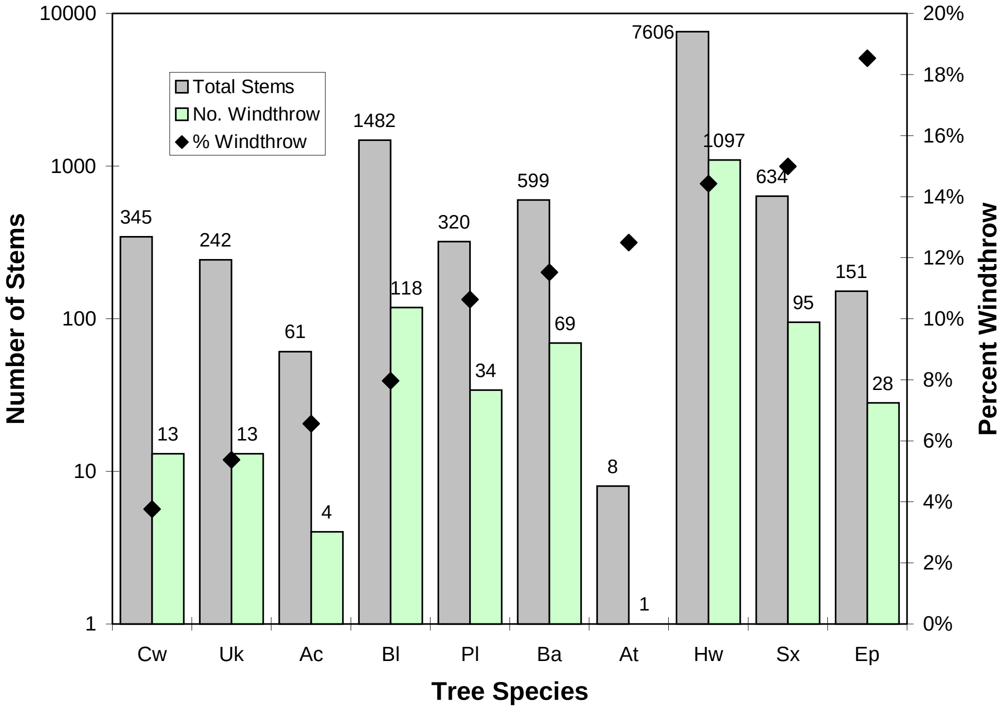

Figure 7. Differences in windthrow rates among tree species in 109 WTPs in the KFD (from Mahon et al. 1999).

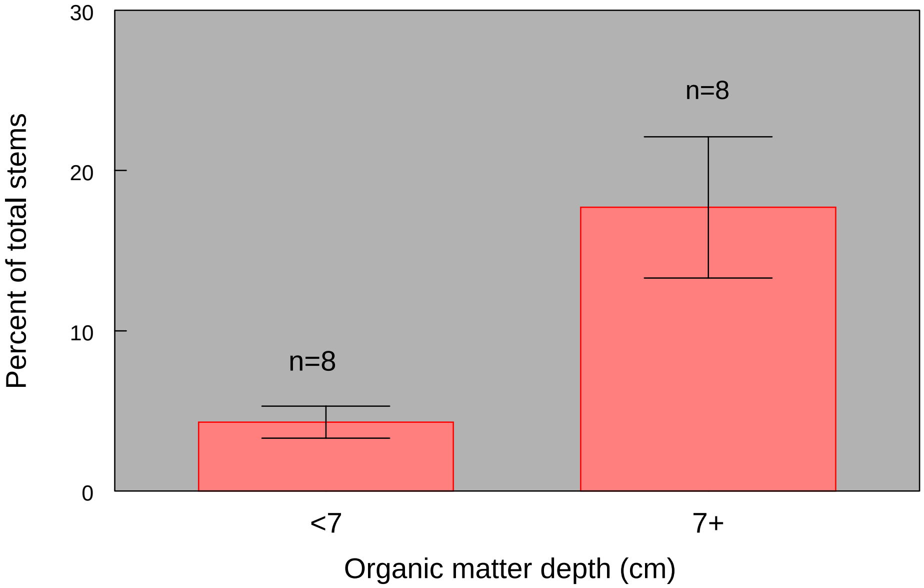

Figure 8. Percent of total trees in reserve affected by windthrow as a function of relative organic matter depth.

Management Implications

Some level of windthrow in reserves is inevitable and is important to the ecosystem for recruitment of coarse woody debris and large organic debris into streams. However, unless short term accumulation of woody debris is a primary objective of the reserve, minimizing windthrow is generally desirable in order to reduce loss of timber value and reduce the risk of the outbreak of bark beetle infestations. Deciding on what level of windthrow is acceptable is up to managers but there are a number of steps that can be taken during the design of reserves to reduce their susceptibility to windthrow. The primary consideration is the size of the reserve. Risk of windthrow falls off rapidly with increasing size of the reserve. Keeping the minimum size of reserves to 1ha will minimize the risk of windthrow. In addition, research has demonstrated higher wildlife values in larger reserves (Mahon et al. 1999). However, reserves < 1ha may still be desirable since there can be more of them for the same amount of reserve area. The relative merits of fewer larger reserves versus many smaller reserves have been a long and continuing debate. The fact is that many naturally occurring remnants (e.g., remnants left by wildfire) are < 1ha (DeLong and Tanner 1996). Many smaller dispersed remnants may be important for the dispersal of organisms with poor dispersal capabilities. For the design of reserves less than 1 hectare the following are recommendations based on our data:

- avoid placing them on exposed ridges or slopes with mesic and drier moisture regime and instead place them in protected draws;

- choose areas with small diameter trees at high density;
- avoid areas with a high component of aspen, birch, spruce or hemlock; and
- avoid areas with deep organic layers or organic soil.

Following these recommendations should provide a reasonable compromise between conserving the biodiversity values associated with leaving reserves and the risk of timber volume loss and bark beetle outbreaks due to excessive levels of windthrow.

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Post-Harvest Windthrow Rates In a Mountain Caribou Management Area North of Revelstoke

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Abstract

Windthrow is being evaluated at the Keystone site north of Revelstoke, a management area for mountain caribou (*Rangifer tarandus caribou*). This site, part of the Interior Cedar-Hemlock zone, was harvested using a group selection (patch cut) silviculture system during 1995/96. Results are presented for windthrow transects monitored for three years. The four treatments being compared are: the edges of group selections (1-2 ha) surrounded by mature timber, the unharvested buffers between these small openings, the edges of similar-sized openings along old clearcut boundaries, and large, unharvested areas in nearby forests. The openings along old clearcut boundaries were harvested at the same time as the group selections.

After three years, there is no significant difference in the rate of windthrow density and basal area along the edge of group selections, in the unharvested buffers, and on the edge of small patches harvested along the boundaries of old clearcuts. Windthrow rates in the large unharvested area were comparable in magnitude to the unharvested buffer areas. Windthrow rates during 1999 were significantly less than the rates for the previous two years. The lack of differences between treatments indicates that the edges of the 1-2 ha patches at this site are not suffering significantly greater windthrow than unharvested areas. Overall windthrow rates of 0.6%/yr (2.63 sph/yr), relative to the pre-harvested stand densities, are comparable to windthrow rates published for other mature or older forests. Windthrow rates for snags were also unaffected by treatment. However, snags were more susceptible to windthrow than live trees. The pre-treatment stand was 7% dead while 42% of the windthrown trees were dead. Across all treatments, most windthrown trees were dead, western hemlock (*Tsuga heterophylla*), followed by live western hemlock and western redcedar (*Thuja plicata*). The orientation of windthrown trees and local valley systems indicate that easterly, followed by northerly or westerly winds, cause most of the windthrow on the Keystone site.

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Introduction

Integrating mountain caribou (*Rangifer tarandus caribou*) and timber management is important in the Revelstoke area because a significant proportion of the annual allowable cut will be harvested from old-growth stands critical for caribou habitat. Clearcutting is the most commonly used silvicultural system in the Columbia Forest District. Alternative silviculture systems that maintain caribou habitat while allowing access to merchantable timber are preferred in areas managed for mountain caribou. In 1992, a joint Ministry of Forests (MOF)/ Ministry of Environment, Lands and Parks (MOELP)/Parks Canada five-year project was initiated to study the ecology of mountain caribou in the North Columbia Mountains area (Flaa and McLellan 1993). This caribou herd is found predominately north of Revelstoke within the Columbia Forest District. One objective of this study was to use caribou micro-habitat selection information (preferred tree size, tree species, foraging behavior of caribou, and lichen species abundance) to design alternative silvicultural systems to maintain habitat and permit timber extraction.

Maintenance of caribou habitat through partial harvesting is being explored throughout the range of mountain caribou. A variety of silvicultural systems is being tested and recent research trials are documented in Stevenson et al. (1994). Many of these trials are located in higher elevation, ESSF forests and use single tree or group selection systems. Targeted volume removals are 30% or less in these trials. The terrain, timber types, and forest health issues, such as *Armillaria* root disease, in the Revelstoke area limit the options available for prescribing alternative silvicultural systems. Difficulties in prescribing, laying out, and harvesting feasibility, in addition to greater costs, also limit the types of alternative silviculture systems that are currently being used. Local foresters agree that the most feasible option for conventional harvesting on relatively gentle terrain, is some form of group selection. More research is required on patch cuts under a range of site conditions and opening sizes.

A key issue related to opening size and shape is windthrow. Windthrown trees provide an important source of lichen for caribou by allowing the animals to forage on previously inaccessible parts of the tree. However, excessive rates of windthrow could reduce the long-term supply of lichens for foraging. Excessive windthrow of merchantable timber is also not desirable economically and silviculturally (Alexander 1987). Windthrow factors in the forests of British Columbia have been summarized (Stathers et al. 1994). This latter report is based primarily on research from clear-cutting studies and it has limited information from the interior wetbelt north of Revelstoke.

Assuming pre-harvest stands have low windthrow hazards, windthrow is hypothesized to minimally increase in patch cuts (small openings <2 ha), relative to unharvested control areas or recent clearcut boundaries. Previous studies have noted that smaller openings can be relatively stable to endemic levels of wind (Coates 1997).

Objectives

The objective of the windthrow component of this research is to determine the impact of alternative silvicultural systems on the windthrow rates along cutting boundaries. The hypotheses being tested are:

1. Is there a significant difference in windthrow rates along the edges of patch cuts, in the unharvested buffers between the patch cuts, along the edges of similar sized openings located along the edge of old, large clearcut areas, and in large unharvested areas?
2. Is there a relationship between windthrow and various site, species, and stand factors, such as: tree species, diameter, height, internal stand characteristics, adjacent stand history, internal stand history, and site series?

Study Area

The site is located north of Revelstoke in the Keystone area of TFL 56, the operating area of the Revelstoke Community Forest Corporation (RCFC). The site is in the Wells Gray Wet Cool Interior Cedar - Hemlock variant (ICHwk1) (Braumandl and Curran 1992). The main site series are the 01, 04, and 05. The Keystone site, the first area harvested with patch-cuts in the Revelstoke Forest District, has a gross area of 71 ha and is surrounded by old clearcuts. It was conventionally winter harvested with ground-based equipment in 1995/96. There are a total of 16 harvested patches ranging in size from 1.06 to 2.02 ha with small wildlife tree reserves of a few trees within some patches. This area is planned for harvesting in four passes with 25% of the volume to be removed every 60 years over a 240 year rotation. Maps of the study area and individual sites are included in Quesnel and Waters (2000).

Methods

Field Methods

Transects were used to assess annual windthrow rates in the following treatments:

i. **Inner patches** - clearcut patches (<2 ha) surrounded by at least 80-100 m of mature forest. Some patches have small wildlife tree patches. Transects were established around the perimeter of these treatment units.

ii. **Unharvested buffer between the inner patches** - undisturbed areas between patches that are at least 30 m from any harvesting boundary. These transects are treated as a control within the larger harvesting unit that includes patch cuts.

iii. **Outer patches** - clearcut patches (<2 ha) adjacent to larger, older clearcuts. Transects were established around the perimeter of these treatment units in the adjacent mature timber. These were considered equivalent to the edge of a recent, large clearcut.

iv. **Unharvested area** - a relatively large, undisturbed over-mature stand near the group selection harvesting. Because of past timber harvesting, only one unharvested area exists in the ICHwk1 at the Keystone site.

Twenty metre wide windthrow transects or strip plots of varying lengths were established at each treatment unit. Considerable variation in transect length was found for different treatments resulting from differences in size and shape of treatment units. Windthrow transects were established just after harvesting in the fall of 1996. At the time of establishment, each transect was assessed to identify existing windthrow. All pre-harvest windthrow with point of germination within 10 m on either side of the transect centre line was marked with permanent tags. The windthrow transects were reassessed in the fall of 1997, 1998, and 1999. For each year after transect establishment, new windthrow was recorded and permanently tagged. Attributes recorded for windthrown trees on the transects included: diameter, height, crown class, species, live or dead, stem broken (wind-snapped) or uprooted, height of breakage, length above break, total length of tree, estimated length of live crown at time of wind damage, orientation, site series, type of damage, and other site or soil characteristics. For dead trees, heights were measured by adding the length for the broken segments estimated to be part of the tree at the time of windthrow.

Data Analysis

A summary of mensuration data, based on timber cruising, was obtained for the site. Density (sph) and basal area (m^2/ha) of live and dead trees were compiled by tree species. This data characterizes the pre-treatment stand. However, the cruise plots are not directly tied to the treatment units and this information is used for general comparisons only. To characterize windthrow for each year, windthrow density and basal area were calculated, by tree species, for live or dead trees and for wind-snapped or uprooted trees. These values were calculated across all treatments. Summary statistics for windthrown trees were also calculated for: dbh, height of stem break, length above break, total length, length of estimated live crown, and height:diameter ratios. For each treatment, density of windthrown trees was determined for the four cardinal directions.

The main data analysis compared yearly and treatment windthrow rates. Total densities and basal areas of windthrow were calculated by year for each transect (= treatment unit). Summary statistics for windthrow densities and basal areas were then calculated for each treatment. As the large unharvested area is a cluster of sub-transects representing one treatment unit, the density and basal area without standard errors were calculated for this unreplicated treatment and this treatment was not included in the repeated measures and analysis of variances (ANOVA) described below. Repeated measures analysis, using a multivariate test, was used to test for a significant treatment x year interaction and for a significant year effect. Year was used as the repeated measure in the multivariate analysis of windthrow rates. A separate univariate analysis used contrasts to compare year to year values. An additional ANOVA model with treatment as a fixed factor was used to compare the effect of treatment on windthrow rates for each separate year. All statistical models were developed after reference to Kirk (1982). The means of the treatments for each year were plotted and orthogonal contrasts were used for specific comparisons (Mead 1988). Windthrow rates for total density and basal area of dead stems on the different treatments were also compared for three years. The statistical models and contrasts were the same as those used for total windthrow.

RESULTS AND DISCUSSION

Stand and site conditions

The pre-treatment stand was dominated by western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*). Overall stand density and basal area were 372.4 sph and 89.7 m^2/ha, respectively. Mortality was 7% (Table 1). The silvicultural prescription indicates that the site has silt loam to loam textured soils with approximately 60% coarse fragments, and the soils were developed from morainal blankets (>1 m deep). Most root restricting layers occur at greater than 50 cm, with root restrictions at 30 cm for a few microsites. These shallow rooting microsites are usually associated with bedrock outcrops or seepage layers.

Table 1. Pre-harvest stand data at the Keystone site[a,b]

	Density			Basal area		
	Live	Dead	Total	Live	Dead	Total
Tree species	sph			m^2/ha		
Engelmann spruce	3.5(<1)[b,c]	0.8(<1)	4.3(1)	0.9(1)	0.6(<1)	1.5(2)
Western hemlock	215.5(58)	21.5(6)	237.0(64)	28.5(32)	5.6(6)	34.1(38)
Western redcedar	128.2(34)	2.8(1)	131.0(35)	52.8(59)	1.2(1)	54.0(60)
Western white pine	0.1(0)	0.0(0)	0.1(<1)	0.1(<1)	0.0(0)	0.1(<1)
Total	347.3(93)	25.1(7)	372.4	82.3(92)	7.4(8)	89.7

[a] Summary of cruise data from Ministry of Forests, Revelstoke.

[b] Average dbh for stand = 54.4 cm, average height = 34.1 m, net volume = 441m^3/ha.

[c] Percent of stand total in brackets.

During field sampling, most of the transects were classified as part of the 05 site series within the ICHwk1. Less area was classified as the 01 and 06 site series. The least area was occupied by the drier 04 site series. Only one tree was uprooted on this drier site series. This indicates that drier microsites may be less susceptible to windthrow in the study area. Of the 51 trees uprooted in this study, all but one occurred in the 05 or 01 site series. These site series have considerable overlap in moisture regime and include mesic or subhygric moisture regimes (Braumandl and Curran 1992). A more detailed assessment of the relative areas of each site series is required prior to interpreting the influence of site series on windthrow rates.

Three years of windthrow at the Keystone site

All factors except year were nonsignificant for density of windthrow (Table 2). As noted earlier, this part of the analysis does not include the large, unharvested area. The plot of residuals for this analysis was not significantly different from a normal distribution. Consistent with these results, comparison of treatments for each year separately did not yield significant treatment effects (Prob=0.4021-

0.7750) nor did it yield significant contrasts between individual treatments (Prob=0.1939-0.9742). A contrast comparing windthrow densities between 1997 and 1998 was not significant while a contrast comparing the windthrow density for 1999 to the densities averaged across 1997 and 1998 was significant (Table 2). The overall windthrow density for 1999 and the rates for each treatment during 1999, were lower than the rates observed the previous two years (Figure 1a).

To determine if a greater number of treatment units would be needed to detect significant differences between treatments for windthrow density, power analysis was used. Power analysis indicated that detection of differences of 1.0 sph/yr between treatments would require a minimum of 38 treatment units. This is approximately two and a half times the number of treatment units used on the Keystone site. Thus, a study with a greater number of treatment units may be required to determine if significant differences exist between some of the treatments. Although statistical differences of the above magnitude may be demonstrated with a larger study, the differences may or may not be operationally significant.

For basal area of windthrown stems, all interactions, main factors, and contrasts for each main factor were nonsignificant (Table 2). The plot of residuals was not significantly different from a normal distribution. Basal area was not as sensitive as density for detecting year to year response in this study (Table 2). This may simply reflect the low, overall windthrow rates observed in the study area. A contrast comparing windthrown basal areas for 1999 to the average values for 1997 and 1998 was almost significant at the $\alpha = 0.05$ level (Table 2, footnote e). Power analysis indicated that a difference of 1 m^2/ha could be detected with 23 treatment units. This is approximately 50% more treatment units than the present study. Similarly, when the treatments were compared each year separately, a comparison of the inner patches to the outer patches for 1998 had a probability of 0.0873. Power analysis of this comparison indicated that the number of treatment units in this study was adequate for detecting a difference of 1 m^2/ha between treatments. Thus, a larger number of treatment units may have enabled the study design to detect year to year variations in windthrown basal area, similar to windthrow density.

Table 2. Summary of multivariate-repeated measures analysis for three years at the Keystone site – density and basal area of windthrow

Variable/ Source of variation	Value[a]	Exact F	Numerator df[b]	Denominator df	Prob>F
Windthrow density (sph):					
1997 + 1998 +1999					
Between subjects					
Treatment[c]	0.948511	0.3257	2	12	0.7282
Contrast: Buffer vs. mean of inner patches + outer patches	0.992837	0.0866	1	12	0.7736
Contrast: Inner patches vs. outer patches	0.959473	0.5069	1	12	0.4901
Within subjects					
Year[d]	0.467075	6.2754	2	11	0.0152
Year*Treatment	0.756106	0.8252	4	22	0.5232
Windthrow basal area (m^2/ha):					
1997 + 1998 + 1999					
Between subjects					
Treatment	0.870773	0.8904	2	12	0.4359
Contrast: Buffer vs. mean of inner patches + outer patches	0.998994	0.0121	1	12	0.9143
Contrast: Inner patches vs. outer patches	0.870909	1.7787	1	12	0.2071
Within subjects					
Year[e]	0.678801	2.6025	2	11	0.1187
Year*Treatment	0.619600	1.4873	4	22	0.2402

[a] Wilks' Lambda.

[b] df = degrees of freedom.

[c] Treatments: buffer between harvested patches, inner patches surrounded by mature forest, outer patches on edge of old clearcut.

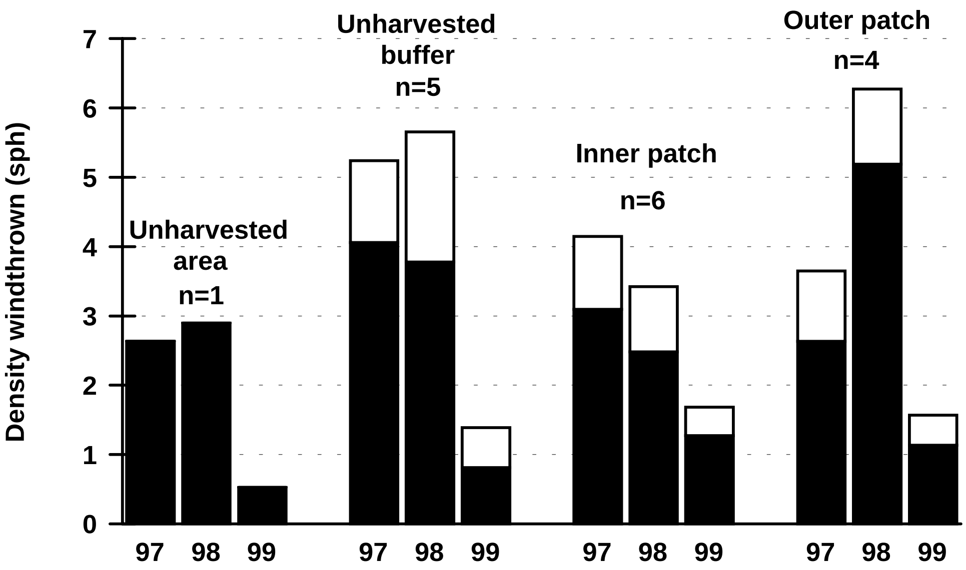
[d] Contrasts from a univariate, repeated measures analysis found that: i. windthrow rates (density) for 1997 and 1998 were not significantly different (F stat=0.4656; df=1,24; Prob=0.5016); and ii. the windthrow rate (density) for 1999 was significantly lower than the mean value across 1997 and 1998 (F stat = 12.3779; df=1,24; Prob=0.0018).

[e] Contrasts from a univariate, repeated measures analysis found that: i. windthrow rate (basal area) from 1997 and 1998 were not significantly different (F stat=2.4261; df=1,24; Prob=0.1324); and ii. windthrow rate (basal area) for 1999 was not significantly different from the mean value across 1997 and 1998 (F stat=3.9876; df=1,24; Prob=0.0573).

Figure1

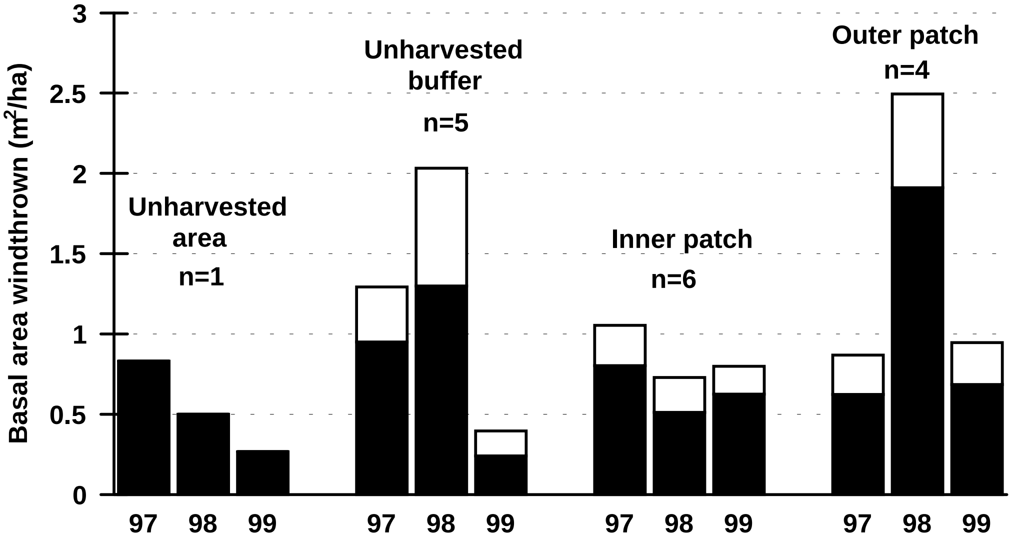
KEYSTONE

Fig. 1a



KEYSTONE

Fig. 1b



Although a significant effect of treatment was not found over three years, the plot of mean values indicates some possible trends (Figure 1). Although unreplicated and not included in the ANOVA, the large unharvested control had values for windthrow density and basal area close to the lowest in magnitude of all treatments each year (Figures 1a, b). The most interesting trend between years exists for the outer patch treatment. In 1997, the rate for this treatment was comparable to the inner patches. In contrast, the rate in 1998 was the highest rate of all the treatments across all three years (Figure 1). As all of these outer patches primarily face east (Quesnel and Waters 2000) and most of the windthrow in 1998 was oriented west (see section 4.4), larger but non-significant windthrow values along the outer patches may simply reflect location within the study site.

Windthrow rates after timber harvesting are expected to decrease with time (Alexander 1964; Stathers et al. 1994). However, the decrease in windthrow density for the unharvested area, after two years of similar but higher rates (Figure 1), suggests that other factors resulted in a generally lower level of windthrow activity during 1999. The most likely factor is a decrease in damaging winds at the study site during 1999 or possibly an interaction between snow loading and frequency of stronger winds. Irrespective of the cause of decreased windthrow rates in the large, unharvested area, additional years of monitoring are necessary to confirm that post-harvest rates have stabilized along the edges of the patch cuts.

Based on three years of sampling, the overall windthrow rates at the Keystone site are 2.63 sph/yr (se=0.353 sph/yr, n=16) for density and 0.80 m^2/ha/yr (se=0.120 m^2/ha/yr, n=16) for basal area. The overall rates at this site are relatively low and comparable to another study in the ICH zone (Coates 1997).

Characteristics of windthrown trees

For density and basal area of windthrown snags, the treatment x year interactions (Prob = 0.2835-0.0723; df = 4, 24) and the year effects (Prob = 0.02339-0.7244; df = 2, 24) were not significant. For both variables, the replicated treatments were also not significantly different for all three years of the study (Prob = 0.1688-0.6333; df = 2, 12). The three year average for density of windthrown snags (0.37 sph/yr) on the large, unharvested area was comparable to the yearly rates for the other three treatments (0.31-0.33 sph/yr). However, snags appear to be more susceptible to windthrow than live trees as a relatively high proportion of the windthrown trees consisted of dead trees. For the three years of sampling, snags formed 42% or more of the windthrown stems and 32% or more of the windthrown basal area for all treatments. Snags formed only 7% of the pre-treatment stands at this site (Table 1). These results have two obvious applications. The small patch harvesting in this study is not yielding a significantly greater rate of snag fall, relative to the large, unharvested areas. The second application is that silvicultural systems in the study area, designed for wildlife management, will have to acknowledge and adjust for greater windthrow rates for snags.

Combined with hazard reduction along the edge of recent harvested areas and active logging roads, the densities of snags will be continuously reduced. Priority may have to be given to live, defective trees and to well anchored snags for maintaining this wildlife resource.

Averaged across all treatments, most of the windthrow was western hemlock followed by western redcedar (Table 3). The exception is the lower density but greater basal area for western redcedar during 1998. These results generally reflect initial stand composition (Table 1). During the first two years of the study, most of the windthrown trees were uprooted western hemlock (1.43-1.52 sph) and western redcedar (0.21-0.98 sph). During the third year of the study, fewer trees were uprooted for both of these species (0.06-0.08 sph).

Compared to live windthrown trees, dead western hemlock had greater diameters, shorter overall lengths, and smaller height:diameter ratios (Table 4). At this site, dead western redcedar had smaller diameters, shorter overall lengths, and slightly greater height:diameter ratios, relative to live windthrown trees. Height:diameter ratios are often used as an indicator of tree susceptibility to windthrow, with larger ratios reflecting taller, thinner trees more readily windthrown (Stathers et al. 1994). This ratio is especially useful in healthy, dense, rapidly growing stands subject to thinning or partial harvesting. At the Keystone site, the undisturbed old-growth stands are more broken and open than young second growth stands. In these old-growth stands, decay is important for weakening many stems. For many dead and live windthrown trees, heart and butt rots were observed and many of these trees had a high proportion of rot or were hollow. The disease organisms observed included: brown stringy trunk rot (*Echinodontium tinctorium*) and laminated root rot (*Phellinus weirii*). Root disease (*Armillaria ostoyae*) was observed on a few trees. Where smaller height: diameter ratios were observed in dead stems, compared to live stems of the same species, this probably reflects a greater degree of decay.

Table 3. Density and basal area of windthrow by tree species: three years post-treatment response at Keystone[a]

Tree species	Density (sph)	Basal area (m^2/ha)
1997		
Douglas-fir	0.10(0.099,<0.1)[b]	0.050(0.0504,<0.1)
Engelmann spruce	0.00(0,0)	0.000(0,0)
Western hemlock	2.60(0.521,0.7)	0.532(0.1238,0.6)
Western redcedar	0.55(0.214,0.1)	0.223(0.0982,0.3)
Total	3.25(-,0.9)	0.805(-,0.9)
1998		
Douglas-fir	0.00(0,0)	0.000(0,0)
Engelmann spruce	0.16(0.114,<0.1)	0.009(0.0080,<0.1)
Western hemlock	2.16(0.497,0.6)	0.314(0.0884,0.4)
Western redcedar	1.28(0.380,0.3)	0.784(0.2856,0.9)
Total	3.60(-,1.0)	1.107(-,1.2)
1999		
Douglas-fir	0.00(0,0)	0.000(0,0)
Engelmann spruce	0.07(0.051,<0.1)	0.051(0.0376,<0.1)
Western hemlock	0.79(0.216,0.2)	0.359(0.0953,0.4)
Western redcedar	0.19(0.105,<0.1)	0.087(0.0470,<0.1)
Total	1.05(-,0.3)	0.497(-,0.6)

[a] n=16, sample size is the number of transects. Values for each species were calculated using a rate for each transect at the site. For example, transects lacking Douglas-fir were assigned a value of 0 for density and basal area.

[b] mean (standard error, percent of pre-treatment stand values).

Direction of windthrow

During the first two years, the fewest trees blew down in a northerly direction (0.58 sph/yr) (Figure 2). Greater numbers were windthrown in a southerly direction both years (0.92 sph/yr). The rate of windthrow in the western quadrant during 1998 was approximately double the rate for 1997. The opposite pattern occurred in the eastern quadrant. These results reflect the direction of storm tracks north of Revelstoke during most years. The main direction of storm movement in the study area is east or west along Downie Creek, Goldstream River, and other side drainages that feed into Lake Revelstoke and the Columbia River. Another cause of windthrow is major storms tracking north to south along the main valley system from Mica to Revelstoke. With the exception of the western quadrant, most quadrants at the Keystone site had greatly reduced windthrow rates during 1999 (Figure 2). The reduced windthrow rates during 1999 in three quadrants at the Keystone site indicate a major reduction in windthrow caused by storms moving north-south, and to a lesser extent, storm activity from the west.

This is a possible explanation for the significantly reduced windthrow rates noted the third year. However, the small overall windthrow rate and the limited number of windthrown trees suggests that this may not reflect the long term pattern for this site.

Since windthrow damage is occurring in all directions, it is not possible to make specific recommendations with respect to orientation of patch boundaries. General recommendations for locating patch cuts would include sites with deeper soils, better drained soils, and topographic locations less susceptible to windthrow (Alexander 1964). Stathers et al. (1994) also make some recommendations for partial harvesting. These include using areas with low windthrow hazard, avoiding partial harvesting near the edge of larger clearcuts, removal of <20% basal area, thinning from below, and avoiding the use of gaps >1/2 tree lengths in width.

However, Novak et al. (1997) have observed that a zone of relatively low wind speeds exists for 3-6 tree lengths from the edge a 10 ha opening in an ESSF forest. This suggest that gaps in tree length may be possible without greatly increasing windthrow rates.

Table 4. Characteristics of windthrown trees at Keystone[a]

Tree species	Dbh (cm)	Height at break point (m)	Length above break point (m)	Total length (m)	Length of live crown (m)	Height: diameter ratio
Douglas-fir						
live	85.0 (-,1)[b]	1.0 (-,1)	32.4 (-,1)	32.4 (-,1)	12.0 (-,1)	38.1 (-,1)
dead	76.0 (-,1)	9.0 (-,1)	14.0 (-,1)	22.5 (-,1)	-	29.6 (-,1)
Engelmann spruce						
live	70.5 (39.50,2)	2 (-,1)	41.0 (-,1)	32.4 (10.60,2)	17.5 (7.50,2)	54.7 (15.62,2)
dead	56.5 (38.50,2)	-	42.0 (-,1)	29.0 (13.00,2)	-	66.5 (22.34,2)
Western hemlock						
live	45.3 (3.15,44)	1.3 (0.50,31)	24.6 (1.18,31)	23.7 (1.18,41)	14.3 (1.07,44)	56.5 (2.25,44)
dead	56.7 (3.27,40)	4.2 (0.80,33)	14.6 (1.07,32)	17.7 (0.90,41)	-	34.6 (2.17,40)
Western redcedar						
live	94.2 (6.05,13)	3.0 (1.97,6)	30.8 (2.44,6)	32.6 (1.21,13)	17.9 (1.98,12)	36.2 (2.33,13)
dead	51.8 (5.90,15)	1.5 (0.70,7)	24.0 (2.16,7)	21.6 (1.92,16)	-	42.1 (2.70,15)

[a] Values for uprooted and wind-snapped trees.

[b] mean (standard error, sample size). Sample size is the number of windthrown trees at the site.

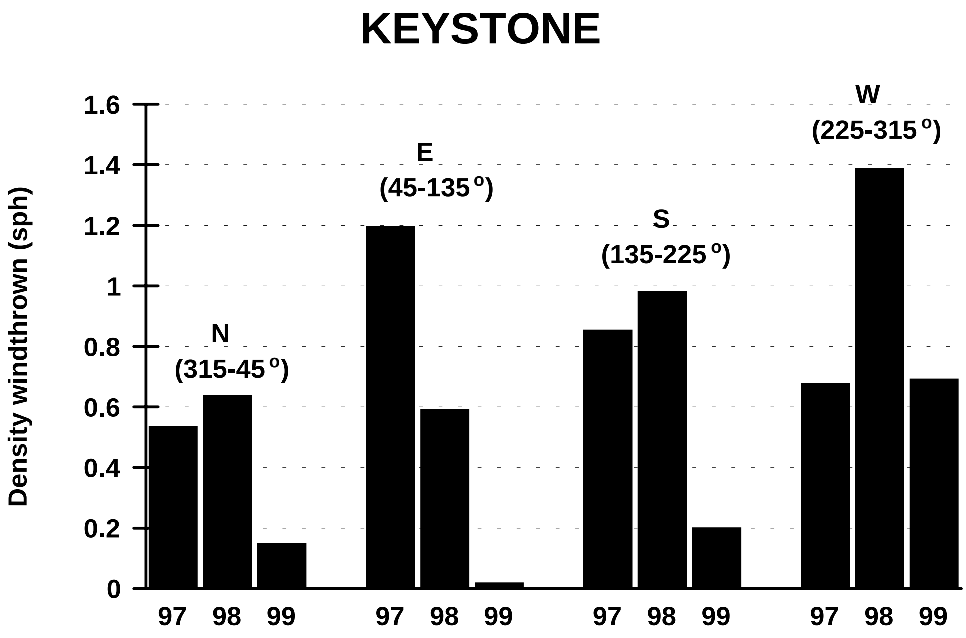


Figure 2. Direction of windthrown trees.

Comparison to other studies

Coates (1997) evaluated windthrow two years after partial harvesting at the Date Creek site. This study, located in mature (120-140 yr) and old-growth (250-300$^+$ yr) forests of the ICH zone of northwestern British Columbia, includes treatments with single tree removal or small openings (<0.5 ha). For Date Creek, the windthrow rates ranged from 5.9 sph on unharvested controls to 8.1 sph on a light removal treatment. These rates include two years of windthrow. The value for the unharvested control at Date Creek is comparable to the total windthrow after the first two years for the large, unharvested area at the Keystone site (5.53 sph) (Figure 1). At the latter site, the windthrow rates for western hemlock during the first two years (4.76 sph) (Table 3) were only slightly less than the rate for this tree species found at Date Creek (5.37 sph) (Coates 1997). As a percentage of the original stand, the Keystone values (0.91-1.1%) are almost identical to the Date Creek value for this species (0.99%).

Windthrown western hemlock at the Keystone site had larger diameters (Table 4) than the mean value of 32.1 cm found at Date Creek (Coates 1997). Total length of live, windthrown western hemlock at Keystone was almost identical to the Date Creek site. As a result, the height:diameter ratios at Keystone were much lower than for the Date Creek site, especially for the dead windthrown stems (Table 4). This supports the field observation that degree of decay is strongly influencing windthrow north of Revelstoke. As indicated by Mattheck et al.

(1993), the susceptibility of trees to wind damage is a function of the ratio of sound wood to stem radius. The windthrow results for western redcedar at the Keystone site differ from the Date Creek site. At the Keystone site, western redcedar windthrow rates after two years were almost eight times greater (Table 3) than the rate of 0.25 sph found at the Date Creek site. The rate of windthrow for western redcedar as a percentage of the original stand at Keystone (0.42-0.98%), was also greater than for Date Creek (0.05%).

Coates (1997) notes that the highest rates of windthrow relative to healthy, mature stands, occurred in a control area consisting of old growth. The higher windthrow rates in the old growth were assumed to result from a high degree of rot and structural weakening in these trees. Many old-growth ICH stands near Revelstoke may have decay characteristics similar to the stands at Date Creek. Height:diameter ratios indicate that the degree of decay may be even greater near Revelstoke (Table 4). After a review of partial harvesting studies, Coates (1997) concludes that a low level of wind damage occurred where the harvesting was dispersed and small openings (<1.6 ha) were used. This is also the observation of Stathers et al. (1994) who note the wind firmness of some very small openings. These authors attribute the low windthrow rates to the reduced ability of strong regional winds to penetrate into the canopies of small openings and for limited opportunities for turbulence to develop.

Huggard et al. (1999) compared windthrow rates 2.7 years after timber harvesting on treatment units with undisturbed controls, single tree removal, and three sizes of clear-felled openings (0.1, 1.0, 10 ha). This study, near Sicamous, B.C., was located in the Engelmann spruce-subalpine fir (ESSF) zone and focussed on subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*). Site, stand structure, tree species, and age for this study limits comparisons to the study sites north of Revelstoke. However, general windthrow rates can be compared. It is worth noting that Huggard et al. (1999) found greater windthrow rates in the harvested areas compared to the unharvested controls, the lowest rates in the 0.1 ha openings, and the greatest rates in the dispersed removal, single tree selection system. A major finding of the Sicamous study, with respect to minimizing windthrow rates after timber harvesting, is that concentrated removal of timber in small clear-felled openings is preferable to dispersed removal. This result suggests that smaller (<1 ha), clear-felled patches should be tested in the ICH zone north of Revelstoke, in preference to single tree removal systems.

Recommendations

The following recommendations are based on the research results plus recommendations from previous studies. These recommendations should help to minimize the amount of post-harvest windthrow in group selection silvicultural systems. These recommendations are applicable to the old-growth ICH stands north of Revelstoke.

1. Group selection should be applied in areas where the trees are deeply rooted and the windthrow hazard is relatively low (Stathers et al. 1994).
2. Boundaries need to be established in relatively windfirm locations. This would include deeper soils, better drained soils, and topographic locations less susceptible to windthrow (Alexander 1964).

3. Microsites with shallow rooting potential should be noted when establishing harvesting patches. The patch boundary should not cross wet, poorly drained areas, or dry ridges. Also, the patch boundaries should either fully include or fully exclude these areas (Stathers et al. 1994).
4. In areas prone to windthrow, feather the edges of patches by removing approximately 20% of the most windthrow prone trees (rotten, shallow rooted, large height:diameter ratios), assuming these can be readily identified (Stathers et al. 1994).
5. Reducing patch sizes to <2 ha sizes should help to ensure acceptable levels of windthrow.
6. Patch cut placement at the edge of existing large clearcuts should be avoided, where possible. Otherwise, a contingency plan to salvage windthrow in these areas should be addressed.

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Wind and snow damage in ESSF: Update from Sicamous Creek

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Abstract:

We used transect surveys at a large-scale experimental site at Sicamous Creek, BC to measure the effects of 5 treatments on wind and snow damage: 10-ha clearcuts, arrays of 1-ha patch cuts, arrays of 0.1-ha patch cuts, individual-tree selection cuts and uncut controls. We also examined edge effects and conditions predisposing trees to damage. Wind and snow damage of subalpine fir (*Abies lasiocarpa*) in 4.7 years following harvesting ranged from 3.2% of basal area per year in uncut forest to 1.9-3.2% per year in harvested treatments, with lowest rates in 0.1-ha patch-cut arrays. Engelmann spruce (*Picea engelmannii*) showed similar patterns of damage, but lower rates (0.3%-1.0% of basal area per year). The rates after 4.7 years increased substantially, particularly in the uncut stands, from those reported after 2.7 years, principally because of stems snapped during the heavy snow winter of 1998-99. Differences in tree characteristics and edge effects are also summarized briefly.

Introduction

The Sicamous Creek project is a long-term interdisciplinary study of the effects of alternative silvicultural systems on high elevation forested ecosystems (Vyse 1997). Huggard et al. (1999) reported on windthrow at this site over the first 2.7 years after harvesting. We compared rates and patterns of windthrow and snow damage in uncut forest and in 4 harvesting systems: individual tree selection, arrays of 0.1-ha patch cuts, arrays of 1-ha patch cuts and 10-ha clearcuts. We also measured the effect of distance to cutblock edge and edge orientation on damage rates, and assessed characteristics of trees that make them more susceptible to damage. Here we report on further wind and snow damage after an additional 2 years. In the summaries in our earlier paper, we did not emphasize the distinction between uprooted stems and snapped stems. Here we separate the types of damage in an attempt to assess the importance of snow as a damaging agent in high elevation forests. Snow damage has been widely reported in

European forests (see Nykanen et al. 1997, Valinger and Fridman 1999) but is a little reported phenomenon in North America. For convenience, we refer to wind damage throughout the paper, although we cannot be sure whether the damage is caused by wind, snow, or some combination of wind and snow.

Materials and methods

Study area

The Sicamous Creek Silvicultural Systems experimental site is located 7 km south-east of Sicamous, British Columbia (50°50'N 118°50'W) in the wet cold subzone of the Engelmann-spruce subalpine-fir biogeoclimatic zone (ESSFwc2; Lloyd et al. 1990). The site is on a north-facing slope, ranging from 1530 m to 1830 m elevation, with gentle slopes in the lower part of the site, moderately steep slopes in middle sections, and varied topography in the upper section. The oldest trees in the stand are approximately 350 years old (Parish 1997), with canopy trees consisting of 82% subalpine fir and 18% Engelmann spruce. Soil moisture regimes range from subxeric in shallow soils on elevated topography to hygric sites in poorly drained areas. This site has been fully described elsewhere (Hollstedt and Vyse 1997, Huggard et al. 1999).

The site has been divided into 15 contiguous study units of 30 ha each. Five treatments were assigned to the units, in a randomised block design (randomisation within lower-, middle- and upper-elevation blocks): 1. Single 10-ha clearcut with 20 ha of leave strip (10-ha CC); 2. Array of nine 1-ha patch cuts with leave strips (1-ha PCA); 3. Array of 55 0.1-ha patch cuts with leave strips (0.1-ha PCA); 4. Individual tree selection (ITS) partial cuts with 20% uniform removal across the size distribution of both tree species and complete tree removal along skid trails; 5. Uncut control (UC). With associated skid trails and roading, each of the 4 harvest treatments was designed to remove 33% of the timber volume from each study unit. Harvesting occurred in winter 1994-95.

Field measurements

Permanent 10m-wide transects, totalling 1160 m to 1850 m per study unit, were used in August 1997 and again in August 1999 to measure windthrow that had occurred since harvesting. The 1997 measurements are described in Huggard et al. (1999). In 1999, each additional uprooted or snapped stem within 5 m of the transect was marked with a permanent individually-numbered tag. The following were recorded: location, tree species, dbh, total length of the stem or snapped stem, height of break if the stem had snapped above ground level, whether the stem was alive or dead at the time of fall, and direction of fall.

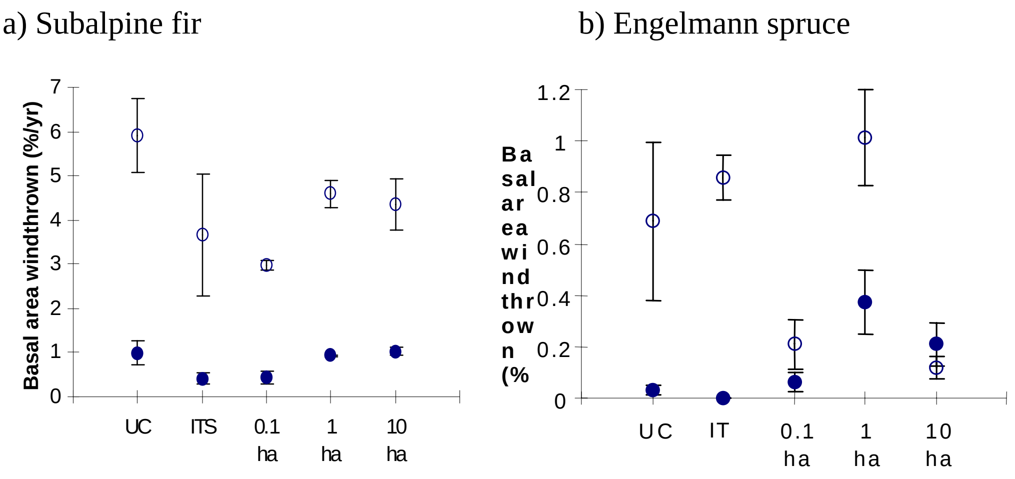
Data analysis

For this update, we followed the data analysis reported in Huggard et al. (1999). We summarize density (basal area/ha) for both uprooted and snapped stems for live subalpine fir and Engelmann spruce. Wind damage was expressed as a percentage of the residual (post-harvest) stand, and converted to an annual post-harvest rate by dividing by the time, 2.7 or 4.7 years, between harvesting and the windthrow surveys.

Results

Wind damage 1997-1999 and overall since harvest

Wind damage was higher in the August 1997 to August 1999 period (2.7 to 4.7 years after harvest) than in the first 2.7 years after harvest. Wind damage in the 1999 sample was highest in the uncut control, and somewhat lower for the harvest blocks (Fig. 1). In contrast, all harvested treatments in 1997 showed increased windthrow compared to the uncut controls (Huggard et al. 1999). Over the entire 4.7 year post-harvest period, annual basal area losses have averaged 3% per year for subalpine fir, with relatively little difference among treatments (Fig. 2). Annual damage to Engelmann spruce was substantially lower, about 1/3 that of subalpine fir in 1997 and 1/6 in 1999. Wind damage to spruce was also more variable among treatments (Fig. 2). For both species, the 0.1-ha patch cut arrays tended to have lower rates of wind damage than other harvested treatments.


a) Subalpine fir

b) Engelmann spruce

Fig. 1. Wind damage between August 1997 and August 1999 from snapping (open symbols) and uprooting (closed symbols) in uncut controls (UC), individual tree selection (ITS), 0.1-ha patch cut arrays (0.1-ha), 1ha patch cut arrays (1-ha) and 10-ha clearcuts (including leave strips, 10-ha), for a) subalpine fir, and b) Engelmann spruce. Damage expressed as percent of stand's basal area damaged per year. Error bars are 1 S.E., based on 3 replicates.

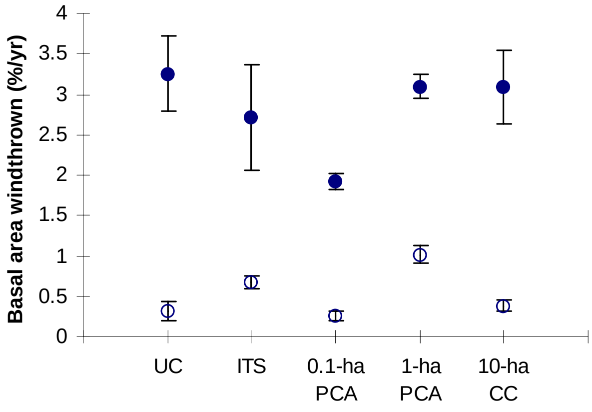


Fig. 2. Overall damage rates over 4.7 years post-harvest for subalpine fir (closed symbols) and Engelmann spruce (open symbols). Error bars are 1 S.E.

Uprooted and snapped stems

The proportion of snapped stems increased dramatically from the 1997 measurement to the 1999 measurement. In 1999, 81.2% of the damaged live subalpine fir and 68.0% of the damaged live spruce were snapped rather than uprooted, compared to 26.1% and 17.2%, respectively, in 1997. Snapped stems measured in 1999 lost an average of 60% of their height, for both species.

The incidence of stem snapping in subalpine fir was greatest in the 15 to 35cm dbh classes, and in stems with the highest height:dbh ratio in that class. The same diameter classes were most prone to windthrow in the 1997 samples, but windthrown trees in 1997 had lower height:dbh ratios than the average for the stand. The counter-intuitive 1997 result was attributed to greater windthrow in sites that produce shorter trees, such as wet areas and exposed knolls (Huggard et al. 1999).

Effects of opening size, distance from opening, and edge orientation

Levels of uprooted live subalpine fir in 1999 were highest 5 m and 25 m from the east edges of 10-ha openings, and 5 m from the north and east edges of 1-ha openings, continuing the pattern seen in the 1997 assessment. Windthrow 25 m from these edges was considerably higher in 1999 than in 1997, suggesting that wind influence is now extending further beyond the original cutblock edge. In contrast to uprooted trees, snapped stems of live subalpine fir were more prevalent away from the cut block edges. Engelmann spruce showed similar patterns, but greater variability with fewer windthrown stems.

Tree fall directions

Uprooted stems in the 1-ha PCA and 10-ha CC units showed significant directionality, with most stems falling between N and NE. This orientation corresponds to the prevailing wind direction, particularly of stronger storm winds. Fall direction of uprooted stems became increasingly random in the more uniform harvest treatments and uncut controls. The orientation of snapped stems in 1999 differed from a random pattern in all treatments, with most broken tops falling between NE and SE.

Discussion

The changes in wind damage between the first 2.7 years post-harvest at the Sicamous Creek site and the subsequent 2 years demonstrate the importance of long-term monitoring at experimental sites. Yearly variability is expected in any natural phenomenon, but at Sicamous Creek we observed substantial changes in the rate of wind damage, patterns among treatments, types of trees damaged, and how the trees were damaged.

We expected that rates of wind damage would decline in 1997-1999 compared to immediately after harvest, but we observed the opposite. This increase suggests that the "immediate post-harvest period" for windthrow is at least 5 years at this site (and/or that an exceptional event occurred between 1997 and 1999). In either case, the 3% annual loss of basal area in subalpine fir is clearly not a rate that can be sustained for many years without serious economic consequences. We can also expect substantial ecological changes in the uncut forest.

After the first assessment we concluded that harvesting at this high-elevation site led to increased windthrow in the 2.7 years following harvesting. This conclusion still holds with respect to uprooted stems but does not hold when we include stems snapped by snow and wind in the winter of 1998/99. Damage in the uncut control was severe and thus harvesting effects are no longer evident. However, the main operational conclusion from our 1997 study still holds: there is no evidence supporting the belief that alternatives to large clearcuts will lead to increased wind damage. Similar to Valinger and Pettersson (1996), we found open ITS stands had the highest wind throw, followed by leave strips adjacent to larger openings, while dense uncut controls or leave strips had high snow breakage. Between these extremes, 0.1-ha patch cut arrays seem to have the lowest overall rates of both types of damage combined.

The high incidence of snapped stems was first noticed after the winter of 1998/99. Snowfalls were unusually high that winter and were close to record levels for the last 30 years. Researchers conducting aerial surveys of wildlife in other parts of the southern interior mountains reported unusually large snow loads in tree crowns in March 1999. We surmise that heavy snow loading combined with winter winds led to breaking of the weaker stems in the canopy, predominantly those in the subdominant and intermediate diameter classes. Damage similar to that at Sicamous Creek was observed over a wide range of sites through the Shuswap Highlands.

We previously concluded that the prevalent stem rots in subalpine fir likely contributed to the higher rate of snapped stems in this species. Given the high rate of damage in intermediate diameter stems, and the widespread nature of the damage, stem snapping that leaves damaged live trees may itself lead to the elevated levels of stem rot. Such effects have been reported in Europe as a result of snow damage (Nykanen et al. 1997). Increasing the incidence of stem rot would exacerbate the long-term timber losses from the observed high rates of wind damage.

We discussed mitigation opportunities based on our 1997 results in Huggard et al. (1999). Ways to reduce losses due to snapping in winters with heavy snow are less apparent. Existing and proposed continued work at the Sicamous Creek site on microclimate, snow hydrology, regeneration and wind damage should help refine these long-term costs and benefits of alternative silvicultural systems.

Acknowledgements

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Section 2. Wind, Windthrow and Landscapes

Patterns Of Wind Disturbance In A Coastal Temperate Rain Forest Watershed, Clayoquot Sound, British Columbia

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Abstract

Disturbance patterns were investigated in a pristine old-growth 7000 ha watershed in Clayoquot Sound, British Columbia, Canada. The primary tools were an air photo record from 1939 – 1988, timber inventory data bases, and field measurements of stand structure. The process domains of floodplains, hollows and hillslopes describe areas of similar geomorphic processes and so disturbance regimes, including different forest types and patterns of wind disturbance. On floodplain terraces (4% of the watershed), *Tsuga heterophylla* and *Abies amabilis* predominate (HA forest type). In hollows on colluvial slopes, (26% of the watershed), *Thuja plicata* and *Tsuga heterophylla* predominate (CH forest type). On bedrock hillslopes, (52% of the watershed), *Thuja plicata* and *Chamaecyparis nootkatensis* occur (scrub forest type). Characteristics of old-growth forests were primarily influenced by process domains and species-specific interactions between wind and pathogens. *Abies* and *Tsuga* primarily die by snapping, likely due to their vulnerability to fungi that cause rot and weaken boles. *Thuja* on colluvial slopes die primarily by uprooting due to root abrasion on bedrock substrate from trees swaying in the wind, creating entry points for fungi. Disturbances were virtually all gap-phase events and do not appear to play a strong role in these forests. There were no stand-replacing wind disturbances in the study area within the past 140 years. Geomorphic disturbances were stand-replacing but were confined to < 5% of the study area. If this pattern is a long-term phenomenon, then forest organisms are primarily adapted to small-scale disturbance events. Because nearly all forests in Clayoquot Sound are old (> 250 years), stand age is not a useful criterion for forest conservation. Process domains may be a more useful for describing ecosystems, both for conservation purposes and as a basis for managing forests for natural variation.

Introduction

The spatial and temporal variability driven by disturbances is now recognized as a vital attribute of ecosystems (Landres et al. 1999). In forests, disturbances create a mosaic of different successional and structural types in the landscape (Heinselman 1973; Connell and Slatyer 1977; Whittaker and Levin 1977; Pickett and White 1985; Foster and Boose 1992). Many of the specialized habitats and functional abilities of natural forests are related to their structural complexity (Franklin 1998). However, forest structure is not solely determined by disturbance, but is maintained by a complex interaction among disturbance, vegetation type, climate and topography (Grimm 1984; Pastor and Broschart 1990; Spies and Franklin 1991; Foster and Boose 1992; Lertzman et al. 1996).

From studies of the role of disturbances in natural systems, the importance of incorporating disturbances into management schemes has also been recognized (Swanson et al. 1993; Attiwill 1994; BC Forest Service 1995; Clayoquot Sound Scientfic Panel 1995; Mangel et al. 1996; Rogers 1996; Landres et al. 1999). Despite their importance, natural disturbances and their influences on forest structure are poorly understood in coastal temperate rain forests, especially in British Columbia. Unlike other temperate forests, wind and geomorphic events, not fire, are considered the primary disturbance agents in coastal temperate rain forests (Alaback 1996). Wind disturbances in coastal forests have been investigated in southeast Alaska e.g. (Harris 1989; Deal et al. 1991; Kramer 1997; Ott 1997; Nowacki and Kramer 1998) and on the east side of Vancouver Island (Keenan 1993), but not on the west coast of Vancouver Island, or the mainland coast.

The following questions were asked in this study in order to understand natural disturbance patterns in a pristine system and to provide background for sustainable forest management;

1. What are the spatial and temporal patterns of wind disturbances in a coastal temperate rain forest watershed?
2. What is the relative importance of gap-phase regeneration versus stand-replacing disturbances?
3. Given that forest structure is a product of disturbance, vegetation type, site and topography, how do these elements interact to create patterns of forest structure at the stand and landscape level?

An entire 7000 ha watershed was chosen as the unit of study for several reasons. First, management is often at the scale of a watershed, which is considered a "natural unit" for ecosystem management. Second, the scale of analysis can influence the results (Lertzman and Fall 1998). Therefore, if management takes place at the watershed scale, then natural disturbance patterns need to be analyzed at the same scale in order to be applicable.

This conference report is a summary of the findings of (Pearson 2000) which details a larger investigation of all disturbances in the Clayoquot Valley watershed. More detailed information, including data, will be submitted for publication in the next few months.

Study area

Clayoquot Sound is a 262,000 ha region located on the west coast of Vancouver Island, BC (Clayoquot Sound Scientific Panel 1995). Twelve percent of the forested area of Clayoquot Sound has been logged, leaving 214,000 ha of pristine forest. There are five pristine watersheds > 5000 ha located in Clayoquot Sound, the Clayoquot, the Megin, the Moyeha, the Sydney, and the Ursus (Moore 1991); BC Ministry of Forests, unpubl. data). Clayoquot Valley was chosen as the watershed for detailed study. It comprises an area of 7700 ha and is located on the southern edge of Clayoquot Sound, approximately 20 km from Tofino.

Where possible, the other watersheds were examined to determine whether the patterns observed in Clayoquot Valley occurred in other watersheds or were unique.

The study watersheds are all glacially-incised valleys that are primarily rock-controlled with little surficial material. They have relatively flat valleys and steep side walls with slopes commonly greater than 20°. Most of the soils in Clayoquot Sound are podzols, while folisols and gleysols also occur (Jungen and Lewis 1978; Jungen 1985). Clayoquot Sound has a maritime climate, with mild, moist conditions (Environment Canada 1993). Precipitation is abundant, the majority of which falls as rain during the winter. Winds in coastal BC generally vary seasonally, although storms with accompanying strong winds can occur at any time of the year (Clague and Bornhold 1980; Cannings and Cannings 1996). In the summer, winds are predominately northwest and west and of relatively moderate intensity. In winter, winds are stronger, southeast and east and frequently of storm intensity. Storm winds are usually southeasterly.

Clayoquot Sound is located principally in the Coastal Western Hemlock (CWH) zone, with the Mountain Hemlock (MH) and Alpine Tundra (AT) zones present at higher elevations (Radcliffe 1991; BC Ministry of Forests, Biogeoclimatic Ecosystem Classification Map for Coastal BC). Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) is a dominant or co-dominant tree species throughout the Coastal Western Hemlock zone (Clayoquot Sound Scientific Panel 1995). Western redcedar (*Thuja plicata* Donn), amabilis fir (*Abies amabilis* (Dougl.) Forbes), yellow cedar (*Chamaecyparis nootkatensis* (D. Don) Spach), Sitka spruce (*Picea sitchensis* [Bong]. Carr), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and shore pine (*Pinus contorta* Dougl. ex Loud. var. contorta) also occur under differing conditions. Sitka spruce is primarily restricted to active floodplains and recent terraces. Douglas-fir occurs as scattered dominants. Shore pine occurs on rock outcrops, in *Sphagnum* bogs and along exposed coastlines.

Methods

The primary tools for investigation were an airphotos series and GIS timber data bases developed for timber inventory. Air photo series were available for 1987/88 at 1:20,000 scale (modern air photos) and for 1939, 1954, 1968/70, and 1981 (the historical photos), which ranged in scale from 1:20,000 to 1:40,000.

Wind disturbances were investigated through an iterative process. First, the modern and historical airphotos for Clayoquot Valley were surveyed for any openings in the canopy or fine-texture patches indicative of stand-replacing disturbances, especially where downed wood was oriented in a prevailing direction. A stand-replacing disturbance was defined as an opening of three median tree heights in radius with $\geq$ 70% tree mortality. From the timber inventory data base, median tree height was 40 m which translated into a circular opening of 4.5 ha. The modern and historical air photos for the Megin, Sydney and Ursus watersheds were also checked for any evidence of stand-replacing disturbances. As a final check, the air photos for the area of a known windstorm, the 1906 blowdown on the east side of Vancouver Island, were checked to determine the duration of visibility of a major storm event on air photos.

Second, stand-level characteristics of forest structure and wind disturbances were investigated. Differences between species in their response to wind have been observed in forests around the world (summarized in (Everham and Brokaw 1996)) and in coastal temperate rain forests (Baker 1915; Harris, 1989; Keenan, 1993). The two phases, or forest types, in Clayoquot Sound (the Hemlock-Amabilis fir (HA) phase and the Cedar-Hemlock (CH) phase) are hypothesized to have different wind disturbance regimes, especially with respect to the occurrence of stand-replacing disturbances (Keenan 1993; Clayoquot Sound Scientific Panel 1995). Therefore, this study adopted the working hypothesis that characteristics of wind disturbance varied between the HA and CH forest types. These forest types were identified from tree species composition information for the fcmap polygons, and were the sampling strata for analysis of wind disturbances. Based on evidence from wind disturbance studies in forests around the world, snapped snags, uprooted trees, mineral mounds and directional azimuth of coarse woody debris were all considered evidence of wind disturbance (Everham and Brokaw 1996; Ott 1997; Rebertus et al. 1997; Greenberg and McNab 1998).

From the fcmap polygon information, plots were established in CH and HA forests types in Clayoquot Valley to determine the nature of wind disturbance characteristics that occurred in these forest types. From that information, which included air photo signatures associated with different forest types, a preliminary classification for wind disturbances was developed, which was tested and further refined from groundtruthing the classification and additional field sampling. From all this information, the air photo survey, field reconnaissance, plot information and groundtruthing, the air photos for Clayoquot Valley were classified for wind disturbances. The air photo classification was developed for the 1987/88 air photo series and checked on the historical air photos. All polygons identified as wind-disturbed were checked on the historical air photos to see if there was any evidence to determine when the storm occurred and for any additional disturbances that were no longer visible on the 1987/88 air photos.

Field methods for stand structure followed Spies and Franklin (1991). Gap transects following Lertzman et al. (1996) were also established to confirm the mortality of canopy trees and further investigate the extent of stand-replacing events. Azimuth of coarse woody debris was determined for wood that would have been dominant or co-dominant trees when living. Field sampling was strongly constrained by accessibility. Sampling was confined to below 500 m elevation. Above 500 m elevation, the air photo signature was relied upon for the classification.

Results

Extent of stand-replacing wind disturbances

There were no openings or fine-textured patches indicative of stand-replacing wind disturbances on the airphotos for Clayoquot Valley or the other watersheds for all the years of record. The 1906 blowdown was clearly visible on the 1987 air photos, 80 years after the event. Therefore this result was considered valid, i.e. there were no stand-replacing wind disturbances detected because they did not occur, not from an artifact of errors in air photo interpretation or duration of visibility of storms on air photos. Given there was no evidence of stand-replacing disturbances on the earliest photos, 1939, this translated into no evidence of stand-replacing wind disturbances for 140 years (80 years from 1939). This result was corroborated with the tree age data in the timber inventory data base. In all the watersheds, the area of polygons with forests < 100 years was extremely small, < 1% of the area of the watershed. In all cases, they were geomorphic in origin; deciduous species in the riparian zone and landslides. The area of the watersheds of polygons with forests 101 – 200 years old, was more variable; <1% in the Sydney and Ursus, 7.5% in the Clayoquot and 19% in the Megin.

The age-class diameter distributions for the HA and CH types also supported the result of no stand-replacing wind disturbances. Two polygons had a pulsed tree diameter class distribution in the HA forest type, with the remainder being in an approximate j-shaped distribution. In the CH forest type polygons, all the tree diameter class distributions were j-shaped, with no pulsed distributions. In both forest types, the diameter class distribution of snags and coarse woody debris were smaller or equal to that of the living trees. Thus, in the dead wood components, there was no evidence of previous stands that had been destroyed prior to establishment of the current stands, as would be expected in a stand-replacing disturbance.

Stand level characteristics of the HA and CH forest types

The CH and HA forest types did show differences in their forest structure with respect to characteristics of wind disturbances, as well as differences in successional patterns. In the HA forest type, the azimuth of coarse woody debris was directional, not random for all polygons sampled. However, the wood was not oriented in the direction of prevailing SE storm winds (i.e. NW). Rather, it was broadly distributed N to S, i.e. in the direction of winds oriented with the watershed's SW –NE topography. Tree death was primarily by snapping, rather than uprooting or standing dead. There was no successional pattern between amabilis fir and western hemlock. Both occurred in all canopy positions in all combinations.

In the CH forest type, none of the polygons sampled had directional coarse woody debris. Rather, all wood was oriented in a random direction. The majority of tree death was by uprooting, rather than snapping. There was a successional pattern with western red cedar always dominant or emergent and virtually absent from the smaller size classes. In contrast, western hemlock was well-represented in the understorey and intermediate size classes but was rarely dominant and never emergent.

The differences in modes of mortality were a function of species, and their occurrence in different forest types, rather than forest type per se. Hemlock died primarily by snapping, even when hemlock occurred in the CH forest type. Western red cedar died primarily by uprooting but there were only two cedar gapmakers in the HA forest type. Conversely, amabilis fir died by snapping, but amabilis fir gapmakers rarely occurred in the CH forest type.

Landscape level patterns of wind disturbances

From the stand-level data, the differences between CH and HA forest types with respect to characteristics of wind disturbances was considered sufficient to support the working hypothesis and they were considered distinct wind disturbance types. The CH forest type was further subdivided into scrub forest based on its distinctive air photo signature plus information from a previous study in the watershed adjacent to Clayoquot Valley, Tofino Creek, where stand-level data for this forest type were obtained (Lertzman et al. 1996) (Table 1.) Occurrence of forest types was strongly related to geomorphology i.e. terrain unit (Table 1.) The HA and CH forest type primarily occurred in the lower elevations of the watershed and the scrub forest type at higher elevations. Further, not all forest types were of equal extent. The HA forest type covered 4% of the watershed, the CH forest type 26% and the scrub forest type 52%. Wind affected 82% of the area of the watershed. For the remainder of the watershed, geomorphic disturbances were the primary disturbance agent or the area was permanently non-forested (rocks and cliffs.) Wind also influences the riparian zone. However, it comprises only 2.4% of the area of the watershed.

Table 1. Classification of forest types and wind disturbances for Clayoquot Valley

Forest type	Terrain Unit(s)	Major species	Air photo signature
HA	floodplain fans and terraces; colluvial cones	amabilis fir, western hemlock	fine-textured gaps; often small; snapped snags visible
CH	moderately steep – steep colluvium; colluvial veneer over bedrock	western red cedar, western hemlock	large, deeply shadowed gaps
Scrub	moderately steep – steep bedrock	western red cedar, yellow cedar, western hemlock	undifferentiated texture with underlying bedrock often visible

Discussion

Extent of stand-replacing disturbances

There was no evidence of stand-replacing wind disturbances in Clayoquot Valley or any of the other watersheds investigated in Clayoquot Sound. This finding contrasts with patterns of wind disturbance reported in some studies in southeast Alaska, but is consistent with results from other studies in coastal temperate rain forests. However, in southeast Alaska, stand-replacing disturbances varied from 0.85% (Harris 1989) to 20% of the forested landscape (Kramer 1997), i.e., two orders of magnitude difference. Even where stand-replacing disturbances occur, the area of the landscape they influence varies widely. In studies of tree age structure in southern coastal BC and Vancouver Island, forests were multi-aged with pulsed or continuous patterns of recruitment (Beese and Sandford 1992; Inselberg 1993; Daniels 1994; Arsenault 1995). From evidence of the similarity in the gap-phase structure of these forests, despite their geographical and climatic differences, small-scale, low-intensity disturbances commonly occur (Boyle 1996; Lertzman et al. 1996). Results from this study are consistent with these findings, although the other studies did not investigate patterns at the scale of a watershed.

Foster and Boose (1992) postulated that gap-phase regeneration versus stand-replacing wind disturbances was not simply a dichotomy based on the intensity of storms, but rather a complex interaction of wind intensity, site and vegetation. Stand-replacing disturbances in southeast Alaska have been reported to primarily occur on southeast-facing slopes directly exposed to storm winds or in topographically vulnerable areas (Harris 1989; Kramer 1997; Ott 1997). Further, in most wind disturbance studies, a few storms have been found to be responsible for the majority of the damage, even in areas that experience frequent storms

(Rebertus et al. 1997; Sinton 1996; Harris 1989; Nowacki and Kramer 1998). Finally, even when storm winds are extreme, creation of large patches appears to be a rare event and a patch size distribution in an exponentially declining curve has been reported in all areas, with most patches < 10 ha.

Clayoquot Valley and the other Clayoquot Sound watersheds are not directly exposed to southeast storm winds, which may explain the lack of stand-replacing disturbances. Alternatively, a major storm capable of causing substantial damage to the forest may not have occurred recently enough to still be visible on the air photos (140 years) or in the age class data in the timber inventory data base. Finally, even when major storms do occur, given the typical negative-exponential patch size distribution, large patches are sufficiently rare, that stand-replacing disturbances are also rare. Wind disturbance patterns in watersheds in Clayoquot Sound may be analogous to eastern deciduous forests where most wind disturbances are small-scale events. While catastrophic wind disturbances do occur in eastern deciduous forests, they are sufficiently rare (once every several tree generations) that multi-aged forests develop, often with shade-tolerant species as dominants (Bormann and Likens 1979a; Runkle 1985; Webb 1989; Payette et al. 1990; Runkle 1990).

Landscape-level patterns of wind disturbance

The Process Domain Concept is a hypothesis that spatial variability in geomorphic processes governs patterns of disturbances, which in turn influence ecosystem structure and dynamics (Montgomery 1999). One can therefore define and map domains within a watershed characterized by different geomorphic processes and so disturbance regimes, and these divisions have ecological significance. The results from this study generally supported the Process Domain Concept model. The process domains of hillslopes, hollows and floodplains correspond to different forest types, which in turn have different disturbance patterns with respect to the influence of wind disturbances. Disturbance patterns also varied as a function of location in the watershed, another prediction of the Process Domain Concept model.

Scrub forest is the most extensive forest type in Clayoquot Valley, encompassing 52% of the watershed, and occurring on bedrock hillslopes. While stand-level processes could not be investigated in the scrub forest type in this study, its classification as a different forest type was considered valid based on air photo signature and evidence of characteristics of wind disturbances in other studies. Extensive areas of southeast Alaska have been surveyed for wind disturbances and scrub forests have been found to have no evidence of stand-replacing events (Harris, 1989: Kramer, 1997). Scrub forests occur on less productive sites and organic soils and have relatively open canopies with short, tapered trees (Harris 1989). These characteristics result in a stand that is relatively unaffected by wind because the small, open crowns are highly permeable to wind, the canopy is of uniform height and trees are small, so canopy roughness is minimal. In this forest type in Tofino Creek, the watershed adjacent to Clayoquot Valley, standing dead was the most frequent form of mortality (Lertzman et al. 1996), in contrast to uprooting and snapping, the predominant forms of mortality for the CH and HA forest types respectively.

Patterns of stand structure in HA and CH forest types

Stand-level structure in the HA and CH forest types is a result of interactions between species, site characteristics, wind and biotic agents. In the HA forest, snapping is the primary mode of mortality due to the vulnerability of dominant tree species to biotic agents which in turn leaves them vulnerable to wind. Western hemlock and amabilis fir are vulnerable to rots, especially heart rots, leaving them more likely to snap rather than uproot (Kimmey 1956; Hennon 1995).

Patterns in the HA forest type generally support Hennon (1995)'s model of heart rot succession where the interaction between wind and heart rots creates a pattern of gaps slowly opening and closing on the landscape from death of canopy trees by snapping. Processes in the HA forest type are primarily gap-phase regeneration, the majority of gapmakers are snapped, and snags are of variable height, which would be consistent with snapping from wounding from heart rot invasion. Hemlock and amabilis fir in the CH forest type also primarily snapped, indicating that this pattern is species- rather than forest-type specific. Studies in southeast Alaska have also found the majority of gapmakers to be snapped in hemlock forests (Hocker 1990; Ott 1997; Hennon and McClellan 1998).

While western redcedar is more resistant to rots than western hemlock and amabilis fir (Burns and Honkala 1990; Scharpf 1993), biotic agents also play a role in the predominance of uprooting in the CH type, and in cedar. The CH forest type is primarily located on steep to moderately steep colluvium, and cedars are often dominant or emergent. In other regions, trees rooted on bedrock surfaces have been observed to be uprooted with abraded root systems (Day 1949; Stone 1977). The basal roots of large trees make firm contact with rock surfaces when soils are shallow over bedrock or boulder parent material. Unless these surfaces are smooth, the roots are abraded when the tree sways in the wind. This abrasion not only physically affects root strength, but also provides entry courts for decay (Redmond 1957; Whitney 1961). Uprooted trees often have short, peg-like roots that appear ground off (Hermann and Petersen 1969; Hintikka 1972; Stone 1977). In Clayoquot Valley, large uprooted cedars were often observed with abraded root systems of considerably less area than living trees. Emergent cedars would be especially exposed to wind that would cause movement of their root plates on bedrock, further exacerbating root abrasion.

Successional patterns in the HA and CH forest types

In the HA forest type, both western hemlock and amabilis fir occurred in all diameter classes in varying abundances in both the living and dead wood components. In the CH forest type, there was a strong species-specific pattern with respect to tree diameter class distribution. Western redcedar was confined to the larger size classes and is absent from the intermediate and understorey classes, while western hemlock occurred only in the smaller size classes and was absent from the canopy. There was no evidence that the HA and CH forest types were successional phases of each other. Rather they are distinct and separate ecosystems where succession is internal and cyclical rather than progressive, a result corroborated by successional patterns after the 1906 wind storm on the east side of Vancouver Island (Keenan 1993). Successional patterns varying as function of site has also been found in subalpine forests in Colorado (Donnegan and Rebertus 1999) and in forests in northwestern Pennsylvania (Runkle 1985). Finally, there is no support that the most commonly used model of forest succession, the "stand-initiation model" (Oliver and Larson 1996) is applicable to forests in Clayoquot Sound's watersheds beyond the confined areas of geomorphic disturbances.

Implications for forest conservation and management

If "old growth" is a criterion for conservation of forests, it is imperative to understand the characteristics of old-growth stands and how to identify them (Lugo 1997). Old-growth forests are usually defined by structures that develop over time since stand-replacing disturbances (e.g. (FEMAT 1993)). However, age criteria used to identify old-growth forests in the Pacific Northwest based on these criteria have not proven applicable in other life zones (Lugo 1997). Many attributes of old-growth forests that are of value to biodiversity are associated with structural diversity, especially the presence of large diameter trees and dead wood (Franklin 1988; Ruggiero et al. 1991; Clayoquot Sound Scientfic Panel 1995; Franklin 1998; Lofroth 1998; MacKinnon 1998). In the absence of stand-replacing disturbances, this structural diversity is not associated with age, i.e. time since disturbance.

Forest structure is not solely determined by disturbance, but is maintained by a complex interaction among disturbance, vegetation type and topography (Grimm 1984; Pastor and Broschart 1990; Spies and Franklin 1991; Foster and Boose 1992; Lertzman et al. 1996). For example, to identify "old-growth" mangroves one has to account for differences in stand structure and function due to geomorphology, within site environmental gradients and regional disturbance regimes because mangrove forest structure varies dramatically along several natural gradients (Lugo 1997). Such an approach may be necessary in coastal watersheds. In the absence of stand-replacing disturbances, process domains may more effectively describe forest structure than does age because they encompass the integration of site factors that determine forest structure, and so value to biodiversity.

Further, the most productive forests also contain the tallest trees, and so the greatest structural diversity. In the absence of stand-replacing disturbances, such stands could be at least preliminarily identified by height information in timber inventory data bases. Their identification is important because productive forests, such as the riparian forests, are often of small extent in coastal watersheds, given the typical steep, rock-controlled topography. (The riparian zone comprised only 2.4% of the area of the Clayoquot Valley watershed.) The relationship between tree height and forest structure, including structural diversity, would need to be more rigorously investigated to determine if there is a strong relationship that is relevant to biodiversity. However, given the importance of productive forests to biodiversity, including the riparian forest (Franklin 1999), it is a reasonable working hypothesis.

If the absence of stand-replacing disturbances is a long-term phenomenon, then biota in these forests have adapted to small-scale events and the range of natural variation is at the scale of gap-phase regeneration. Geomorphic disturbances are stand-replacing but very confined geographically and in extent, < 5% of the watersheds, so do not influence the majority of the forest. In areas outside the protected watersheds, if the intent of forest practices is to model natural disturbance patterns, this would require maintaining a matrix of closed forest with small openings (Lertzman et al. 1996), assuming the pattern of no-stand replacing disturbances is widespread in the forests of Clayoquot Sound. The degree to which gap-phase regeneration is the dominant disturbance process beyond the watersheds of Clayoquot Sound is unknown, especially for BC's mainland coast where landscape patterns of wind disturbance have not been investigated. It is reasonable to hypothesize that a gradient exists analogous to the one reported in southeast Alaska where forests directly exposed to southeast storm winds experience stand-replacing disturbances while those in sheltered topographies do not. This is an important area for further research because one of the goals of ecosystem management in BC is to model natural disturbance patterns, which includes the size of openings.

Approaches to conservation and natural resource management are developing rapidly in response to changing perceptions of biodiversity and ecological systems (Poiani et al. 2000). The inadequacy of focusing conservation strategies solely on species is now well recognized because this approach failed to protect lesser known species, processes or function (Franklin 1993). Larger-scale approaches at the level of ecosystems and landscapes are the only way to conserve existing biodiversity and so manage forests sustainably. The shift in focus from protecting species to ecosystems, however, has brought new questions as to how ecosystems are defined and delineated (Poiani et al. 2000).

While the Process Domain Concept (Montgomery 1999) may be regarded as a working hypothesis, the results of this study demonstrate that dividing the watershed into hillslopes, hollows and floodplains does have ecological significance and does form a basis for describing natural variation at the scale of a watershed. Process domains are certainly superior to regarding a watershed as a homogeneous unit or considering all forests within broad elevational ranges, such as variants, to be homogeneous, especially with respect to protecting representative ecosystems. This landscape-level spatial context is also important with respect to stand-level patterns. In the HA and CH forest types, stand-level structure is a function of species, site characteristics, and interaction between wind and biotic agents. Assuming the patterns in Clayoquot Valley are broadly applicable to forests in Clayoquot Sound, then structure left in a variable retention scenario will be influenced by those factors as well.

Through various initiatives, the BC Government has recognized the importance of natural variation in forests for biodiversity, and the importance of forest management modelling natural disturbance patterns in order to maintain native species and ecological processes (BC Forest Service 1995). The challenge still remains to apply these concepts at the scale of watershed in an ecologically meaningful manner.

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Wind Climatology and High Wind Events in Northeast British Columbia 1995-2000

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Abstract

A study of wind climatology and extreme wind events was carried out in north-central and northeast British Columbia from 1995 to 2000. A total of ten 9.1-m high wind tower were erected to measure windspeed and direction in large clearcut or partial-cut openings.

Extreme wind events, which were defined as beginning when the 1-sec. wind speed exceeds 20m/s (72km/hr), occurred at every site. Three of the more mountainous or exposed sites measured 1-sec gusts over 28m/s (100km/hr). Return intervals for extreme wind events ranged from as little as 26 days up to 605 days. Wind directions during extreme wind events were typically from southerly to westerly as a result of large scale synoptic weather patterns. The spatial and temporal distribution of extreme wind events was concluded to be very dependent on local topography. Detailed data collected during extreme wind events show the very gusty nature of high winds.

Introduction

Detailed data on wind climatology and extreme wind events in north central and northeastern British Columbia is almost non-existent. Existing historical data is limited to a handful of airport locations and is often very generalized (hourly/daily means and maximums taken by visual observation of a gauge or strip chart recording at certain times). This data is of limited use in determining forested areas with high risk of windthrow . In this study, a network of nine-meter high towers were installed in a variety of biogeoclimatic zones and terrain types in north-central and northeastern B.C. The objectives were to collect generalized data on wind climatology and the incidence of extreme wind events as well as characterize these events by collecting detailed, 1-sec measurements of windspeed and direction. These measurements were taken in conjunction with measurements of windthrow in nearby partial-cut forest stands.

Methods

Site Locations

Ten, 10-m high wind towers were erected in the study area between 1993 and 1998. The geographic locations are shown in Figure 1.

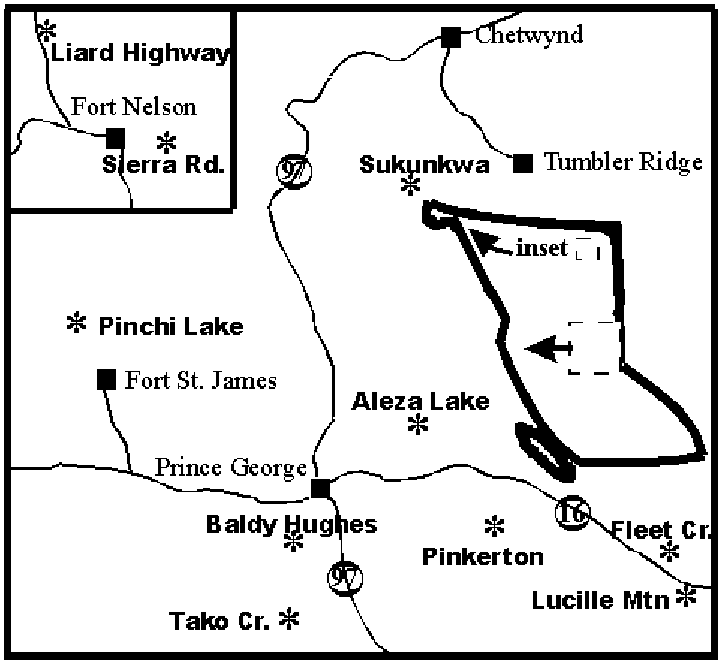

Figure 1. Geographic locations of the ten wind tower sites denoted by asterisks

The Lucille Mtn. and Fleet Cr. sites are located near Mcbride, B.C.; with the former being situated on an exposed mountain slope approximately 900-m above the broad Rocky Mtn. trench and the later, on a gently sloping bench about 150-m above the valley bottom. The Pinkerton Mtn. site is located on an exposed high elevation clearcut in the Cariboo Mtns. southeast of Prince George. The Aleza Lake and Tako Creek sites are located on the gently rolling Interior Plateau east and south of Prince George respectively. The Baldy Hughes site is located on the side of an isolated large hill which rises above the Interior Plateau south of Prince George. The Pinchi Lake site is located northwest of Fort St. James at mid-slope in a narrow valley oriented northwest to southeast. The Sukunkwa site is in an exposed high elevation location on the east side of the Rocky Mtns. south of Chetwynd. The Liard Highway and Sierra Road sites are located on the flat, to gently rolling, terrain of the Fort Nelson lowlands. All towers were located in clearcuts or partial-cuts (sparsely populated with trees) with fetches of >10 tree heights to surrounding uncut forests.

Tower Installation and Instrumentation

The wind towers consisted of three, 3.05-m sections (3-sided, galvanized steel, climbable, Radioshack Inc.) bolted together and guyed at two levels. Towers were bolted to a prefabricated steel baseplate which in turn was bolted to a large tree stump or poured concrete pad (2 sites). Towers were guyed to tree stumps or buried concrete deadmen. The actual height of the tower top where instrumentation was installed varied from 9.4-m to 10.1-m due to varying stump and concrete pad heights.

Instrumentation consisted of an anemometer/windvane (RM Young Inc., Traverse City, Michigan, Model 05130) mounted at the top of the tower. Data were collected using dataloggers (Campbell Scientific Inc., Edmonton, Alberta, Model CR10X) housed in watertight enclosures bolted to the bottom of the tower.

Data Collection

Measurements were logged once per second and general statistics were based on one-minute wind runs. These included hourly averages of windspeed and direction; daily maximum, minimum and mean windspeeds; and daily histograms (eight direction classes) of wind direction. The datalogger was programmed to collect more detailed data in cases of extreme wind events. The threshold for beginning detailed measurements was set to a 1-sec windspeed of 20m/s (72km/hr). The data collected included summaries of minimum, maximum and average windspeed and average wind direction for each minute. This intense data collection continued until the 1-sec windspeed had not exceeded the 20m/s threshold for a period of one hour. At the end of this hour, an additional array consisting of 250 seconds of 1-sec windspeed and direction data was stored by the datalogger. This array was centered on the highest 1-sec gust during the wind event. For the purpose of this analysis, one extreme wind event was separated from the next when six hours or longer had elapsed since the end of the last intense data collection period. An individual extreme wind event therefor, could consist of multiple blocks containing the more frequently collected data.

Results

HighWind Climatology

Table 1 gives wind statistics for each of the ten stations. The sites located in mountainous areas (Lucille, Pinkerton and Sukunkwa) have the highest frequency of extreme wind events (1-sec windspeed > 20m/s). The one exception to this is the Baldy Hughes site, which is second only to Pinkerton in terms of the shortest average return interval for extreme wind events. This clearly illustrates the effects of local topography causing streamlines to bunch up when they are force to go around and over the isolated hill. Pinkerton is by far the windiest site, with a return interval of only 26 days for extreme wind events, compared with almost two years for the Pinchi and Liard Highway sites. The highest recorded 1-sec wind gusts exceeded 28m/s (100km/hr) at Lucille, Pinkerton and Baldy Hughes. Average windspeed, while giving a general indication of windiness, is a poor predictor of peak 1-sec windspeeds at a given site.

Table 1 Summary of windspeed climatology for Prince George Forest Region wind towers 1995-2000.

Site	# of Days	avg wnd spd (m/s)	1-min wnd run max wnd spd (m/s)	# of gust events 1-s wnd spd > 20m/s	avg return interval (days)	max 1-s wnd spd (m/s)
Lucille Mtn	1827	2.8	18.9	14	130	28.5
Fleet Creek	1911	2.5	16.3	5	382	23.0
Aleza Lake	1964	2.1	17.0	9	218	24.1
Pinchi Lake	1814	2.0	14.2	3	605	22.7
Fort Nelson SR	1582	1.5	16.1	6	264	27.8
Fort Nelson LH	1148	1.7	13.0	2	574	21.1
Pinkerton Mtn.	1087	3.4	23.1	42	26	28.2
Tako Creek	797	1.8	14.2	4	199	20.8
Baldy Hughes	742	3.3	19.3	14	53	28.1
Sukunkwa	1152	1.9	14.0	12	96	24.9

The maximum windspeeds based on 1-sec wind runs averaged 1.5 times those based on 1-minute wind runs.

Table 2 documents the wind direction associated with the peak wind gust for 111 extreme wind events. This table shows that peak wind gusts come predominantly from directions ranging from southeast to west. Only three of the 111 peak wind gusts originated from directions in the northeast quadrant. Seven of the eight peak wind gusts at the two Fort Nelson sites originated from the northwest quadrant. There is clear evidence of the influence of topography on wind direction in the table. Four of the five peak gusts recorded at the Fleet Creek site originated from either the up or down valley directions. The high concentration of peak wind gust from the southeast at Pinkerton Mtn. is likely due to local terrain effects.

Figure 2 shows the number of extreme wind events at all sites that occurred in each month. Extreme wind events occur predominantly in the fall and winter months (October through March). It is notable however, that more than one extreme wind event occurred in each month and that nearly one-third (30) of the 111 extreme wind events occurred within the six months from April through September.

The frequency of high winds as a function of time of day was investigated. Figure 3a shows a frequency distribution for times of day when maximum windspeeds occurred (based on 1-minute wind runs) at Pinkerton Mountain. There were two clear peaks in the data; one at around midnight and one in the early afternoon.

Table 2 Number of cases at wind tower sites for various wind directions of peak wind gust during a gust event (1-sec windspeed > 20 m/s).

Site	Wind Direction															
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Lucille Mtn.								1		3	3	1	3			2
Aleza Lake		1							4		1	1	2			
Fleet Creek			1					1							3	
Pinchi Lake							1	1						1		
Fort Nelson SR											1			2	1	2
Fort Nelson LH													1	1		
Pinkerton Mtn.					1		19	6	4		3	3	3	3	1	
Baldy Hughes							1	2	7	1	2	1				
Sukunkwa								1	1	2	3	3	2			
Tako Creek										1	1	1	1			
Totals	0	1	1	0	1	0	21	13	16	7	14	10	12	7	5	4

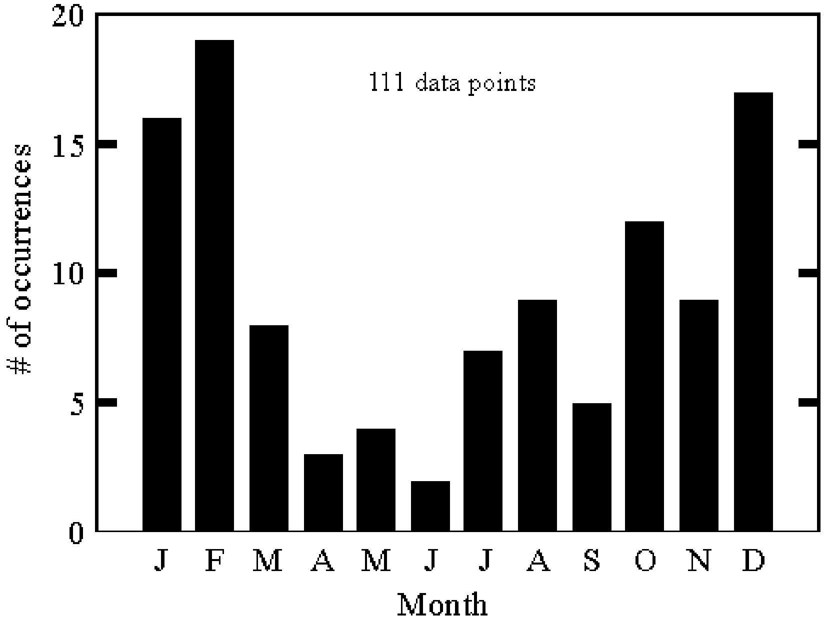

Figure 2. Number of occurrences of extreme wind events (1-sec windspeed > 20 m/s) at all sites in the various months.

This pattern was typical for nearly all the sites. Figures 3b and 3c show the frequency distributions when only considering days with maximum windspeeds >10m/s and 15 m/s respectively.

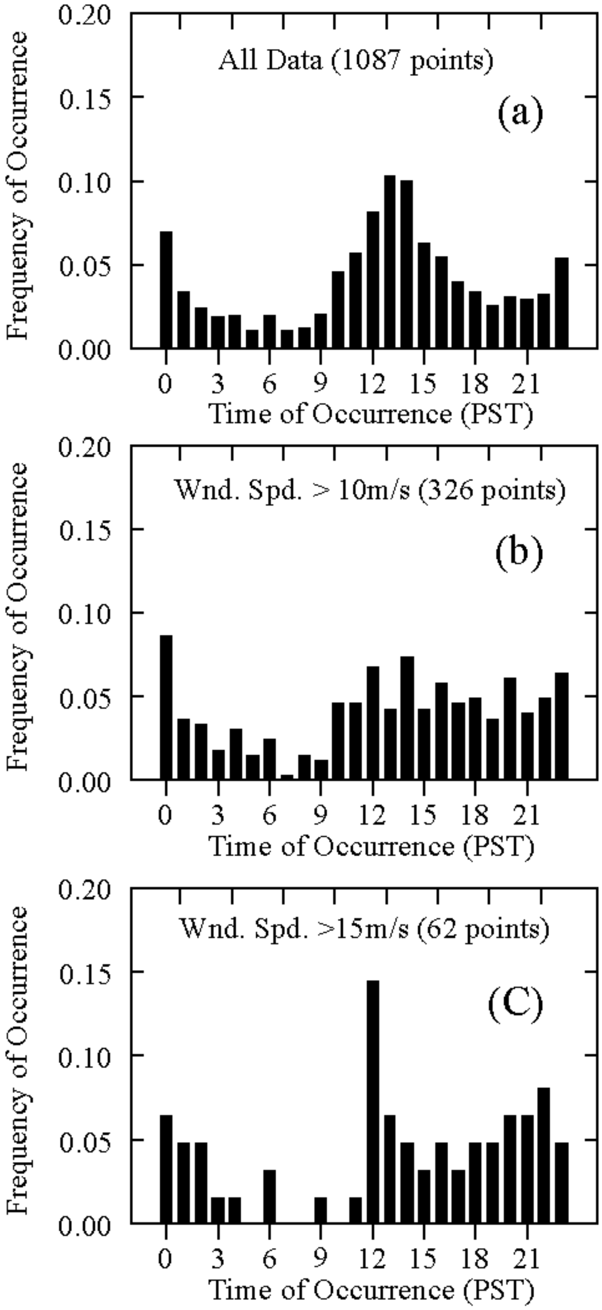

Figure 3. Frequency distributions of time of daily maximum windspeed (based on 1-minute wind runs) at the Pinkerton Mtn. site for (a) all windspeeds (b) windspeeds > 10m/s and (c)windspeeds > 15m/s

These figures show a more even distribution for the time of maximum windspeeds with some indication that the midnight maximum may persist for windspeeds > 10m/s. It is clear that much of the mid-day peak seen in Figure 3a is due to relatively light winds. Figure 4 shows the frequency distribution of times for peak wind 1-sec wind gusts during extreme wind events at all sites. The graph shows that times of peak windspeeds are distributed relatively evenly throughout the day. The peak at 1600 PST is probably not very significant, given the limited number of observations.

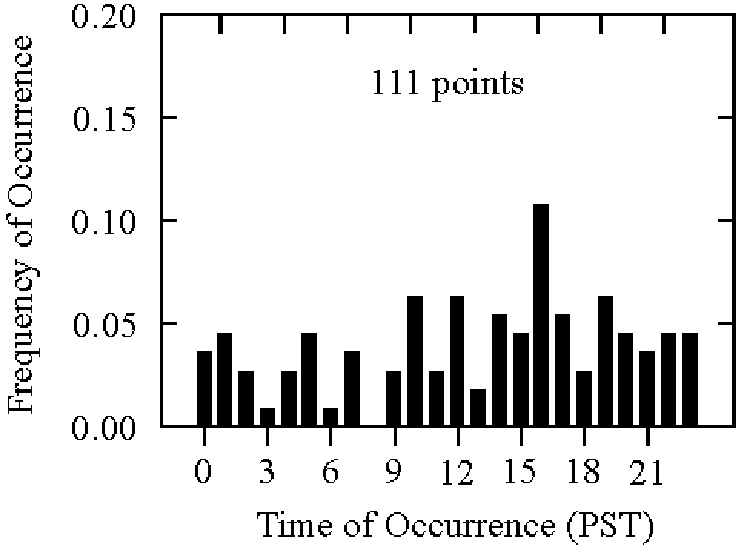

Figure 4. Frequency distribution of times for peak 1-sec wind gusts during extreme wind events at all sites.

Analysis of the dates of 88 extreme wind events since October 1997 shows an interesting pattern. For 74 of these dates, an extreme wind event occurred at only one of eight sites (10 sites after October 1998). One date had wind events at four sites, three dates had wind events at three sites and ten dates had wind events at two sites. This shows, that despite the fact that many of these extreme wind events are related to large scale synoptic weather patterns, each site has specific local conditions which lead to high windspeeds.

Case Studies

To give the reader an appreciation for the kinds of data collected during this study, a al case study is presented here. The case study focuses on an extreme wind event that occurred at Lucille Mtn. on January 11 and 12, 1996. Figures 5a and 5b show daily and hourly data respectively surrounding the time of the extreme wind event. Figure 5a shows that typical daily maximum windspeeds for the weeks before and after the wind event were generally in the 5-10m/s range; however during the January 11-13 storm cycle daily maximum windspeeds exceeded 15m/s. Note the daily average windspeeds during the storm cycle were not particularly high. Figure 5b shows hourly average windspeeds for the time period surrounding the extreme wind event. Hourly average windspeeds are generally less than the daily maximum values, but greater than the daily averages. Hourly average wind speeds during the extreme wind event were in the 9-11m/s range.

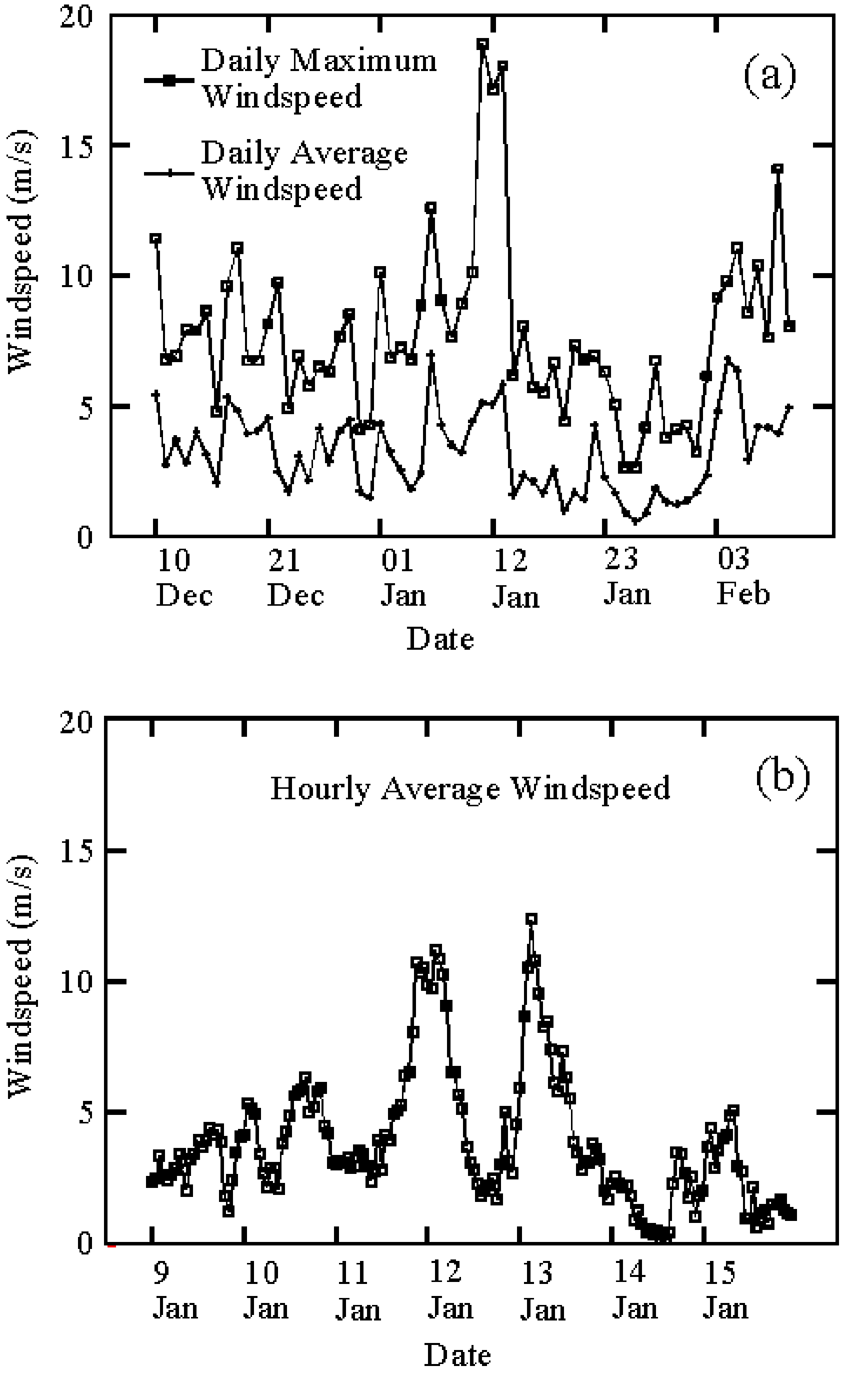

Figure 5. Lucille Mtn. windspeed (1-minute wind runs) data December 1995 to February 1996. (a) Daily maximum and average windspeeds, for the period 10 December 1995 until 10 February 1996. (b) Hourly average windspeeds for the period 9-15 January 1996.

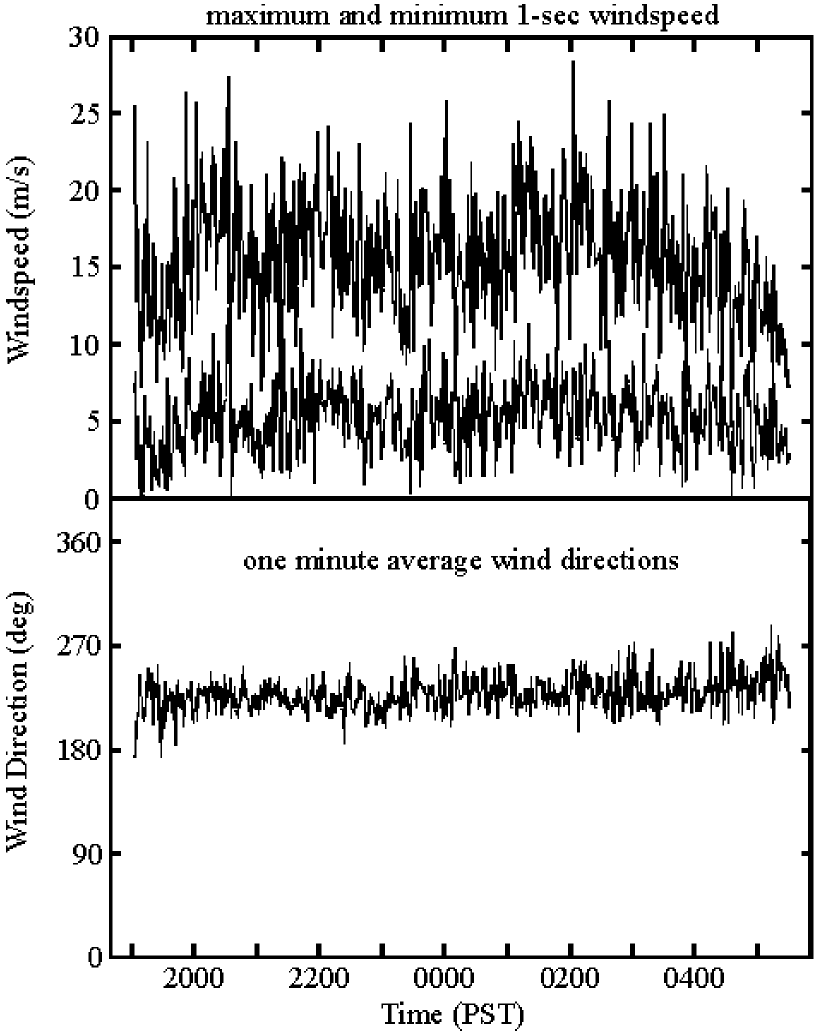

Figure 6. One minute maximum and average windspeeds, and one minute average wind direction (based on 1-sec wind runs) for the duration of the extreme wind event of 11-12 January 1996.

The storm event lasted from approximately 1900 PST on the 11th until 0500 PST on the 12th. This length of storm is atypical of most of the extreme wind events recorded at other sites except for Pinkerton Mountain. Typical wind events have peak windspeeds just over 20m/s and last for one or two hours. Maximum windspeeds exceeded 20m/s for numerous minutes throughout the storm. The storm peak was 28.5m/s at approximately 0203 PST. The gusty nature of this storm is clearly evident in the highly variable maximum windspeeds and in the fact that minimum windspeeds for a given minute were often below 5m/s, despite the high maximums. Wind direction was also highly variable but only within a limited range of about 45° centered around 220° (southwest).

Figure 7 graphs the 250 second long array of 1-sec windspeed and direction data centered around the peak storm gust.

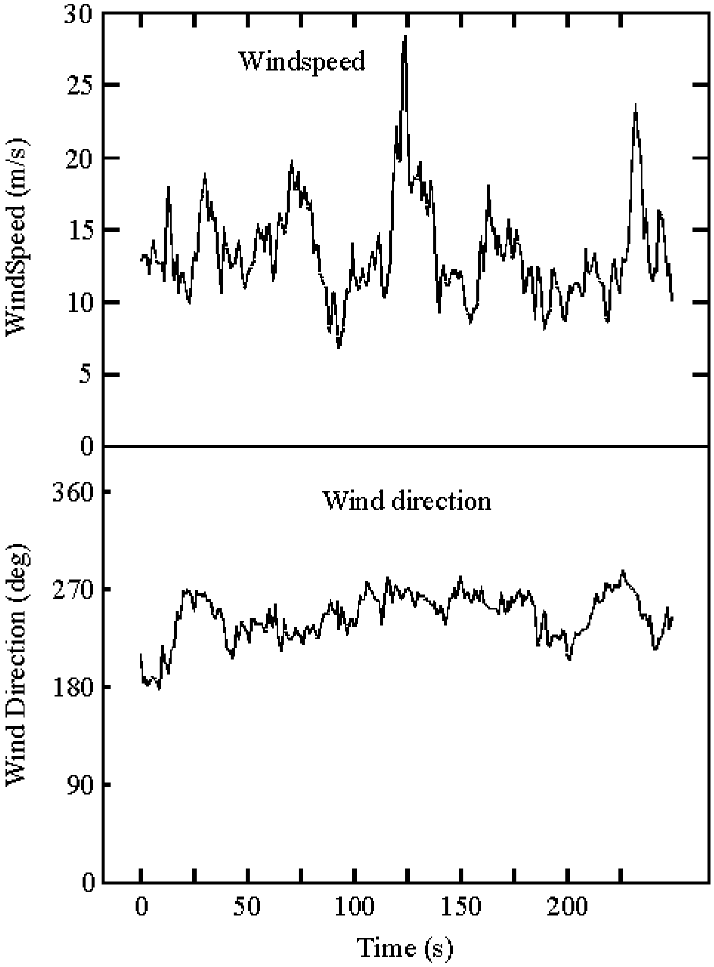

Figure 7. One-second windspeed and direction measurements for a 250-s period at about 0203 PST on 12 January, including the peak storm gust of 28.5m/s.

Conclusions

Potentially damaging high windspeeds are present throughout northeast and north-central British Columbia. The frequency and severity of these winds is highly dependent on the local terrain. Open, high elevation sites and isolated hills on the plateau experience more frequent extreme wind events. Wind directions during extreme wind events are predominantly from southerly and westerly directions. Extreme wind events are concentrated in the winter months, but can occur in any month. Despite large scale synoptic forcing, most extreme wind events recorded in this study were isolated to only one of the ten sites on a given date. This shows that very specific local weather conditions and topography lead to high winds and presents a difficult challenge to those attempting to model windspeeds and directions over a wide area.

The Lucille Mtn. case study, centered around the 11-12 January 1996 extreme wind event, illustrated the very gusty nature of high winds. Understanding the fine structure of gusts is important to an overall understanding of windthrow. The data set collected in this study is a valuable resource to modelers and could be used for further study of wind gust structures during extreme wind events.

Mapping and Investigating the Mean and Extreme Wind Regime of Coastal British Columbia

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Abstract

A collaborative wind climatology Ph.D. research project is underway within the Department of Geography at Simon Fraser University to investigate the wind environment in coastal BC. The project involves Professor W.G. Bailey, graduate student Brian Sieben, the Science Council of British Columbia and collaboration from Weyerhaeuser Company Ltd. and BC Hydro. Hourly wind data is being analyzed from long-term Environment Canada climate stations in coastal BC. The most appropriate probability distribution to estimate extreme winds in British Columbia will be evaluated. The influence of short record lengths on extreme value statistics will be evaluated. Probability distributions will be utilized to determine the 5, 10, 50 and 100 year extreme wind events for each long-term climate station. A wind prediction model calibrated for British Columbia terrain will be selected to predict the average and extreme wind speed at unmeasured forest locations. The prediction model will be used in conjunction with a digital elevation model in a geographical information system to map mean monthly winds as well as 5, 10, 50 and 100 year extreme wind events in coastal BC. Such maps may aid in locating future wind turbine power plants. Maps of extreme wind events may aid in the identification of terrain susceptible to extreme winds allowing utilities and forest companies to minimize wind related damage.

Introduction

Throughout the fall, winter and spring seasons, coastal British Columbia is subject to a succession of mid-latitude cyclonic storms accompanied by high winds. Complex topography interacts with these storms to produce wind speeds often approaching hurricane force (>100 km/h) as seen on the Brooks Peninsula of Vancouver Island (Stewart *et al*., 1995). Tree blowdown is significant in British Columbia representing annual losses equal to 4% of the annual allowable cut (Mitchell, 1994). Tree blowdown onto transmission lines is responsible for most service disruptions in electrical transmission in British Columbia (BC Hydro, 1999).

Despite the significance of wind damage in coastal British Columbia, the wind regime is poorly understood. This problem is being addressed in a collaborative research project in the Department of Geography at Simon Fraser University involving Climatology Professor W.G. Bailey, Ph.D. student Brian Sieben, the Science Council of British Columbia's G.R.E.A.T. scholarship program and industrial collaboration from Weyerhaeuser Company Ltd. and B.C. Hydro. In addition, there are seven supporting organisations from across Canada.

This study forms the basis of Brian Sieben's Ph.D. thesis research and has three primary objectives. The first objective entails an investigation of the historical wind record at Environment Canada climate stations. This investigation will include the generation of wind roses, summary statistics by month (mean, maximum and minimum winds) and an extreme value analysis. The second objective entails the production of maps depicting extreme winds that can be used to identify transmission line corridors and stand edges at risk from blowdown. The third objective is to produce maps of mean monthly winds that would be useful in locating future wind generation stations (Figure 1) and in the management of air pollution.

Methodology

This study involves the analysis of many years of hourly wind data collected by Environment Canada. Data quality concerns in the historical record of wind observations must be fully investigated before detailed analysis of the wind record can be undertaken. Such concerns include the movement of climate stations, changes in anemometer height and changes in measurement frequency.

Summary statistics including the mean, maximum and minimum winds will be calculated for long-term Environment Canada climate stations in coastal and western British Columbia. In addition, wind roses similar to Figure 2 will be produced for each long-term climate station allowing dominant wind directions to be graphically depicted.

The extreme value analysis technique fits a series of extreme wind events to a probability distribution and utilises that distribution to predict an event of interest. Using extreme value analysis, it is possible to predict the frequency or return period for events for which there is no record, such as the 100 year wind event. Detailed extreme wind climatologies have been produced in jurisdictions outside of British Columbia, such as Alberta (Flesch and Wilson, 1993). The goodness of fit of several probability distributions including the Weibull and Gumbel distributions must be investigated to determine the most appropriate distributions for use in British Columbia before an extreme value analysis of wind can be completed in British Columbia. The influence of record length on extreme value statistics will be evaluated and extreme value statistics will be calculated for long-term Environment Canada climate stations.

Most long-term Environment Canada climate stations in British Columbia are at airports and lighthouses (Environment Canada, 1993). It is therefore necessary to utilise wind prediction models to extrapolate wind to unmeasured forest sites. Existing physical and empirical wind models will be tested and evaluated for BC terrain. Predicted winds will be validated through the use of wind data from remote non Environment Canada climate stations such as BC Ministry of Forests fire weather stations, BC Hydro climate stations, BC Highways avalanche climate stations, and forestry research climate stations.

Maps of extreme winds indicating the 5,10, 50, and 100 year wind events will be produced. The maps will be produced using a wind prediction model, a digital elevation model, the historical wind record and a probability distribution. This mapping will be computationally intensive due to the need to extrapolate extreme wind events across the landscape for the period of record.

Anticipated Applications

It is anticipated that project results will include the determination of the most appropriate techniques for extreme value analysis of the wind record and the development of techniques to map extreme wind events. These techniques will be applied produce a climatology of the wind regime in coastal British Columbia and will include a report summarising the wind regime at coastal BC climate stations and maps depicting the spatial extent of mean and extreme winds. The report outlining the wind record at coastal BC Environment Canada climate stations will provide wind roses, summary and extreme value statistics such as the 5, 10, 50 and 100-year wind events. Maps output from the geographical information system depicting the spatial extent of mean and extreme winds will likely be produced at a landscape scale and at a more detailed 1:10,000 scale in locations of interest.

Wind is the dominant disturbance regime in coastal British Columbia forests (Clayoquot Sound Scientific Panel, 1995), yet little information is available on the frequency of the landscape disturbance interval. This research will assist in determining the wind caused landscape disturbance interval in coastal BC. In addition, documenting the wind environment will provide field foresters information on wind direction and magnitude that will likely assist with the planning of cut block layout to minimise blowdown. Most importantly, the research will identify and map terrain subject to high winds. Once mapping is complete, high risk stands and transmission line corridors subject to high winds could be targeted for windthrow mitigation treatments such as those outlined in

Stathers *et al.* (1994). Maps of terrain subject to high winds may aid in locating future wind turbine power plants. Finally, knowledge of the mean and extreme wind environment in western and coastal British Columbia could be integrated into the research activities of other research groups.

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Figure 1. Wind generating plant at Cowley Ridge (Pincher Creek) Alberta. Information from this Ph.D. research project may assist in determining locations for such plants in British Columbia.

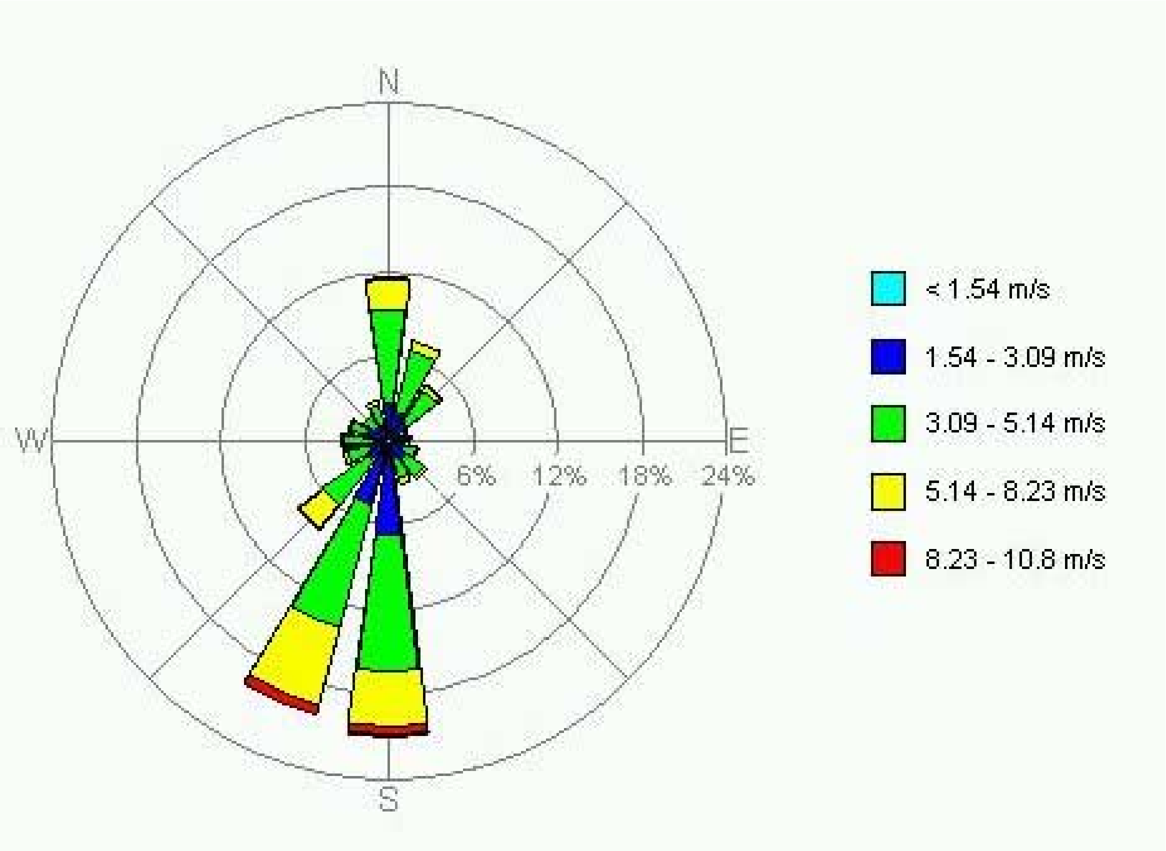

Figure 2. A hypothetical wind rose (directional histogram) indicating the dominant wind direction is from the south. Similar wind roses will be produced for long-term Environment Canada climate stations during this study.

EXTRAPOLATION OF HIGH WINDS IN COMPLEX TERRAIN

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ABSTRACT

This paper describes a technique developed to estimate severe winds in complex and data-sparse topography. The technique is used to characterize the 2-dimensional horizontal wind field in the McGregor Model Forest (MMF) of British Columbia under a typical storm scenario. An analysis of historical wind extremes in the central interior of British Columbia reveals that southerly gusts associated with fall and winter cyclones account for most of the extreme wind events. Synoptic climatology and map pattern classification techniques are used to identify recurring and representative map patterns for moderate, strong and severe southerly wind events. These "keyday" scenarios are then simulated with a 3D mesoscale numerical model whose output is used to determine wind speed ratios between grid points in the complex forested terrain and a neighboring airport location. The speed ratios provide an estimate of the winds likely to occur above the forest canopy in the MMF based on a single wind measurement at the Prince George Airport.

1. INTRODUCTION

Strong gusty winds can knock down trees in forested areas resulting in economic loss to the forest industry, particularly if inappropriate forestry practices are employed in areas prone to strong winds. The probable occurrence of severe winds and their directional and seasonal characteristics must be known before wind risk management strategies can be implemented and appropriate siliviculture systems designed. However, implementation of such strategies is often hindered by two compounding factors: 1) wind measurements in forested areas are spatially limited, typically restricted to airport locations; and 2) local terrain plays a considerable role in modifying wind speed and direction especially in mountainous regions. The complex terrain and sparsity of wind data in British Columbia forests would typically require the use of either empirical extrapolative techniques or numerical modelling. This project employs both techniques by modelling synoptic composites of severe-wind events to derive wind speed ratios between grid points in the complex forest terrain and a neighbouring airport location.

2. STUDY AREA

The McGregor Model Forest (MMF) is located 30 km northeast of Prince George and encompasses an area of 181,000 hectares within the boreal forests of BC's central-interior (Figure 1a). The terrain ranges from rolling hills in the west, to the steep western slopes of the Canadian Rockies in the east (Figure 1b). The southern portion of the MMF is characterized by a broad east-west drainage basin formed by the confluence of two major rivers. The McGregor River flows southwest out of the Rockies and into the Fraser. The Fraser

River flows northwest out of the Rocky Mountain Trench and traverses the southern edge of the McGregor Plateau, where it turns southward back toward Prince George.

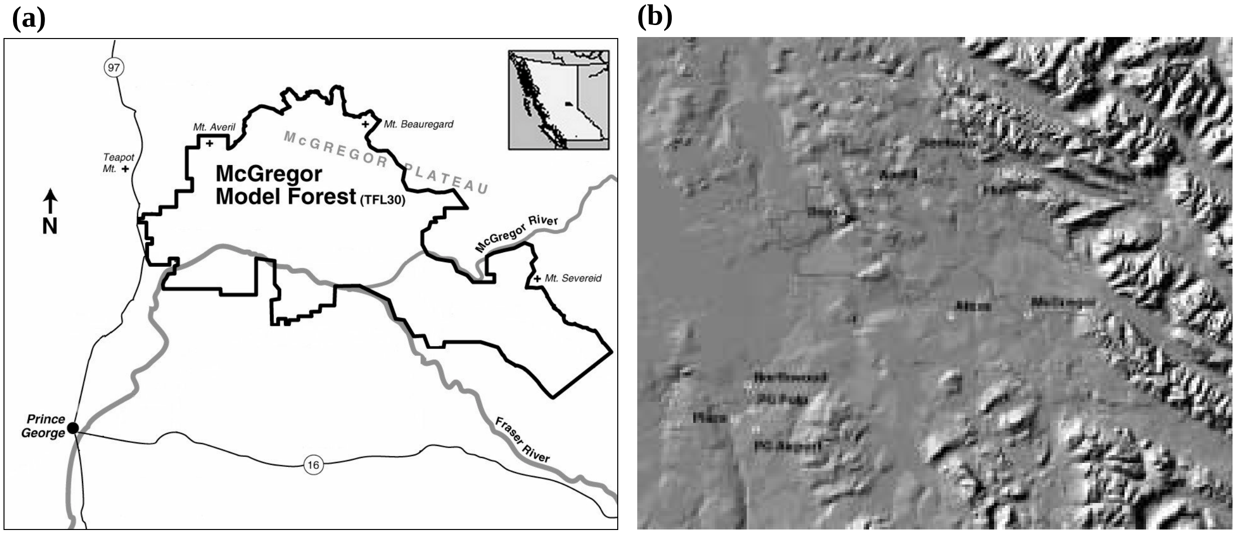

Figure 1. (a) Location of the McGregor Model Forest in the central-interior of British Columbia. (b) Digital elevation model (100 m resolution) of study area and location of wind monitoring stations.

3. OBJECTIVES

The main goal of this project was to assess the influence of local topography on high winds, in order to help identify areas of windthrow-prone terrain in the MMF. Specifically, the objectives of this study were: 1) to determine the synoptic climatology of the prevailing storm winds; and 2) to test and develop a model for extrapolating high winds across the MMF under this flow condition.

4. METHODOLOGY

An overview to the technique developed to extrapolate high winds under the prevailing storm condition is shown in Figure 2. Because accurate records on windthrow were not being maintained locally, it was impossible to determine in advance the importance of any particular storm type. An analysis of historical wind extremes recorded at four airport locations in the central-interior revealed that southerly gusts associated with fall and winter cyclones account for most of the extreme-wind events in the region (Murphy and Jackson 1997). Synoptic climatology and map pattern classification techniques were then used to identify recurring and representative map patterns for moderate, strong and severe southerly wind events (Murphy and Jackson 1998). Atmospheric soundings taken at the Prince George airport during the these three “keyday” storms were next used to initialize a series of 12-hour numerical weather simulations. The maximum wind simulated at each grid point was recorded, and gridded wind maximums were constructed for each keyday scenario. Each grid of maximum wind speeds was normalized by the corresponding maximum simulated for the airport. This provided a gridded set of speed ratios stratified by storm category. To extrapolate high wind estimates under a southerly flow condition, the synoptically parameterized model multiplies the mean surface wind speed at the airport by the appropriate grid of speed ratios. A more detailed description the synoptic climatology and numerical modelling methodologies are given in the sections below.

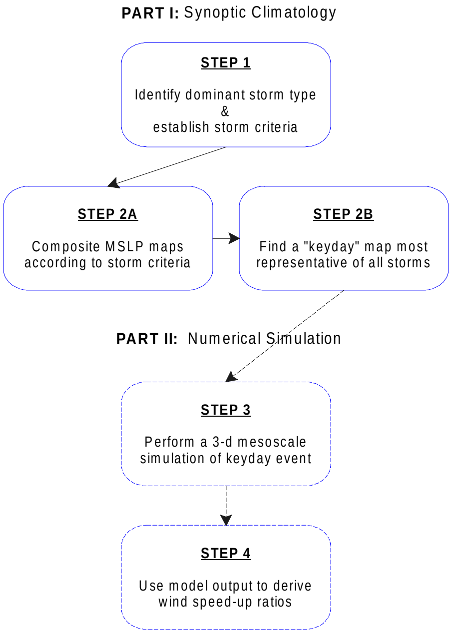

Figure 2. Overview to methodology used to extrapolate high winds from the Prince George airport, to the McGregor Model Forest.

4.1 Synoptic Climatology

To determine the climatology of the windy season, daily mean sea-level pressure maps from October through March were averaged for the 25-year period 1970-1994 using GrADS and model output from the NCEP/NCAR Reanalysis Project. A storm composite was then constructed by including only those maps where the daily extreme gust speed at the Prince George Airport was from a southerly direction. This composite was made up of six hundred and twenty-six storm cases were. A pressure anomaly map for gusty southerly winds was then constructed by subtracting the storm composite from climatology and the statistical significance of the composite was tested at the 99% level using a Student's t-test. The analysis was repeated to construct individual composites for moderate (51-70 km/h), strong (71-90 km/h) and severe (>90 km/h) wind storms. Map-pattern classification techniques were next used to identify a representative map pattern for each storm category. The criteria established for satisfying this objective was to find a single "keyday" map which was correlated at r=0.7 or higher, with at least 50% of the maps in its respective category. Using Kirchhofer's (1973) sums-of-squares technique, three daily mean sea-level pressure maps were subsequently identified as model scenarios for moderate, strong and severe winds under a southerly flow condition.

4.2 Numerical Simulation

The numerical weather model used to perform the keyday simulations was the Colorado State University Regional Atmospheric Modeling System (CSU RAMS) (Pielke et al. 1992). RAMS is a 3-dimensional, mesoscale model for simulating and forecasting meteorological phenomena in terrain following coordinates. The model advances gridded fields of atmospheric variables such as velocity, pressure and temperature from an initial state through a series of discrete time steps, to a future state based on the set of equations which govern atmospheric motions and thermodynamic properties. While RAMS is a complex model, capable of performing highly sophisticated and detailed weather simulations, a simplified modelling approach was adopted from the outset in this work. The intent was to use the model in a diagnostic, rather than prognostic mode, to quickly obtain a dynamically balanced realization of the flow under each storm scenario. Atmospheric soundings taken at the Prince George airport during the three keyday storms were used to initialize a series of 12-hour simulations. Each keyday simulation was initiated at 12 UTC (4:00 a.m PST) and "nudged" at the top and lateral boundaries toward the subsequent afternoon conditions at 00 UTC (4:00 p.m. PST). The model was executed on a Silicon Graphics Power Indigo 2 using a 5 second time step. Each time step required approximately 35 seconds of CPU time, making the total run time 84 hours or 3.5 days per simulation. After three hours of simulation the model was observed to have reached a dynamically balanced state. The largest hourly wind maximums recorded in the nine hours beyond the first three hours of simulation were then used as an estimate of the largest wind speed likely to occur above the forest canopy under each storm scenario. Wind maximums at a mean height of 78.6 metres above ground (model level, k=3) were selected for this purpose. Gridded wind maximums were subsequently constructed for each keyday storm scenario.

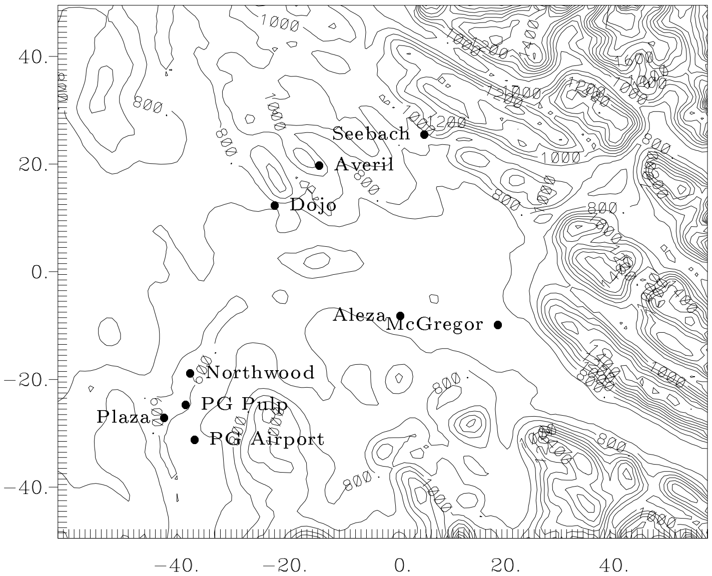

Figure 3. RAMS model domain showing smoothed topography (1 km resolution).

A 120 km x 100 km grid encompassing the MMF and its upwind region to the south and west was selected for the modelling exercise. To resolve the topographic influences of the main terrain features in the MMF, a horizontal grid size of 1 km was selected. Since a finer grid size would have also demanded a smaller time step in order to preserve numerical stability, a 1 km grid size was also deemed as the finest practicable given computer memory and CPU constraints. Terrain data were obtained at a resolution of 100 metres and were subsequently smoothed to 1 kilometre using a silhouette averaging scheme that preserved realistic heights and eliminated computational instability associated with $2\Delta x$ topographic wavelengths (Figure 3). The model had 29 vertical levels and extended to a height of 16 km (using a spacing of 50 m at the surface which was stretched by a factor of 1.2 for each successive level, to a maximum separation of 1000 m). The minimum attention necessary to obtain realistic results was given to the model optimization parameters. For example, since the intention was to model topographic influences on the wind field, and not edge effects of individual cutblocks, a uniform surface roughness corresponding to coniferous forest cover was selected.

5. RESULTS

5.1 Storm Composites and Keyday Events

The prevailing climatological surface map feature during the fall-winter period is the Aleutian Low (see Figure 4a). The cyclonic flow around this semi-permanent feature, and the relatively weak pressure gradient over the Interior, explains why the prevailing winds for the region are generally light and from a southerly direction. In contrast, the storm composites exhibit a strong southeast-to-northwest oriented pressure gradient over the Interior, situated between a deeper than normal low in the Gulf of Alaska, and a stronger than normal Idaho High. Of the 626 storms identified, 45% were associated with daily extreme gusts greater than 50 km/h (202 fell into the moderate category, while 70 and 11 were strong and severe storms respectively). The composite map and pressure anomaly for strong southerly winds are shown in Figures 4b and 4c, respectively. Increments in speed class category are accompanied by an intensification of the pressure gradient and decreasing pressure over the Interior, attributable to the eastward propagation of the storm centre. An examination of surface weather records from the Prince George airport reveals that the peak gust events are also accompanied by above normal temperatures and precipitation, and that the amount of rainfall and warming associated with the storm events increase with storm intensity.

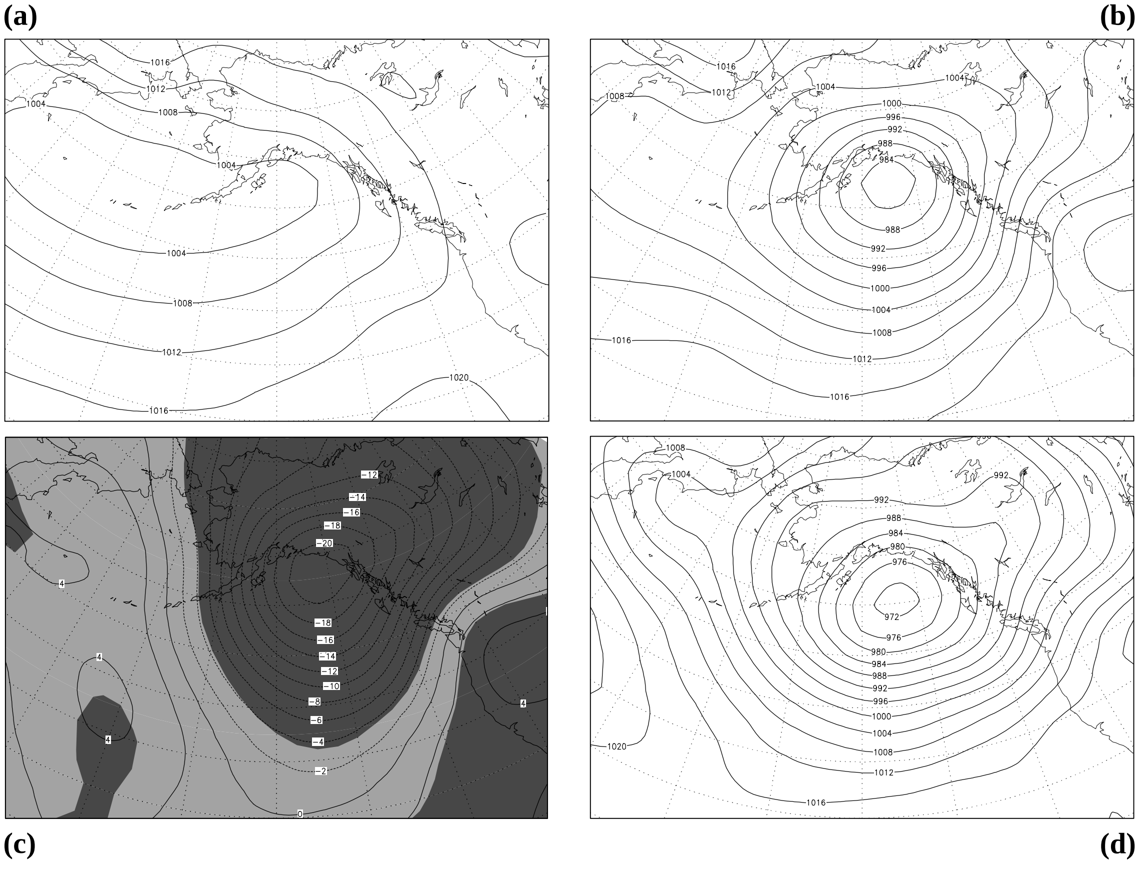

Figure 4. (a) Mean sea-level pressure climatology for the fall-winter period in millibars. (b) Storm composite for strong southerly gusts (71-90 km/h). (c) Deviation from normal climatology (millibars) and statistical significance at the 99% level (shaded region). (d) Keyday mean sea-level pressure map identified by map-pattern classification analysis for strong wind events (October 25, 1994).

Application of the map-pattern classification criteria resulted in three keyday maps which are correlated at r=0.7 or higher with 50%, 89% and 73% of the maps in the moderate, strong and severe storm categories respectively. The daily extreme gust speed recorded at the Prince George airport during the keyday storms were approximately equal to their mean composite value and suggests that the selected maps represent archetypical patterns for moderate, strong and severe winds. While pressure values for the keyday maps are generally lower than their composite values, the pressure patterns in the vicinity of the composite-criteria area (i.e. the Central-Interior) are very similar. The moderate and strong keyday storms were both fall events (October 22, 1993 and October 25, 1994 respectively). The severe keyday storm was a winter event, occurring January 20, 1973. The keyday map for strong winds is shown in Figure 3d. Further evidence that strong synoptic winds in the Interior are associated with decaying storms in the Gulf of Alaska are also seen in the results here. Pressure at the centre of the keyday storms was seen to increase with increments in gust speed category, and troughing in northeast corner of the strong and severe keyday maps is indicative of storms propagating over the coastal barrier.

5.2 Numerical Simulation of Keydays

Results from the strong keyday simulation are depicted in the plots shown in Figure 5. The top frame shows the initialization field interpolated onto the model grid from the 12 UTC sounding taken during the storm event. The initializing wind field represents a unbalanced condition, and has not been adjusted for kinematic effects. After six hours of simulation (centre row) the winds have been adjusted for kinematic effects, and are showing the influences of topography. The strong keyday windfield was generally stronger than the moderate keyday across the entire domain. Winds were even more intense in the severe keyday simulation. One exception was a wind jet which developed in the strong keyday event where there is a merging wind flow out of the McGregor, Torpy and Fraser river valleys. The most striking feature of the simulated windfield is the nearly easterly flow that develops across the central drainage basin as the southerly synoptic flow encounters the northwest-to-southeast oriented mountains along the eastern boundary and the McGregor Plateau along the northern boundary. The general flow patterns in all three simulations were similar: an easterly flow develops over the broad central drainage basin; winds speed up as air is forced over the McGregor Plateau; and there are strong outflow winds along the deeper McGregor and Fraser river valleys. Winds across the drainage basin were more easterly for the moderate and strong category where winds appear to be steered around the McGregor Plateau. Differences between the moderate category storm and the strong and severe storms became more apparent at the end of the 12-hour simulation (00 GMT). The moderate keyday winds were lighter and veered (clockwise shift) by as much as 90 or 180^o over the drainage basin. The strong and severe keyday windfields continued to show a southeasterly flow over the Plateau.

Direct validation of the keyday simulations was not possible due to the limited availability of observations during these storm events. Three southerly gust events during the 1995-1997 storm season were simulated to assess the representativeness of the keyday storms, and the suitability of RAMS to this application. Wind data from a temporary climate network deployed in the MMF, supplemented with data from existing stations (Figure 1b), were used to assess the validity of these simulations. Simulated winds were more comparable to hourly winds than gusts and showed general agreement with 10 metre winds in a clear opening. Frictional effects were evident at the 3-metre stations (Dojo, Flute and Seebach) where the observed winds were significantly lower than the simulated value. Prevailing wind directions at the 10-metre towers showed reasonable agreement with the simulated wind field. Simulated directions at the 3-metre stations were plausible when subgrid effects were taken into consideration. While the model validation performed was rather qualitative, the similarities noted between the keyday simulations and the validation runs lend support to both the representativeness of the keyday storms, and the ability of RAMS to provide a realistic estimate of the windfield under each storm scenario.

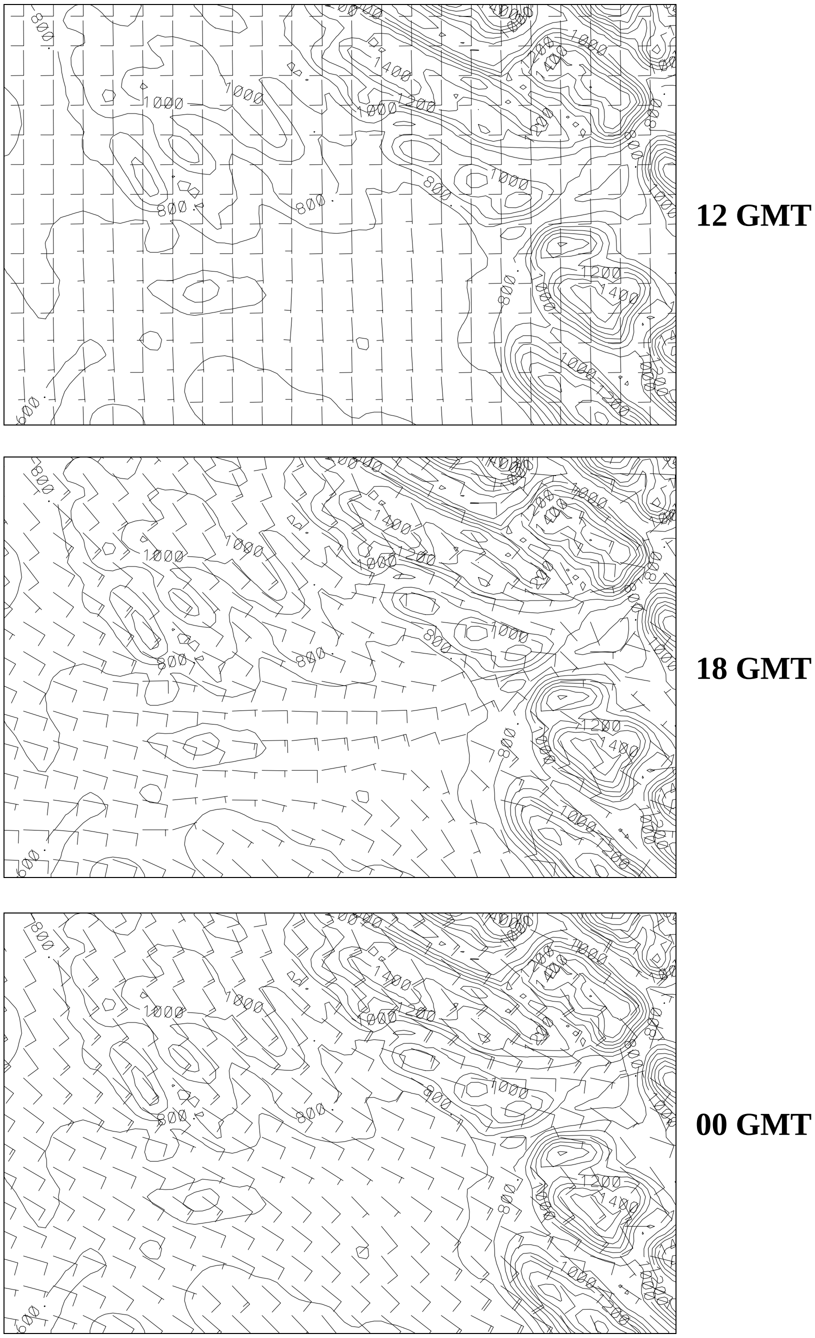

Figure 5. Plots show the results of the strong keyday simulation for model level k=3 (corresponding to a mean height of 78.6 metres). Shown from top to bottom is the initialization field (12Z), a snapshot of the windfield after six hours of simulation (18Z), and at the end of the model run (00Z). Wind barbs are shown every four grid points (i.e. every 4 km) using speed intervals of 5, 10 and 50 m/s for a half barb, full barb, filled barb respectively.

The speed and direction of the maximum winds simulated at each grid point during the strong keyday model run is shown in Figure 6. The wind maximums at each grid point did not necessarily occur at the same time at each grid point during the simulation, and the plot therefore should not be interpreted as a snapshot of the windflow. The plot is shown over a digital elevation model which has a higher resolution (100 m) than was actually modelled (1 km). For presentation purposes, wind vectors are only shown every 3 grid points. The wind vectors are colour coded according storm category, with yellow, orange and red denoting moderate, strong and severe winds respectively (blue vectors are less than 50 km/h). The simulated winds are not representative of true gusts however, and are more comparable to hourly winds. Actual gust speeds would be even higher than those indicated in Figure 5. According to Linacre (1991) mean wind to gust ratios are typically in the range of 1.2 - 2.0. Within the MMF, all winds simulated during the moderate keyday were less than 51 km/h. Moderate and strong category winds which occurred during the strong and severe keyday simulations were generally associated with flow over hills, valley funneling or outflow conditions. Winds greater than 90 km/h occurred along the mountain ridge line located southeast of the McGregor camp station during the severe keyday simulation.

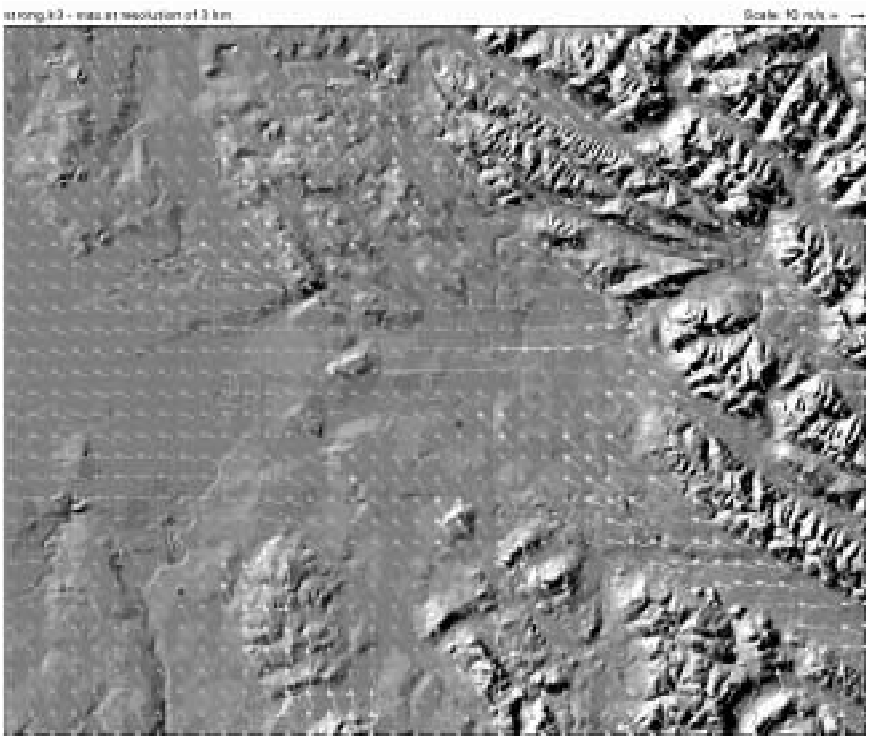

Figure 6. Maximum wind simulated at each grid point during the strong keyday model run. Wind vectors (shown every 3 grid points) are colour coded according storm category, with yellow, orange and red denoting moderate (51-70 km/h), strong (71-90 km/h) and severe (90+ km/h) winds respectively (blue vectors are less than 51 km/h).

5.3 Extrapolation Model (speed ratios)

The set of gridded wind maximums from the keyday simulations were used to test and develop a more generalized model for extrapolating the maximum wind speeds likely to occur in the MMF for any given wind speed at the airport which was greater than a threshold value and from a southerly direction. Therefore, as was the case with the numerical simulations, the synoptically parameterized extrapolation model described here has a horizontal resolution of 1 km, and provides an estimate of the maximum mean wind speed above the forest canopy, rather than a gust maximum.

The wind speed ratios derived from the moderate keyday simulation were found to be equally applicable to extrapolating winds in the other two storm categories. A comparison of the keyday simulations and three validation scenarios suggested that there are possibly two wind regimes related to a difference in the prevailing storm tracks between the moderate and the strong and severe events. The moderate category storms appear to track westward through the central interior, which may account for the anticyclonic shift in the flow to a more northwesterly direction. The strong and severe events are thought to be related to storms tracking northeastward. However, since the interest here is primarily in strong and severe winds, a vector average of wind directions and scalar average of wind speeds was performed for the latter case. The final model design is reflected in Figure 7. Figure 7a provides a contour map of the moderate wind speed ratios. Wind directions for the average of the strong and severe keydays is given in Figure 7b. Given the wind reversal seen in the southeast corner of the model domain during the moderate keyday simulation, application of the moderate wind speed ratios in this region may not be appropriate to strong and severe wind storms.

Validation of this extrapolation technique is limited to verifying the magnitude of the wind estimates, as verification of the wind direction was addressed during the numerical simulation of the keyday storms. The validity of the extrapolated wind speeds was assessed by the comparison of observed daily wind maximums under a strong southerly flow, to the extrapolated wind speed determined by application of the moderate keyday speed ratios. The period of record available at each of the available wind monitoring stations varied from 2 to 8 years (1989-97), with the stations deployed as part of this project having the shortest record (Averil, Dojo, Flute and Seebach). Validation storm dates where identified by the occurrence of southerly gusts (180 ±10^{o}) greater than 35 km/h occurring at the Prince George airport during the fall and winter months. No severe-gust storms were recorded at the airport during the entire validation period. The maximum daily hourly wind which occurred at the airport during each of the identified gust-events was entered into the model, and a corresponding wind maximum was extrapolated for each of the wind monitoring locations.

The extrapolated wind maxima are compared to the observed daily maximum at each station in the scatter plots given in Figure 8. With the exception of Averil and Flute (not shown), the correlation between the observed and extrapolated wind maximums were statistically significant at the 95% level. The correlation for Flute was negative and is not included in Figure 7. It should be noted that the wind monitor at this station experienced failures during many of the high wind events. It is suspected that this may have been related to the heavy rainfall and subsequent freezing which typically accompanied the storm events. In the case of Averil, increasing the sample size by lowering the gust threshold and increasing the number of allowable wind directions resulted in a significant decrease in the correlation coefficient. The correlation and test results shown for Averil therefore only include storm events which satisfied the original model criteria. The effects of surface friction are clearly evident at the 3-metre wind stations (Dojo, Seebach and Flute) where the observed wind speeds are significantly lower than the extrapolated value.

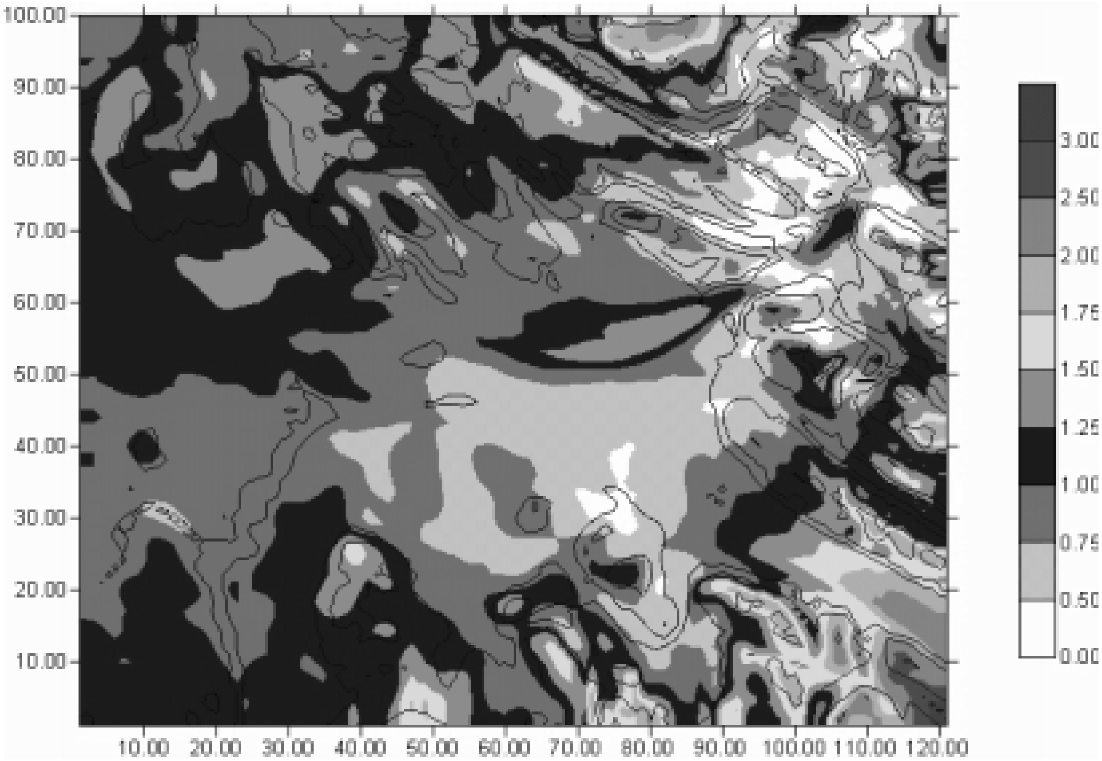

Figure 7a. Contour plot of wind speed ratios derived from wind maximums simulated for the moderate keyday storm category.

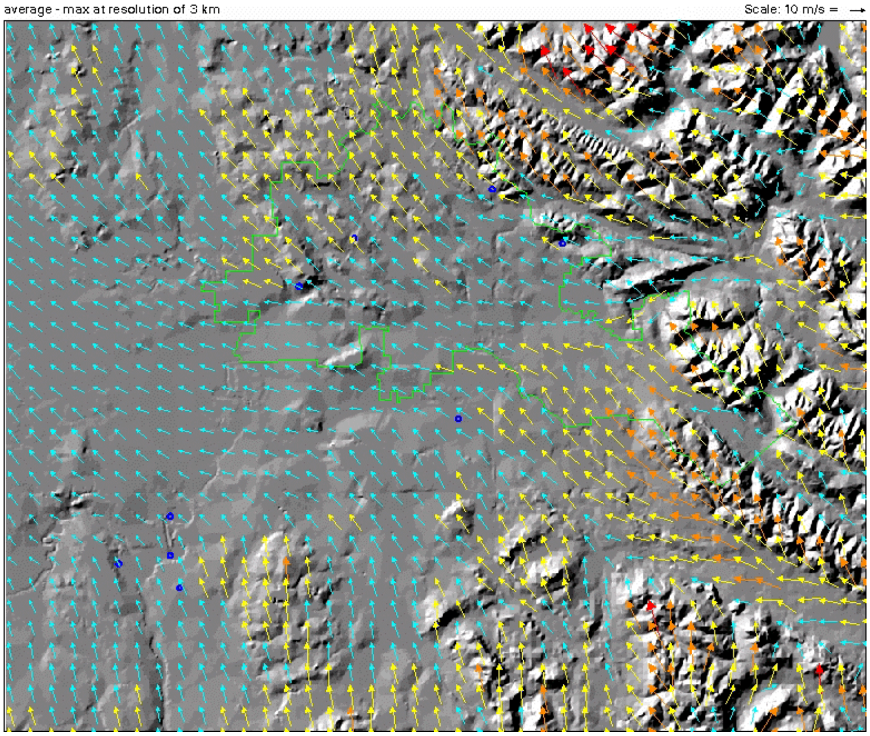

Figure 7b. Vector average of wind directions, and scalar average of maximum wind speeds, simulated for the strong and severe keyday storms at a mean height of 78.6 m and horizontal resolution of 3 km.

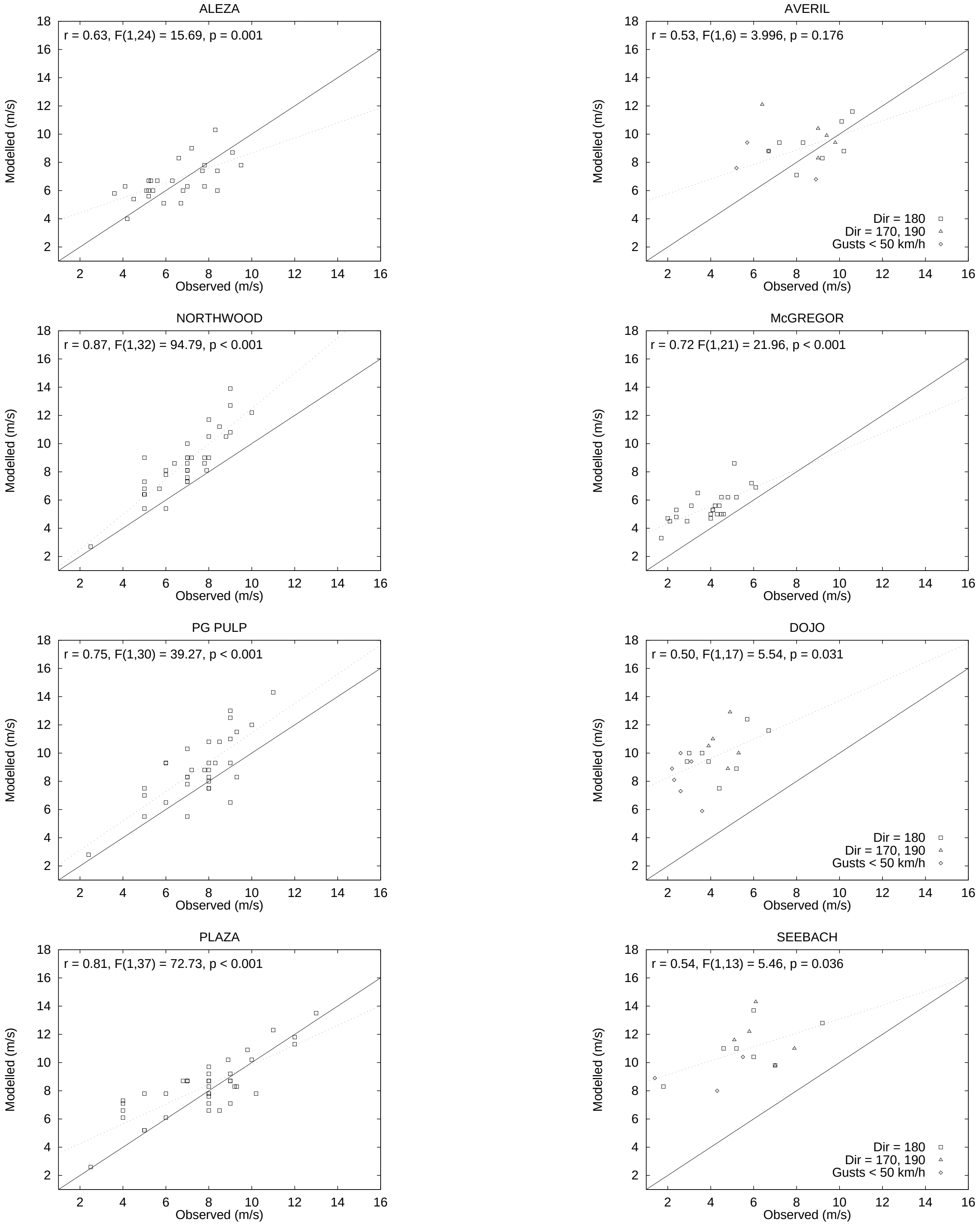

Figure 8. Validation of wind speed ratios: comparison of observed daily maximum hourly wind vs. extrapolated wind maximums under a synoptic southerly flow using moderate speed ratios. (Broken line is the regression line and the solid line is the 1:1 line.)

6. CONCLUSIONS AND EXPECTED BENEFITS

The model described here is intended to provide an estimate of the winds likely to occur above the forest canopy in the MMF based on a single wind measurement at the Prince George Airport. The model strictly only applies when there is a strong southerly flow with winds gusting higher than 35 km/h. Given the rather simplistic approach taken in initializing and configuring the RAMS model, the results of the keyday numerical simulation were promising. The similarities noted between the numerical simulations of the keyday and validation storms supports both the representativeness of the keyday storms, and the ability of RAMS to provide a realistic estimate of the windfield under each storm scenario. The wind speeds extrapolated for storm events which occurred during the validation period correlated well with 10 metre winds in a clear opening, and wind directions agreed favourably with the prevailing storm winds measured at each monitoring station. Taken together with the qualitative validation of the numerical simulations, the results are encouraging and should provide an adequate picture of prevailing storm winds in the MMF.

Windthrow involves complex interactions between many factors, including stand development which influences tree stability, site conditions that influence tree anchorage, and topography and stand structure that cause highly variable wind conditions (Navratil, 1995). By providing a potential-risk surface for terrain prone to severe winds, this project represents a first step in moving toward a winthrow-hazard classification scheme for the MMF. For instance, the information on areas prone to severe winds could be entered into a GIS framework together with information on soil properties, stand conditions, etc. to provide a threat rating for windthrow occurrence.

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Dr. Peter Jackson is an Associate Professor in the Environmental Studies Program at the University of Northern British Columbia. Dr. Jackson is a mesoscale meteorologist whose research mostly concerns windflow in complex terrain (i.e. in mountains, forests, and along coastlines) and environmental applications including assessing areas prone to strong winds which could induce windthrow, and dispersion of atmospheric pollutants in those regions. In pursuing this theme he and his research group use both surface and Doppler Sodar observations, analytical models, and the CSU RAMS and MC2 numerical models. Before joining UNBC, between January 1992 and June 1995, he was Assistant Professor in the Geography Department at the University of Western Ontario. He holds a BSc (1984) and PhD (1993) in Atmospheric Science from the University of British Columbia. Between degrees, he was a meteorologist (weather forecaster) with the Meteorological Service

Section 3. Monitoring and Modelling Windthrow Risk

Radarsat Monitoring Windthrow Decimation Of Riparian Strips, Northern Vancouver Island

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Abstract

Since December 04, 1996, the **RA**dar **I**maging **N**atural **S**ystems (**RAINS**) project has been monitoring 65 riparian leave strips with RADARSAT Fine 2 (F2) beam mode C-band imagery on northern Vancouver Island. RADARSAT F2 image data were acquired on 12 dates ranging from December 04, 1996 to April 11, 2000. These data, prepared as multi-temporal colour composites, were used to monitor the riparian strips. Fifty strips were located on 1995 aerial photographs and 15 strips were found on the RADARSAT images. Riparian strip detectability depends on strip condition, contrast with surroundings, and radar shadows. By Nov. 29/97, total strip length measured on the air photos and RADASAT images was 24.24 km, with 18.06 km created after December 1993 (Post Forest Practices Code strips). At that time, 3769 m (or 20.86%) of the post Forest Practices Code strip length had been decimated. By April 11, 2000, measurements taken on the RADARSAT multi-temporal colour composites indicated that 6418 m (35.5 %) of post code strip length had been decimated. Holes in strips were confirmed by field work. Most of the post code decimation occurred on two landforms: ground moraine and till/rock, where 37.9 % and 43.9 % respectively of strip length has gone down.

Introduction

The British Columbia Forest Practices Code (FPC) provides guidelines for forest operations and silvicutural prescriptions, and requires protection of fish-bearing river and stream reaches through a system of riparian reserve and management zones (collectively termed riparian leave strips). Fish-bearing streams less than 1.5 m wide have a management zone 30 m wide , while non-fish bearing less than 3 m wide have a management zone of 20 m. (B.C. M. of F., and B.C. MELP, 1993)

The riparian leave strips are found in, or alongside new clearcuts (Figure 1). On northern Vancouver Island, these strips are subject to severe wind and rain storms. Many of the strips are quickly decimated through wind-throw (Figure 2). RADARSAT Fine 2 beam mode data can image these strips (Murtha, 1998) (Fig 3) since extant strips leave radar shadows. Strip detectability depends on condition (Murtha and Mitchell, 1998), since loss of trees from the strips eliminates the radar shadow, and contrast with the tone of the surrounding cutblock terrain (Murtha, 2000a).

Figure 1. August 1995 aerial photograph showing the intact riparian strip 16 bisecting the cutblock. When viewed stereoscopically, 55 co-dominant tree crowns can be counted. The photograph was taken days after the cutting was finished and the logs can be seen lining the left side of the road. Aerial photography by Foto Flight Surveys, Calgary.

Purpose

To report on the results of measurements of holes in riparian strips on RADARSAT F2 multi-temporal colour composites.

Figure 2. Riparian strip 16 as it looked on August 20, 1997. This strip was created in August 1995. And was decimated by windstorms during the autumn/winter of 1995/96. The strip was 300 m in length. The RADARSAT image taken on 96/12/04 showed that the strip had been decimated. The landform

of the cutblock is ground moraine, with ablation till deposited on basal till. Photo by P. Murtha.

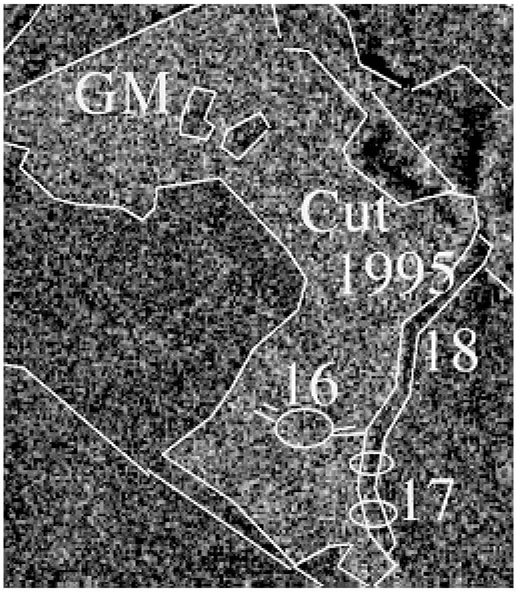

Figure 3. The RADARSAT Fine 2 beam mode image acquired on 96/12/06 showed no trace of riparian strip 16, even though the image data clearly showed riparian strips 17 and 18 on the right side of the cutblock. Small holes are circled in strip 17. Decimated riparian strips do not show on the RADARSAT images. Note the light tone of the cutblock which is on ground moraine. RADARSAT image Copyright Canadian Space Agency, 1996.

Study Area

The study area, located on northern Vancouver Island, between the communities of Port Hardy, Port McNeill and Port Alice has been the site of the **RA**DAR **I**maging **N**atural **S**ystems (**RAINS**) project c-band radar studies since 1993 (Murtha and Pollock, 1996). It is located in the Nahwitti Lowlands Ecosection and in the Coastal Western Hemlock (CWH) Biogeoclimatic Zone (Klinka *et al.*, 1991). The surficial geology has been mapped according to textures, genetic materials, surface forms, and modifying processes (Lewis, 1985). The dominant tree species are western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western red cedar (*Thuja plicata* Donn), amabilis fir (*Abies amabilis* (Dougl.) Forbes) (Lewis, 1985), and Sitka spruce (*Picea sitchensis*) (Bong.) Carr),. The study area borders on the Port Hardy airport where Environment Canada maintains a weather station.

Methods

Fifty riparian strips were located on RADARSAT Fine 2 (F2) and Standard 4 (S4) data were acquired on 16 dates between December 04, 1996 and April 11, 2000 of the study area on northern Vancouver Island (Table 1) . Most of the images were acquired at night-time during rainstorms. These images were used to assess the tone of the cutblocks and evaluate the riparian strips. 1995 normal colour aerial photographs were used to photo interpret the landform (Mollard, 1978) of the cutblocks and to located and number riparian leave strips. The landforms of the cutblocks included lakebed (LB), glacio-marine (GL-M), drumlinized till plain

(DTP), ground moraine (GM) and till/rock (T/R). The materials associated with the landforms have been related to surficial materials from surficial geology map by Lewis (1985) (Table 2). Fifty riparian strips were located on the aerial photographs and then they were measured for length, width, orientation, and interpreted for condition. A summary of methods used to evaluate damages to riparian strips is given in Table3.

Table 1. RADARSAT data acquired over northern Vancouver Island, December 04, 1996 through to April 11, 2000. Pacific Standard Time would be the day previous at 18:21 hrs (Fine 2) or 18:17 hrs (Standard 4)

Date in UTC	RADARSAT Data	Daylight	Weather	FUNDING
December 04, 1996	Fine 2	No	heavy rain, strong winds	ADRO - CSA*
December 11, 1996	Standard 4	No	heavy rain	ADRO - CSA
February 14, 1997	Fine 2	No	heavy rain, windy	ADRO - CSA
April 03, 1997	Fine 2	No	gale force winds, drizzle	ADRO - CSA
July 08, 1997	Fine 2	Yes	drizzle	ADRO - CSA
July 15, 1997	Standard 4	Yes	overcast, scattered drizzle	ADRO - CSA
August 01, 1997	Fine 2	Yes	overcast, no rain for 6 hr	ADRO - CSA
August 25, 1977	Fine 2	Yes	light rain	ADRO - CSA
November 05, 1997	Fine 2	No	rain	ADRO - CSA
November 12, 1997	Standard 4	No	rain	ADRO - CSA
November 29, 1997	Fine 2	No	heavy rain	ADRO - CSA
December 06, 1997	Standard 4	No	overcast, no rain	ADRO - CSA
August 20, 1998	Fine 2	Yes	overcast, no rain	MELP
November 24, 1998	Fine 2	No	rain	MELP
March 24, 1999	Fine 2	No	frontal rains	MELP
April 11, 2000	Fine 2	NO	data not yet received	MELP

*ADRO = Application Development and Research Opportunity; CSA = Canadian Space Agency

Table 2. Landforms (Mollard, 1978) that occur in the study area with landform codes. Map unit and surficial materials from surficial geology map by Lewis (1985).

Landform	Code	Map Unit	Materials
Glacio-marine	Gl-M	mOvS[1]:sisWl[2]	Glacial marine till and marine sediments
Lakebed	LB	mOvS[3]	Glacial lacustrine fine sand, silts and clays
Drumlinized till plain	DTP	sfMbm[3]	Basal till
Ground moraine	GM	sfMbh[4] & sfMbm	ablation till on basal till
Till/rock	T/R	sfMbh & bedrock	ablation till on bedrock close to surface

1. mOvS = mesic Organic veneer Swamp; 2. SisWl = silty sandy marine level plain; 3. SfMbm = sandy fine morainal blanket, rolling, and 4. sfMbh = sandy fine morainal blanket, hummocky; (Terminology from Lewis (1985)

Table 3. Summary of methods used to assess damage to riparian strips

- 12 dates of Fine 2 images were used to evaluate the riparian strips;
- 13, 512 by 512 pixel sub-scenes were selected from each RADARSAT Fine 2 scene
- Each subscenes was registered to NTS map sheet (92L/11),

- each of the remaining 12 dates for each subscene were co-registered in order to create multi-temporal colour composites (MTC).
- 65 strips were examined. 50 strips were located on 1:20,000 1995 colour aerial photographs. 17 strips were pre-FPC (<1994). (15 new strips were found on the RADARSAT images and confirmed by field data.)
- The length, width, and direction and condition of the original 50 strips were measured on 1995 colour aerial photos. Since the landform of each cutblock was photo interpreted, the landform for each strip was recorded.
- The RADARSAT MTCs were used to measure the strips created after August 1995.
- Holes in all strips were measured on the August 25/97, November 29/97, August 20/98 November 24/98, March 24/99 and April 11/00 RADARSAT subscene images.

The accuracy of the measurements were compared with the aerial photographs.

For example, strip 31b (Figure 4) had two holes clearly evident on the aerial photographs, with a cumulative length of 4 mm, making 80 m at a scale of 1:20,000.

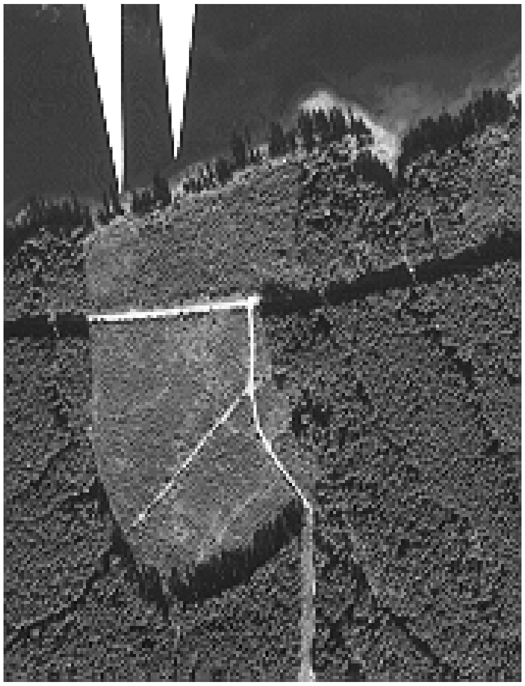

Figure 4. August 1995 aerial photograph showing riparian strip 31b. Pointers indicate holes which measure a total of 4mm in length. Stereoscopically a wind-thrown tree is visible by the left hand hole. At the original scale of 1:20000, the lineal distance of holes equals 80 m. Aerial Photography by Foto Flight Surveys, Calgary.

The same holes measured on the RADARSAT composites (Figure 5) with ER Mapper software gave length of 88 m. These tests indicate that measurements made on the RADARSAT MTC are within +/- 10 % of measurements made on the aerial photographs.

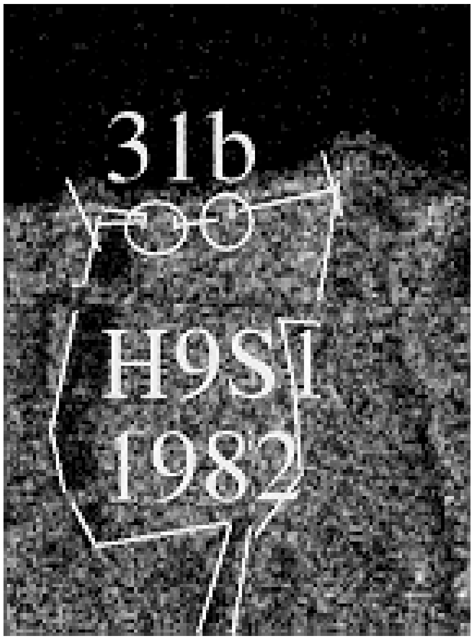

Figure5. The holes in riparian strip 31b are circled in this RADARSAT image acquired at night, during rainstorms from 800 km in space. Using ER Mapper image analysis software, the measured holes totaled 88 m. The tone of the cutblock is almost as dark as the surrounding forest. The cutblock was planted in 1982 to 90% hemlock and 10% spruce (H9S1). The plantation trees make the cutblock dark. RADARSAT images Copyright Canadian Space Agency, 1996, 1997, and 1998.

Results

For the relatively flat study area on northern Vancouver Island, RADARSAT Fine 2 beam mode data can be used to assess decimation of riparian leave strips in clearcuts on northern Vancouver Island (Murtha, 2000b). Multi-temporal colour composites are essential. The best composites have two light cut-block dates (late November, December) assigned to red and green displays to make cutblocks yellow, and one dark cutblock date (August) assigned to the blue display which makes the light toned trees blue. Blue riparian-strip trees contrast with the yellow cutblock. Holes were measured in the riparian strips. Holes are noted when the colour of the cutblock bleeds through the riparian strips or when the radar shadow of the strip disappears. The results of all hole measurements according to Pre-, and Post-code strips are given in Appendices 1 and 2, and are summarized in Table 4.

Table 4. Total Length of holes measured in riparian strips on RADARSAT F2 images.

	Strip Length meters	Total Holes 97/08/ 25	Total Holes 97/11/ 29	Total Holes 98/08/ 20	Total Holes 98/11/ 24	Total Holes 99/03/ 24	Total Holes 00/04/ 11
Pre- Code[1]	6180	1833	1833	1886	2228	2228	2228
%		29.66%	29.66 %	30.5 %	36.05 %	36.05 %	36.05 %
Post-Code[2]	18062	2749	3769	4731	5542	5945	6418
%		15.2 %	20.86 %	26.2 %	30.68 %	32.91 %	35.5 %
Total	24242	4582	5602	6617	7770	8173	8646
%		18.9 %	23.1%	27.3 %	32.05 %	33.7 %	35.6 %

1. Pre-code strips were created prior to 1994.
2. Post code strips were created after 1993.

Since the landform of the cutblocks was photo interpreted and ground checked, damage to riparian strips can be related to the landform of the cutblock. The result of hole measurements in pre-code and post-code strips stratified according landform are given in Tables 5 and 6.

Table 5. Pre-Code strips: Total Length of holes measured on RADARSAT F2 images and stratified according to landform.

Landform	Length	97/08/25	97/11/29	98/08/20	98/11/24	99/03/24	00/04/11
GL-M	1200	0	0	0	0	0	0
LB	3160	408	408	461	803	803	803
GM	1820	1425	1425	1425	1425	1425	1425
Total strip length %	6180	1833	1833	1886	2228	2228	2228
		29.5 %		30.5 %			36.05 %

GL-M = glacio-marine; LB = lakebed; GM = ground moraine

Table 6. Post-Code strips: Total Length of holes measured on 6 dates on RADARSAT F2 images and stratified according to landform.

Landform	Length	97/08/25	97/11/29	98/08/20	98/11/24	99/03/24	00/04/11
GL-M*	260	0	0	0	0	0	0
%	1.44						
LB*	4320	175	340	428	675	777	847
%	23.92	0.96	1.88	2.37	3.73	4.30	4.69
DTP*	400	20**	20	20	20	20	20
%	2.21	0.11	0.11	0.11	0.11	0.11	0.11
T/R*	7422	1199	1934	2662	2997	3103	3260
%	41.09	6.63	10.70	14.74	16.59	17.18	18.05
GM*	5660	1355	1475	1621	1850	2045	2149
%	31.34	7.50	8.17	8.97	10.24	11.32	11.90
Total strip length	18062	2749	3769	4731	5542	5945	6276
	100	15.22	20.86	26.19	30.68 %	32.91	34.74

* GL-M = glacio-marine; LB = lakebed; DTP = drumlinized till plain; T/R = till/rock; GM = ground moraine

** hole due to slash burn

Conclusions

The results indicate that as of the RADARSAT April 11, 2000 image:

35 clearcuts had 65 riparian strips with a total length of 24.24 km;

Post-code strip length measured 18.06 km, while Pre-code strip length measured 6.18 km;

Only 18 strips (5 Pre-code and 13 Post-code) comprising 5.52 km (22.78 %) are intact;

Since 1993, 35.5% (6.42 km) of post-FPC strip-length has been decimated;

Most Post-code strips holes are found on ground moraine or till/rock where 5.41 km (5409/18062 or 29.95 %) the strip length has been decimated;

The most stable strips are found on the glacio-marine and lakebed deposits.

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Appendix 1.

17 Pre (1994) Forest Practices Codes riparian strips classified according to year of cutting, landform, total length, and length of holes measured on the RADARSAT images

*Landform: LB = lakebed; GM = ground moraine; T/R = till/rock

Strip #	Cut Name	Year Cut	Landform	Length (m)	Hole 97/08/25	Hole 97/11/29	Hole 98/08/20	Hole 98/11/24	Hole 99/03/24	Hole 00/04/10
04	Kathy	1984	LB	160				20	20	20
10	LONG	1992	TGM	240	240	240	240	240	240	
11	LONG	1992	TGM	100	100	100	100	100	100	
12	WMist	1991	LB	580				40	40	
14	WMist	1991	LB	800				224	224	224
19	Pl94	1993	Gl-M	800						
20	Pl94	1993	Gl-M	200						
22	Pl94	1993	Gl-M	200						
28	STP85	1985	LB	500						
29	STP85	1985	LB	320	320	320	320	320	320	320
30	EMist	1991	LBt	400						
31B	Inlet	1982	LB	400	88	88	141	199	199	199
32A1	Rip32	1992	TGM	300						
32A2	Rip32	1992	TGM	200	105	105	105	105	105	105
32B	Rip32	1992	TGM	180	180	180	180	180	180	180
32C	Rip32	1992	TGM	400	400	400	400	400	400	400
32D	Rip32	1992	TGM	400	400	400	400	400	400	400

Appendix 2. 48 Post (1993) Forest Practices Code according to landform, total length, and length of holes

Strip	Year Cut	Land form	Length (m)	Holes 97/8/20	Holes 97/11/29	Holes 98/8/20	Holes 98/11/24	Holes 99/3/24	Holes 00/4/10
01	1995	TGM	100	100	100	100	100	100	100
02	1995	TGM	300	26	26	26	26	26	26
03	1995	TGM	220						
05	1996	DTP	400	20	20	20	20	20	20
06	1996	TGM	200						
07	1996	TGM	460	20	20	48	48	148	148
07a	1996	TGM	280				41	56	56
08	1996	TGM	480				30	78	78
09	1994	LB	80						
13	1994	LB	320		30	30	57	57	57
16	1995	TGM	300	300	300	300	300	300	300
17	1995	TGM	400	94	94	134	176	176	176
18	1995	TGM	440	95	95	153	202	202	202
21	1994	Gl-M	100						
23	1994	Gl-M	160						
24	1994	TGM	300	300	300	300	300	300	300
25	1994	LB	1200	175	310	398	472	574	574
26a	1994	LB	200						
26b	1994	LB	200						
31a	1996	TGM	440		60	80	113	118	357
33	1995	TGM	280	280	280	280	280	280	280
34	1995	TGM	140	140	140	140	140	140	140
35	1995	TGM	400						
36	1995	T/R	800				230	264	330
36a1	1997	T/R	380		131	380	380	380	380
36a2	1997	T/R	320		60	320	320	320	320
37	1994	LB	900				146	146	146
38	1994	LB	220						
39	1995	T/R	500	82	82	82	82	82	82
40	1995	T/R	600			74	74	74	74
41	1995	T/R	500						
42	1995	T/R	300						
43	1995	T/R	260						
44	1995	T/R	300	90	90	90	90	90	90
45	1995	T/R	480			145	172	177	177
46a	1995	T/R	200	60	60	60	60	60	60
46b	1995	T/R	80	80	80	80	80	80	80
47	1995	T/R	300	167	167	167	167	167	167
48	1995	T/R	650	160	160	160	160	160	160
49a	1995	T/R	360	360	360	360	360	360	360
49b	1995	T/R	200	200	200	200	200	200	200
50	1997	TGM	920		60	60	94	121	128
51	1997	LB	640						
52	1997	LB	560						70
53	1997	T/R	450		450	450	450	450	450
54	1997	T/R	162						
55	1997	T/R	350		50	50	70	118	156
56	1997	T/R	230		44	44	102	121	174

Modeling and Mapping Cutblock Edge Windthrow Risk Using GIS

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Abstract

Empirical models of windthrow risk prediction are well suited to the diverse terrain, stand and management conditions in BC. Geographic information systems (GIS) enable calculation of topographic and management variables and compilation of the large datasets necessary for model building. In this study, readily available sources of stand level data - forest cover maps, ecosystem/terrain maps, topographic maps - were combined with aerial photograph detection of clearcut edge windthrow to build a dataset containing 3000 - 50m long by 40m deep clearcut edge segments on northern Vancouver Island. The resulting logistic regression models accurately predicted damage in 71-76% of test segments and adequately fit using Chi-square tests on test data. Landscape scale maps of windthrow risk can be produced by incorporating these equations into ArcView map-calculator.

Introduction

Windthrow results from complex interactions of climatic, biophysical and management factors. Documenting the relationship between these factors enables prediction of damage and design of lower risk harvesting plans. There are two basic approaches to windthrow risk modeling - mechanistic and empirical. Mechanistic models predict the likelihood of damage using estimates of the critical windspeed for tree failure and the probability of such a wind occurring at a given location. These models are built by winching trees over to determine resistance, placing tree crowns in wind tunnels to determine drag, and using wind tunnel, or numerical modeling to determine local modification of the regional wind regime. They must be calibrated in field studies of damage occurrence on a range of sites (Quine 1995). Mechanistic models have been successfully developed for uniform stands in Europe and eastern Canada (e.g. Smith et al. 1987, Peltola and Kellomaki 1993).

The empirical approach used in this study is more suitable where stands have complex structure and composition, and where geography and soils are heterogeneous. In the empirical approach, regression models relate presence or magnitude of wind damage in sampling units to their environmental and management attributes (e.g. Fleming and Crossfield 1983, Andrus and Froehlich 1992, Fridman and Valinger 1998). For the construction of empirical models, information about large numbers of sample units is necessary. Geographic information systems (GIS) provide the opportunity to assemble stand or landscape level information, generate new variables, analyze, and map the results. Wright and Quine (1993) used a GIS to analyze damage caused by a strong wind event in a forest in North Yorkshire, but did not built a predictive model. Moore and Somerville (1998) in New Zealand used GIS software to run a mechanistic model with a tree/stand critical windspeed component and an airflow component. They concluded that their model provided reasonable predictions for a test area with non-complex terrain but performed poorly in more complex terrain due to inaccurate prediction of wind speeds.

The objectives of this project were to: develop a GIS based procedure for building windthrow risk models and maps from stand level data; and to investigate the relationship between site, stand and management factors and damage severity. The model fitting procedures and results are reported more comprehensively in Mitchell et al. (2001). This paper focuses on the GIS procedures for data assembly and mapping.

Methods

Six 1:20,000 mapsheets, covering an area of 900 square kilometers of Western Forest Products Limited (WFP) Port McNeill Tree Farm Licences on Northern Vancouver Island were selected as representative of the range of biophysical conditions in this landscape. The area includes the Nahwitti Coastal Lowland physiographic region to the east, and the northern extension of the Vancouver Island Ranges to the west (Lewis, 1985). Low pressure systems originating over the Pacific Ocean produce high fall and winter winds from the southeast (Environment Canada 1994). Major forest types in the eastern portion of the study area include open-grown overmature western redcedar (*Thuja plicata* (Donn)) dominated stands (CH) in low-lying poorly drained areas intermixed with dense thrifty western hemlock-amabilis fir (*Tsuga heterophylla* (Raf.) Sarg.; *Abies amabilis* Forbes.) stands (thrifty HA) which originated following a major windstorm in 1906. In the more mountainous western portion, the forest is dominated by overmature western hemlock (mature HA). The area has a long history of forest management and approximately half of the study area is occupied by regenerating clearcuts.

The steps in model construction are summarized in Table 1. ArcView® GIS software (ESRI, 1996) with Spatial Analyst and 3-D Analysist extensions was used for data compilation. For each of the six mapsheets, PAMAP® coverages of logging history, forest cover, ecosystem and ecosystem polygons were obtained from WFP and converted to ArcView coverages. Digital TRIM topographic maps with 20m contour intervals were obtained from the BC Ministry of Environment. Digital terrain models were constructed using triangular interpolation networks and topographic variables such as elevation, ground aspect, and ground slope, were determined using ArcView functions, and a script was written to calculate distance limited topographic exposure (Table 2) using the methods of Hannah et al. (1995).

Table 1. Summary of procedures used to build windthrow risk models.

Step	**Procedure**
1	Information Assembly • Obtain layers for ecosystem, stand, logging history • Obtain TRIM contours.
2	Translate data to ArcInfo/ArcView format if necessary.
3	Create sample units and management variables. • Create 50m long * 40m deep cutblock boundary segments from logging history coverage using segmenting script and ArcView buffering function. • Calculate edge exposure scores using UTM coordinates of segments.
4	Windthrow detection and mapping. • Identify and map potential edge windthrow on high resolution (e.g. 1:15,000 colour aerial photos). • Digitize damage polygons. • Verify windthrow status of 30% of segments in field. • Rate damage severity and add to database.
5	Determination of topographic variables. • Produce TIN. • Determine topographic variables aspect, elevation, slope. • Calculate TOPEX2000 scores using DTM and topex script.
6	Construction of segment database for polygons. • Overlay coverages with edge segments and extracted segment database. • Keep segments with forested boundaries for analysis (3000 segments). • If have multiple rows per edge segment, keep largest polygon as representative.
7	Model fitting and testing. • Import polygon database into SAS and merge in topographic and management databases. • Calculate % of segment damaged and created set of response variables. • Determine correlations between independent variables, build contingency tables. • Fit logistic regression models using 60% of edge segments. • Test predictions using other 40% of data.

Table 2. Steps in Calculation of Topex2000.

Step	Procedure
1	Build the 3 D model based on TRIM contours.
2	Convert DEM to 100*100m grid cells.
3	Obtain UTM coordinates for each grid cell and Z value representing elevation.
4	For each grid cell within the area of interest carry out the following analysis: • Calculate the vertical angle from the ‘point of observation’ grid cell to the grid cell at 2000 m distance to the North. • Repeat calculation from the point of observation grid cell to the grid cell at 1900m distance to the North, and then for each cell working back towards the point of observation grid cell. • Retain the x,y coordinates, z- value, and vertical angle of the cell for which the largest angle from point of observation cell is obtained. • Repeat calculations for each of the other cardinal directions: NE, E, SE, S, SW, W and NW.
5	Add up the 8 vertical angles obtained using calculations in step 4. This is the Topex2000 score for the first point of observation cell.
6	Move to the next cell, this is the second point of observation cell in the grid and repeat Steps 3 and 5.
	In ArcView for visibility analysis there is a ‘line of sight’ function which projects a line in a given direction and identifies which segments of this line would be visible from the point of observation. The UTM coordinates of the beginning and end of each visible segment along this line can be obtained. ArcView’s ‘line of sight’ was substituted in Step 4.
	Calculation of TOPEX2000 for edge segments follows the same procedure but the calculation is initiated from each segment centroid.

Site and stand variables were obtained from the coverages provided by WFP (Table 3). Edge windthrow polygons were mapped using 1:15,000 nominal scale colour aerial photographs taken during August 1995. Stereo-photo pairs for all cutblocks within the study area identified as having been logged between 1987 and 1994 in the logging history records were obtained. The cutblock boundaries were inspected under stereo-magnification enabling detection of high contrast objects approximately 1m wide. Areas with visible windthrow or with canopy gaps not obviously associated with rock, swamp or harvesting were outlined. Approximately 30% of the cutblock boundaries were inspected by helicopter and videotaped and 10% were visited on the ground to confirm the detection and classification of windthrow. The principle uncertainty was with edges damaged by slashburning, however these contained large numbers of snags which were visible on the aerial photographs. The boundaries of each cutblock were divided into 50m segments, each with a unique segment identification number. Avenue scripts were written which used the UTM coordinates of each segment to calculate management variables (Table 3). Using the buffering function in ArcView, linear edge segments were converted to edge segment polygons, 50m long by 40m deep. Overlaying the segment polygons with windthrow polygons enabled determination of damage severity, calculated as the proportion of the area of an edge segment polygon overlayed by windthrow polygons. A composite database for each boundary segment was built in ArcView and then exported to SAS (SAS Institute, 1989) for data management and analysis. Where the segment polygon overlapped more than one polygon of a given layer, the dataset contained multiple records for the segment. In this case, the record for the largest polygon within the segment was retained for analysis. Boundary segments not adjacent to timbered boundaries were deleted, leaving a total of 3000 segments. Prior to analysis 60% of the segments were randomly assigned to the 'model building' dataset, and 40% were reserved for model testing.

Table 3. Summary of independent variables.

Variable	Name	Description	Unit
AGE	stand age class	from forest cover label; class 1-7 in 20 year increments, e.g. 1=0-20 years; class 8=141-250 years	
HEIGHT	stand height class	from forest cover label; class1-7 in 10m increments, e.g. 1=0-10m	
STOCK	stocking class	from forest cover label; class 1=dense, 2=normal, 3=open	
SITE	site quality class	converted from forest cover label; 0=L (poor), 1=P (low), 2=M (medium), 3=G (good)	
COAST	side of island	E - east coast mapsheets	
		W - west coast mapsheets	
SPC	leading tree species	C - western redcedar, H - western hemlock, B - amabilis fir, O - Sitka spruce, shore pine or cypress	
ECO	ecosystem type	DM - dry medium, MM - moist medium, MR - moist rich, WP - wet poor, WM - wet medium, WR - wet rich.	
SURFM	surface material	M - morainal, C - colluvial, O - organic	
SLOPE	slope	ground slope	%
ASPECT	aspect	ground aspect	º
ELEV	elevation	ground elevation	m
TPX2000	TOPEX2000	topographic exposure to distance; sum of maximum angle to ground within 2000m for each of 8 cardinal directions	º
TPX2000S	TOPEX2000 south	same as above but for 135, 180 and 225º directions only; multiplied by 8/3 to bring into same scale as topex2000	º

Table 3. Summary of independent variables.

Variable	Name	Description	Unit
TIMELOG	time since logging	years since logging of adjacent opening	years
EDGEEXP	edge exposure	sum of distance across opening from segment for all eight cardinal directions	m
EDGEEXPS	edge exposure south	sum of distance across opening from segment for 135, 180 and 225° directions only	m
BRGCN	bearing to centroid	bearing from segment to cutblock centroid	°
BRG	bearing	bearing perpendicular to edge of segment towards opening	°

The correlations between continuous variables were calculated, and the relationships between discrete variables were assessed using contingency tables and Chi-square tests. Prior to model building nominal variables were converted to indicator variables, and directional variables were converted to ordinal classes (Table 4). For model building, logistic regression was used. These models predict the probability of an event (windthrow) occurring. Segments were classified as being windthrown if the percent of segment area within a windthrow polygon exceeded a chosen threshold. Two sets of models were fit, one for a low damage cutpoint (>10% of segment area damaged - WTC10), and another for a higher cutpoint (>50% of segment area damaged - WTC50). The former is useful where any level of damage detectable from aerial photographs is of interest. A series of models were fit. These included a full model in which the best fit model was selected from all of the available variables and interaction terms using forward selection, and simplified models in which variables were pre-selected. Models were evaluated using the proportion of correct classifications, the Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow, 1989), and with a Chi-square test for data grouped by stand type.

Table 4. Indicator variables and conversion of directional variables to ordinal values.

Variable	Description
coast	default = E, C1=1 if COAST=W
leading species	default = C, S1=1 if SPC1=O, S2=1 if SPC1=H, S3=1 if SPC=B
ecosystem type	default = MM, E1=1 if ECO=DM, E2=1 if ECO=MR, E3=1 if ECO=WR, E4=1 if ECO=WM, E5=1 if ECO=WP
surface material	default=M, M1=1 if SURFM=O, M2=1 if SURFM=C
ground aspect	0-45 or 315-360=1; 45-135 or 225-315 = 2; 135-225 = 3
segment bearing	0-45 or 315-360=1; 45-135 or 225-315 = 2; 135-225 = 3
bearing to cutblock centroid	0-45 or 315-360=1; 45-135 or 225-315 = 2; 135-225 = 3

Results

A number of associations between site and stand characteristics were observed. The major forest cover types are associated with specific site features. Overmature CH stands were found primarily on organic soils on low to medium quality sites at low elevation, with only 20% of stands reaching height class 5. Hemlock stands were most commonly found on moist medium sites on morainal soils. The proportion of segments damaged (WTC10) significantly varied ($p \leq 0.05$) with all independent variables except slope, aspect, TOPEX2000, edge exposure and coast. A higher proportion of segments were damaged in moist ecosystems than in dry or wet ecosystems, and on mineral soils than on organic soils. A higher proportion of hemlock dominated stands were damaged than stands dominated by cedar or other species. Damage increased with increasing site quality, stocking and stand height. Damage increased in years 1-4 and then began levelling off. The proportion of segments with damage and damage severity was highest for south facing segments and lowest for north facing segments (Figure 1).

The simplified models which use selected forest cover, topographic and management variables (Table 5) were very similar to the best-fit models in overall accuracy of prediction and goodness-of-fit. For WTC10 and WTC50 the simplified models accurately predicted damage status for 72% and 75% of the test segments respectively. They were better at predicting the status of undamaged segments than damaged segments (Table 6). In the Hosmer-Lemeshow test, the test dataset was sorted by the predicted probability of damage, and then grouped into 10 equal sized groups. For each group, the predicted number of segments damaged was compared to the actual number of segments damaged (Table 7). For both models, there is reasonable correspondence between actual and predicted damage across a range of risk classes, except for the lowest risk groups.

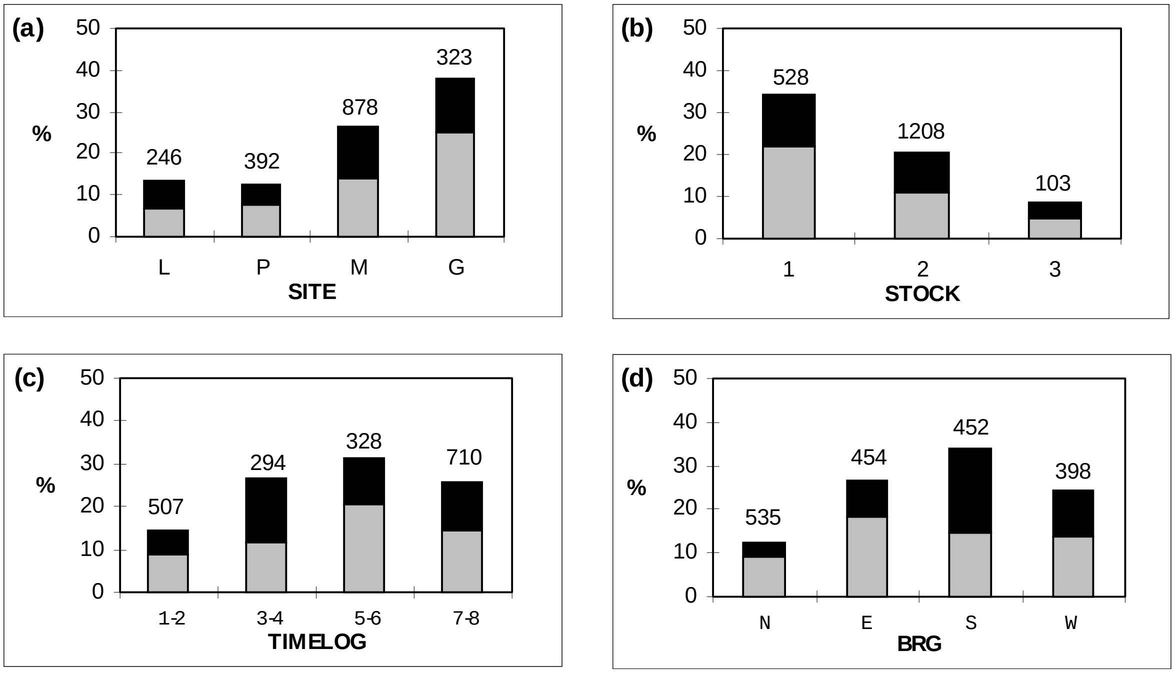

Figure 1. Percentage of segments damaged for classes of independent variables. The number above each bar is the number of segments in the class. The darker portion of each bar indicates the proportion of segments with severe damage (>70% of segment area).

Table 5. Variables and coefficients in simplified models.

		WTC10	WTC50
Intercept		-2.5176	-4.4235
Height class	From forest cover label.	0.2496	0.2310
	Classes: 1-7 representing 10m increments		
Stocking class	From forest cover label. (see page 7)	-0.8349	-0.5199
	Classes: dense=1, normal=2, open=3		
Time since logging	From logging history.	0.0894	0.1098
	1995-logging date. Values from 1-8		
Edge orientation	Bearing towards which segment edge faces	0.6788	0.9514
	Classes: north=1, east or west=2, south=3.		
Topographic exposure	Topex2000 score (see below)		-0.00947
Coast	Side of island: east coast mapsheets=0, west coast mapsheets=1		1.0787

Note: these equations calculate the ‘logistic’ value which is then converted to probability’ using equations 2 and 3 in Tables 9 and 10.

Table 6. Percent of correct predictions using test data.

	WTC10	WTC50
	% of correct predictions using test data	
Damaged correctly predicted	52	54
Undamaged correctly predicted	77	78
Total correct predictions	72	75

Table 7. Percent of actual and predicted damaged segments using test data sorted by predicted probability of damage and divided into 10 groups.

	WTC10		WTC50	
Group	Actual %	Predicted %	Actual %	Predicted %
1	13	7	6	3
2	3	11	5	5
3	11	14	3	7
4	15	18	8	9
5	15	21	12	11
6	24	24	8	14
7	22	27	18	17
8	30	32	18	21
9	48	40	23	26
10	44	49	43	38

The regression equations can be incorporated into spreadsheets that tabulate the characteristics of proposed cutblocks and used to calculate the probability of damage in each boundary segment. Using the procedures in Table 8, the equations in Tables 9 and 10 can be entered into ArcView map-calculator to produce maps of windthrow risk.

Table 8. Procedures used to build maps in ArcView.

Step	Procedure
1	Obtain forest cover and TRIM data.
2	Edit database to add variable Coast with value of 1 for west coast mapsheets and 0 for east coast mapsheets.
3	Create grid coverage (100*100m cells) for Height Class [Ht_class] and Stocking Class [St_class] variables.
4	Build 3D model based on TRIM 20 m contours for the whole study area including the areas represented by the adjacent maps.
5	Convert DEM coverage to grid cover using the 100 m cell size.
6	Select the area of interest (mapsheet).
7	Calculate Topex2000 score for each grid cell for selected distance = 2000 m for 8 cardinal directions (see Table 2).
8	Use Map Calculator to input the equations from Tables 9 and 10.The outputs are probability grid covers with different value range for each mapsheet. To unify the value range and intervals, set the lower boundary to 0.00, the upper boundary to 0.90, and the number of classes to 6.The management variables in the regression equations are held constant to represent south facing cutblock boundary segments located on the north side of large openings which have had 8 years of exposure following harvesting.
9	Risk estimates are unreliable for stands less than 10 m tall, so stands in Height Class 1 are masked by overlay in grey color.
10	Areas with no-data are shown in white.
11	Areas labeled as non-forest or NSR types are beige and brown.
12	Create the windthrow risk overlays: grid covers overlaid with polygons representing recently logged sites, non-forest, and no data.

Table 9. Map formulas used to calculate windthrow risk for 10% cutpoint (WTC10)

Map Calculation	Formula
1	(([Ht_class]*0.2496)-([St_class]*0.8349)-2.5176+(8*0.0894)+(3*0.6788))
2	(2.71828.AsGrid.Pow([Map Calculation 1]))
3	([Map Calculation 2] / ([Map Calculation 2]+1))
	Uses Variables: a) [Ht_class] b) [St-class]

Table 10. Map formulas used to calculate windthrow risk for 50% cutpoint (WTC50)

Map Calculation	Formula
1	(([Ht_class]*0.2310)-([St_class]*0.5199)-4.4235+(8*0.1098) +(3*0.9514)-([Topex2000]*0.00947)+([Coast]*1.0787))
2	(2.71828.AsGrid.Pow([Map Calculation 1]))
3	([Map Calculation 2] / ([Map Calculation 2]+1))
	Uses Variables: a) [Ht_class] b) [St_class] c) [Topex2000] d) [Coast]

The resulting maps show the probability of damage occurring within 8 years of harvest to the south facing boundaries of large openings if located in a given 100*100m map cell. For the ‘probability for 10% cutpoint’ (WTC10 equation) maps, this is the probability of at least 10% of the area within a boundary segment being damaged. The WTC50 maps highlight those areas where more severe damage is likely (Figure 2).

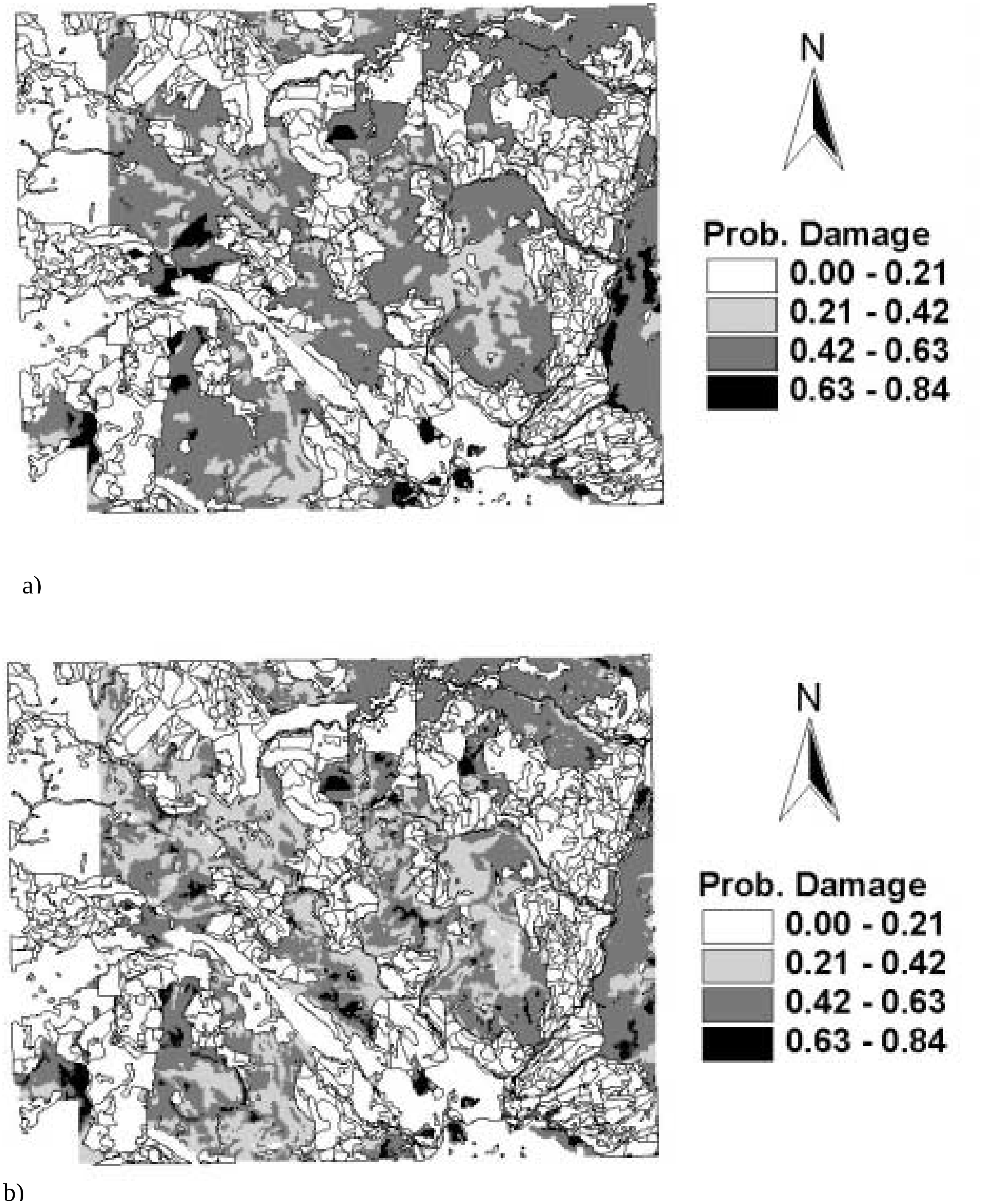

Figure 2. Map for 150 km2 area of Northern Vancouver Island showing probability of a south facing 8 year old cutblock boundary segment experiencing greater than a) 10% of segment area (WTC10), and b) 50% of segment area (WTC50).

Discussion

The vulnerability of boundaries to damage is consistent with the dominant storm wind directions recorded at the local AES climate stations. The concentration of damage in early years following exposure of the edge by harvesting is consistent with the observations of other authors (e.g. Moore 1977; Harris, 1989). Increasing damage with site quality was also observed by Fleming and Crossfield (1983) in boreal forests Harris in southern Alaska. Height and site quality are correlated (r=0.71) and substitute for each other in the simplified models. In the full models however, height had a negative coefficient, suggesting that there is some other property of high quality sites which contributes to risk. Increased damage with higher stocking is generally attributed to high slenderness and lower stability of individual trees (e.g. Becquey and Riou-Nivert, 1987; Mitchell, 2000). It is worth noting that for the more severe damage model (WTC50) stocking drops out, indicating that damage in high density stands is largely concentrated at the edge. Species itself was not significant in any of the models, suggesting that stand properties captured by the stocking, site and height variables are more important than species alone.

Organic soils are generally considered low strength (Anderson et al., 1989), but in this study, damage was more severe on morainal and colluvial soils. This likely reflects the open structure of the CH stands found on the organic soils. The large undecayed logs on these sites may also provide better anchorage than finer textured peats. TOPEX2000 was significant for the more severe damage model, but overall topographic variables contributed less than expected. The variables used are surrogates for actual windflow, and may not be well correlated in this complex terrain. Numerical modeling such as that used by Murphy and Jackson (2001) would likely improve prediction of risk. The simplification of the models with only minor loss of fit reflects underlying associations between site and stand variables, such as those between site quality and stand height, forest cover type and parent material, topographic exposure and elevation. While these associations may be more pronounced on northern Vancouver Island, it is likely that these associations are general and are linked to the ecophysiology of windfirmness.

The procedure presented in this paper can be used in any location with endemic windthrow for which stand level data and recent high resolution aerial photographs are available. Because the equations are derived empirically they should not be applied where conditions differ from those where the model was built. The models use stand level information from broad scale inventories and indicate conditions at the stand level not at the microsite or tree level. Furthermore, aerial photograph interpretation of wind damage does not detect low levels of damage which might be important in riparian areas or areas of unstable terrain.

Conclusion

The regression models built using aerial photograph detection of wind damage and stand level variables adequately predict the probability of damage to cutblock edges in the Port McNeill area. The portability of these models to other locations with different stand types and wind regimes is currently being tested. Further development of the topographic and management variables is also underway.

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Riparian Windthrow – Northern Vancouver Island

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Abstract

Windthrow in riparian reserves and riparian management zones along streams on Northern Vancouver Island is chronic. It can range in degree, from isolated individual trees or small groups of trees to occasional areas where all the trees are windthrown. This study documents the amount and distribution of windthrow and evaluates relationships among various environmental and management factors, and windthrow. The factors most strongly associated with windthrow in riparian forests are: the type of treatment applied to the boundary, the character of the leave strip (one-sided versus two-sided strips), strip width, rooting depth, exposure of the boundary to wind, tree height and tree species. To a lesser degree, soil drainage, landform morphology, and the position of the boundary on the slope relative to certain morphologic features of landforms are also important.

Introduction

The implementation of the BC Forest Practices Code (FPC) has resulted in a significant increase in the number and type of riparian reserves and forested riparian management zones being established along streams on Northern Vancouver Island. This increase in the frequency of forested riparian buffers is leading to increasing concern over the amount of windthrow that occurs, and the possible effects of this windthrow on stream channels and other ecological values within these riparian areas. These concerns are coupled with a desire to predict where windthrow is most likely to occur and to develop methods to control riparian windthrow or mitigate its effects.

This study was set up to document the amount and distribution of riparian windthrow, and to evaluate relationships among various environmental and management factors and the frequency of windthrow. The focus of the study is on riparian management areas set up within the Northern Vancouver Island operations of Western Forest Products Ltd. At the time field sampling for this study was conducted, riparian reserves and management zones established to FPC standards had experienced one or two winter storm seasons. Streamside management zones established under the guidance of the BC Coastal

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Fish/Forestry Guidelines (CFFG) that are comparable to the riparian management areas as defined by the FPC were also sampled. Most of these streamside management zones had experienced several winter storm seasons.

Objectives

The study objectives included:

- Evaluation of the extent of riparian windthrow in logged areas on Northern Vancouver Island that were harvested to FPC and/or CFFG standards.
- Evaluation of factors associated with riparian windthrow.
- A qualitative evaluation of the short-term effects of riparian windthrow on streams.
- Development of a rapid, relatively low-cost, field methodology suitable for the assessment and monitoring of post-harvest windthrow conditions.

Study Area

The study includes the Port McNeill, Holberg and Jeune Landing operating areas of Western Forest Products Ltd.

The Port McNeill and Holberg operating areas are located within the Nahwitti Lowland subdivision of the Hecate Depression on Northern Vancouver Island. The Nahwitti Lowland encompasses the northern end of Vancouver Island north of a line drawn between Englewood and Quatsino Sound. It is an area of low rounded hills and ridges within the Hecate Depression. Elevations rarely exceed 600 meters above sea level (a.s.l.) except for a few isolated summits (Holland, 1976).

The Jeune Landing operating area lies within the northern portion of the Vancouver Island Mountains, a major northwest to southeast-trending physiographic unit that forms the core of Vancouver Island (Holland 1964). Elevations range from sea level to 2200 meters. This portion of the Vancouver Island Mountains can be subdivided into two sub-units consisting of the North Vancouver Island Ranges and the Vancouver Island Fiordland (Hoadley 1953; Yorath and Nasmith 1995). The North Vancouver Island Ranges tend to be more rugged and have greater relief than Fiordland.

Most of the study area lies within the Submontane Very Wet Maritime variant (CWHvm1) of the Coastal Western Hemlock (CWH) biogeoclimatic zone and the Southern Very Wet Hypermaritime variant (CWHvh1) of the CWH biogeoclimatic zone. Western hemlock, balsam and cedar dominate the forest cover within the area. There are large areas of second growth plantations within the study area.

Climate

Northern Vancouver Island is characterized by cool, wet winters and moist, warm summers. Snow is usually confined to higher elevations but is often present for short periods at lower and mid elevations and the area is subject to occasional rain-on-snow events. High intensity/long duration storms, often accompanied by strong winds, occur during the fall and winter months. The highest monthly precipitation averages occur between October and January. Snow generally occurs between November and March.

Methods

The initial phase of the project included a helicopter reconnaissance of a number of riparian reserve and riparian management zones in Western Forest Product's operating areas on Northern Vancouver Island. We then reviewed past logging plan maps to identify candidate harvest units and riparian areas that were logged to FPC or CFFG standards and had experienced one to several winter storm seasons. This compilation involved WFP's Port McNeill, Holberg and Jeune Landing Operations. The Port McNeill and Holberg operating areas are located within the Nahwitti Lowland while the Jeune Landing operation is confined to the northern portion of the Vancouver Island Mountains.

Between 60 and 65 logged blocks contained forested riparian areas that appeared to meet the selection criteria, of these, 58 blocks proved suitable for study and were sampled during the course of the project. The field phase of the study involved ground traverses of all forested riparian areas within each block selected for sampling.

All riparian reserve zones and forested riparian management zones[5] in FPC blocks and streamside management zones in CFFG blocks on S1 to S6 streams were sampled if they had experienced at least one winter season. Each riparian strip was stratified into distinct geomorphic and/or geometric 'entities'. This stratification resulted in the creation of unequal length plots or 'sample segments'. The sample stratification or separation was based on the following field criteria:

- The type of forested riparian area. Riparian areas were classified as 1-sided leave areas or 2-sided leave areas (i.e., external stand edges versus strips of timber bounded by clearcut areas on either side).
- Significant changes in the orientation (aspect) of the riparian boundary.
- Change in classification of the stream contained within the riparian area.
- Visible and significant changes in slope, terrain and/or soils along the boundary.
- Changes in forest type along the boundary.
- Type of riparian treatment: untreated, feathered, thinned.
- The sample segments (plots) had to be a minimum of 50 meters long. Shorter segments were discarded.
- Two-sided riparian strips were sampled on both sides, each side of the strip was treated as a separate sample.

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[5] The term 'forested riparian management zone' is used to distinguish between "forested" riparian management zones where trees are retained and riparian management zones where all or almost all trees are cut. Riparian areas where small conifer regeneration (i.e. generally less than 2-3 meters tall) was retained were not sampled.

- Changes in the amount or character of windthrow did not affect sample selection.

We used stratified, unequal length sample segments (plots) to improve sampling efficiency and to ensure that any visible environmental differences that could potentially exert a significant effect on windthrow response were sampled. For example, random or systematically located plots that fell across significant changes in soil type or boundary orientation could well confound any subsequent analysis if these factors strongly affect windthrow susceptibility. Because the two important target variables (percent windthrow and distance of penetration of windthrow) should not be affected by sample segment length we did not feel that differences in the length of the plots would significantly affect the outcome of the study. Additionally, some terrain types are inherently quite variable over relatively short distances so sampling the full length of such ‘strata’ should generate a more representative estimate of the amount windthrow occurring within these more heterogeneous terrain types. For the objective of estimating cumulative windthrow along riparian boundaries, unequal length sampling segments work very well. All segments along all riparian strips traversed were sampled, except for a few short (<50 meter) segments that were discarded. We selected a minimum sample segment distance of 50 meters because we were interested in making a qualitative assessment of the spatial patterns of windthrow present in the area and felt that shorter sampling segments would likely obscure any spatial pattern that might exist.

Much of the data collected in the field was restricted to visual classification of such items as soil type, slope morphology, surficial materials, boundary geometry, and stream class. In order to streamline data collection we did not collect data on the actual number of trees windthrown or standing. Instead, we made visual estimates of the amount of windthrow present based on nominal classes of: 0, 1, 2, 5 and then increasing increments of 5 or 10%. Similarly, we visually estimated the ‘average’ primary and secondary orientations of windthrown trees in a sample strip rather than the orientation of each individual tree. We developed a qualitative wind exposure index, or ranking matrix (Figure 1), to represent the vulnerability of boundaries that are subject to winds from more than one direction. Forest types and heights were estimated visually and then compared to forest cover information included on the logging plan map for the block. We also recorded any stand edge treatments that had occurred along each sample segment. In total 447 riparian segments were sampled representing about 76 kilometers of falling boundary.

We carried out simple graphical analysis of the data to identify obvious trends and patterns in the data that might be associated with changes in riparian windthrow. Two non-parametric tests, the Mann-Whitney, and the Kruskal Wallis, were used to test for significant differences in amount of windthrow between or among variable categories. We also carried out a limited amount of segmentation analysis using CHAID (Chi-squared automatic interaction detector – SPSS, 1998) to develop a prototype windthrow hazard classification (decision tree) for Northern

Vancouver Island. The use of segmentation analysis to develop windthrow hazard models was pioneered by Kennedy (1974), for studies of windthrow in Northern Ireland.

Results and Discussion

Riparian windthrow within the study area averaged about 21% of the standing timber along stream edges. There are a large number of plots with only a minor amount of windthrow and conversely only a limited number of areas with substantial amounts of windthrow (Figure 2). The average distance of penetration of windthrow into the standing timber was about 12 meters.

Two-sided riparian strips are in general much more vulnerable to windthrow than one-sided riparian strips (Tables 1 and 2). Two-sided strips experience about twice the amount of windthrow as one-sided strips. The distance windthrow penetrates in to the residual stand is also higher for two-sided riparian strips.

The type of edge or strip treatment has a significant effect on the amount of windthrow. Strips with feathered edges tend to experience the least amount of windthrow (7%), followed by untreated strips (18%). The lower amounts of windthrow along feathered edges is most likely due to the successful identification and removal of the more vulnerable trees along these edges. There may be a secondary compensating effect in that removal of these trees means that they cannot knock other trees over in the process of blowing over themselves (i.e., the ‘domino effect’ is constrained). Uniformly thinned strips and strips where only the smaller merchantable trees have been retained experience substantially higher percentages of windthrow among the retained trees (Table 1 and Figure 3). The distance windthrow penetrates into riparian areas does not appear to vary significantly between feathered and untreated edges but appears significantly greater in thinned areas where only smaller trees have been retained.

Except for rooting depth, where there is a tendency for more windthrow to occur as rooting depth increases, comparisons of between various environmental variables and the amount of windthrow in thinned, two-sided leave strips show no significant differences. These treatments are not discussed further. Rather we focus on the apparent relationships between various environmental variables and windthrow along untreated or feathered riparian strips.

There are a large number of variables that are associated with windthrow along untreated and feathered riparian edges. A number of these factors co-vary so although most will be discussed below, not all need to be taken into account when evaluating the potential for windthrow along a riparian boundary.

The width of riparian strips appears to play a significant role, with wider strips having less windthrow (Figures 4 and 5). The effect appears to be more pronounced for two-sided compared to one-sided strips. For one-sided strips, the effect of increasing width appears to diminish once the strip is 25 to 30 meters wide. However, for two sided strips, windthrow frequencies appear to continue to decrease up to a width of about 40 meters (these distances represent the strip width on one side of the stream only).

The location of a boundary relative to morphologic features on a hillslope can have an effect on the amount of windthrow experienced (Table 2). Falling boundaries located along the edge of steep stream escarpments and gully sides appear to experience substantively more windthrow than boundaries at other slope locations. Boundaries that are set back 10 to 20 meters from the edges of these features appear to experience much less windthrow (these setback boundary locations are classified as 'hillslope-escarpment' and 'hillslope-gully' in Table 2). Downhill boundaries on slopes of 10 to 60% and boundaries on level or very gentle slopes may experience slightly lower rates of windthrow than lateral boundaries. Lateral boundaries, which run up or down hillslopes, typically lie perpendicular or diagonal to the long-axis of a valley and so may be more vulnerable to up and/or down-valley winds.

The presence of shallow soils and shallow rooting as well as asymmetrical root, stem and crown development in the trees growing along gully and escarpment slopes may be the reason they are more vulnerable to windthrow. Typically, the crowns of the trees along gully sides and stream escarpments are more extensive (heavier) on the downhill (stream) side of the tree and some trees on these steep slopes lean out into the gully or over the stream. Shallow rooting and the asymmetrical form of these trees may make them more vulnerable to wind than trees located some distance back from the gully or escarpment edge. It is possible to feather the edges of setback boundaries but it is very difficult to feather a stand edge on a gully sidewall or steep stream escarpment unless trees are felled to waste. Consequently, some of the lower windthrow rates seen along setback boundaries compared to gully and escarpment edges may be due to the presence of feathering treatments.

The exposure or orientation of a boundary segment to storm winds is a significant factor. Boundary exposure (i.e., lee through windward) is defined as the relative orientation of the boundary to the apparent direction of winds in a block determined from the orientation of windthrown trees along the boundaries within the block. We define primary and secondary boundary wind exposure based on the apparent dominance (primary and secondary) of windthrow orientations around a block. Table 2 lists the windthrow amounts for the primary boundary exposure (boundary exposure 1). As boundary exposure ranges from lee through parallel to windward we assume that greater wind forces are applied to the trees along the boundary. As shown in Table 2 and Figure 6 there is an increasing amount of windthrow as well as increasing depth of windthrow penetration from lee through windward boundary exposure classes.

A similar, but perhaps more sensitive measure of apparent wind force is what we call the 'wind exposure index' (see Figure 1, for the derivation of this index). This index attempts to rank the cumulative effect of the primary and secondary winds for each specific segment (sample) along a riparian boundary. Reference to Table 2 and Figure 7 shows a strong relationship between the amount of windthrow and the wind exposure index. This index should be useful at the field level for identifying boundaries that are potentially vulnerable to windthrow, either through the use of likely wind orientation determined from natural windthrow within a proposed block and/or by the documentation of post-harvest windthrow orientations in nearby areas.

A weak but still important relationship occurs between the valley axis orientation and windthrow. Riparian boundaries located in NE-SW and NW-SE trending valleys are more prone to windthrow than boundaries located in E-W and N-S trending valleys (Table 2). This finding suggests that some valley orientations favour the confinement of regional storm winds whereas other valley orientations may tend to disperse or disrupt these winds. This relationship may prove be more important in areas of high relief where valleys are well defined, than in areas of low relief where the valleys are not well defined.

There are several relationships that associate windthrow with the character of the riparian forests themselves (Table 2 and Figures 9). The strongest relationship is with the height class of the stands forming the riparian strips. There is a general increase in windthrow up to height class 4 and then a slight decrease or plateau in windthrow frequency with increases in height class. Because of small sample sizes, the apparent relationship between windthrow and taller height classes should be interpreted with caution.

A companion relationship is seen with age class as derived from forest cover maps. Windthrow is greatest for age class 4 and then decreases slightly to age class 8 (age classes 5 and 6 were combined because of the small number of cases in these categories). Age class 4 corresponds to a moderate number of ±90 year old, relatively tall, dense, uniform hemlock stands that regenerated after a severe windthrow event(s) in the early part of the century (these stands are known locally as the '1908 blowndown', but may include stands of earlier and later origin).

There is also an apparent relationship with the dominant tree species present in the various riparian strips. Stands dominated by hemlock appear to be more vulnerable to windthrow than either cedar or balsam fir. The sample for balsam dominated stands is quite small so the values for balsam should be interpreted with caution. Similarly, the '1908' stands are dominantly hemlock so this factor may bias the 'species' results somewhat. The hemlock trees in the '1908' stands tend to have a high height to diameter ratio that will tend to predispose them to windthrow.

No significant relationship was present for stand density class although there does appears to be a slight increase in windthrow as stand density increases. Again, there is likely some correspondence between this factor and the relatively young '1908' stands as they are typically quite dense.

There is no significant difference present between windthrow rates and surficial material types (Table 2). There are weak indications that morainal landforms may be slightly more prone to windthrow. Many of the areas dominated by morainal deposits are well to imperfectly-drained, with relatively deep rooting and moderately tall trees.

There is a moderately significant relationship between windthrow and soil drainage class areas (Table 2). Well to imperfectly drained sites (e.g., complexes of podzols and gleyed podsols) have the highest windthrow values followed closely by more uniform, well drained sites. Imperfectly to poorly and poorly drained sites (e.g., humic gleysols and/or humisols) have lower amounts of windthrow.

There is a strong trend of increasing windthrow with increasing rooting depth (Table 2, Figure 8). This result is contrary to most reported relationship between rooting depth and windthrow. On Northern Vancouver Island, we think that this result may be related to a correspondence between rooting depth and tree height. As rooting depth increases, tree height tends to increase, but there is also a general increase in the amount windthrow. It may be that the overturning forces generated by very strong winds at the base of taller trees growing on sites where there is relatively deep rooting simply overwhelm the resisting forces of the soil-root system.

Analysis of the data set for untreated and feathered riparian strips using CHAID points to a number of environmental and management-related factors associated with windthrow (Figure 10) and that can be used to generate windthrow hazard ratings. The general trend in the analysis is that rooting depth is the most useful variable for predicting the expected windthrow along a specific riparian boundary, with windthrow increasing as rooting depth increases. The next most useful variables depending on the particular branch of the CHAID tree that is being partitioned include the edge treatment (feathered or untreated) and the width class of the riparian strip. Once these variables have been stepped off, the model chooses wind exposure index to further partition the data and then finally height class. Similar decision trees can be generated to estimate the distance windthrow is likely to penetrate into a stand edge. The current analysis indicates that the multi-variate decision tree approach first pioneered by Kennedy in 1974 has significant promise as a practical tool for estimating windthrow hazard along setting boundaries.

Summary

The factors most strongly associated with windthrow in riparian forests are: the type of treatment applied to the boundary, the character of the leave strip (one-sided versus two-sided strips), riparian strip width, rooting depth, exposure of the boundary to wind, tree height and tree species. To a lesser degree, soil drainage, landform morphology, and the position of the boundary on the slope relative to certain morphologic features of landforms are also important.

Windthrow tends to in increase with increases in rooting depth, wind exposure and tree height. Narrow leave strips and 2-sided riparian strips are more prone to windthrow, especially when thinned. Stands dominated by cedar tend to be more windfirm than stands dominated by hemlock. Feathered edges tend to experience less windthrow than untreated edges. Slope morphology, and the position of the boundary relative to certain morphologic features of hillslopes can be important.

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Table 1. Management factors affecting windthrow (mean values) - all cases

Factor	N	% windthrow	Sig. levels	Penetration (m)	Sig. levels
Leave type:			**0.000**		**0.000**
One-sided	229	14		11	
Two-sided	218	28		14	
Treatment			**0.000**		**0.000**
Feathered edge	58	7		10	
None	283	18		12	
Uniform thinning	18	34		11	
Thinned small trees retained	88	35		14	

Note: all thinned strips are two-sided riparian areas but not all two-sided strips are thinned.

Table 2. Factors affecting windthrow – untreated and feathered edges

Factor	N	% windthrow	Sig. levels	Penetration (m)	Sig. levels
Leave type			**0.032**		**0.008**
One-sided	229	14		11	
Two-sided	112	21		14	
Boundary geometry			**0.099**		**0.138**
Escarpment edge	9	23		15	
Gully edge	29	29		14	
Hillslope-escarpment	25	17		13	
Hillslope-gully	57	13		13	
Downhill	44	13		12	
Flat to gentle	64	10		8	
Lateral	113	19		13	
Boundary exposure 1			**0.000**		**0.000**
Lee	18	5		9	
Lee diagonal	48	9		9	
Parallel	73	12		11	
Windward diagonal	121	21		13	
Windward	81	20		14	
Wind exposure index			**0.000**		**0.000**
1	1	1		40	
2	3	0.3		5	
3	22	8		9	
4	18	6		8	
5	47	9		8	
6	61	13		10	
7	66	18		13	
8	69	21		13	
9	54	27		17	
Valley axis			**0.041**		**0.063**
E-W	36	10		12	
N-S	182	14		11	
NE-SW	44	24		14	
NW-SE	79	21		13	

Table 2 Factors affecting windthrow – untreated and feathered edges cont'd

Factor	**N**	**% windthrow**	**Sig. levels**	**Penetration (m)**	**Sig. levels**
Dominant tree species			**0.044**		**0.153**
B	19	11		10	
C	125	10		11	
H	197	21		13	
Age class			**0.043**		**0.286**
4	19	23		19	
5.5	10	18		10	
8	292	16		12	
Height class			**0.015**		**0.117**
2	10	6		9	
3	32	10		8	
4	117	20		15	
5	118	15		11	
6	41	15		12	
7	3	1		12	
Stand density class			**0.165**		**0.441**
1	26	22		15	
2	286	16		11	
3	9	9		10	
Surficial material groups			**0.189**		**0.166**
Fluvial	12	7		7	
Fluvial and morainal	27	14		14	
Morainal	275	18		12	
Morainal and organic	9	5		6	
Organic	16	10		9	
Rock and morainal	2	15		10	
Soil drainage class			**0.022**		**0.071**
1 (well drained)	256	16		12	
2 (well to imperfectly)	52	24		13	
3 (imperfectly to poorly)	16	4		7	
4 (poorly)	17	9		8	
Rooting depth category			**0.000**		**0.103**
0.3 m	22	11		12	
0.4 m	72	9		10	
0.5 m	105	12		13	
0.6 m	70	24		14	
0.7 m	25	24		15	
0.8 m	15	38		17	
0.9 m	2	75		15	
1.0+ m	5	70		14	

Note: all values are mean values

Figure 1 Wind Exposure Index

	Boundary exposure 2	Lee	Lee diagonal	Parallel	Windward diagonal	Windward
		1	2	3	4	5
Boundary exposure 1						
Lee	1		**3**	**4**	**5**	**6**
Lee diagonal	2	**3**	**4**	**5**	**6**	**7**
Parallel	3	**4**	**5**	**6**	**7**	**8**
Windward diagonal	4	**5**	**6**	**7**	**8**	**9**
Windward	5	**6**	**7**	**8**	**9**	

Note: Wind Exposure Index = (Boundary exposure 1 rank) + (Boundary exposure 2 rank)

Wind Exposure Index rank:
3= very low
4 = low
5-7 = moderate
8 = high
9 = very high

The wind exposure index (WEI) is a simple, qualitative scoring scheme, developed for the riparian windthrow study, that ranks the expectation that a specific falling boundary segment will be affected by strong winds from more than one direction. The primary and secondary (or co-dominant) windthrow orientations for a block are compared in turn to each specific boundary segment orientation (aspect) to determine the primary and secondary exposure categories for that boundary segment (i.e., lee, windward or an intermediate exposure category). The assumption is made that the post-logging windthrow orientations in a sample block or boundaries in the immediate vicinity indicate the dominant wind directions that may affect a specific boundary segment. A simple ranking matrix is then created that lists boundary exposure categories along the x and y axes, defined as lee through windward and ranks them consecutively (i.e., lee = 1, parallel = 3, windward = 5). The individual rank values are added vertically and horizontally to determine the WEI for specific boundary segments or riparian sample strips. When there is only one windthrow (wind) orientation the WEI can be less than 3.

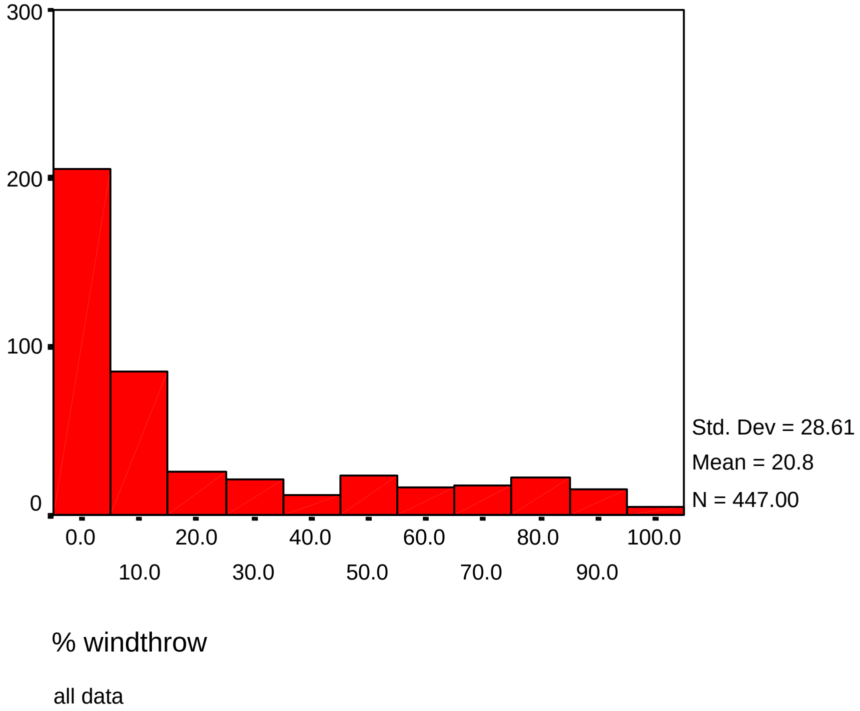


Figure 2 Windthrow distribution along all riparian edges (y-axis = number of samples)

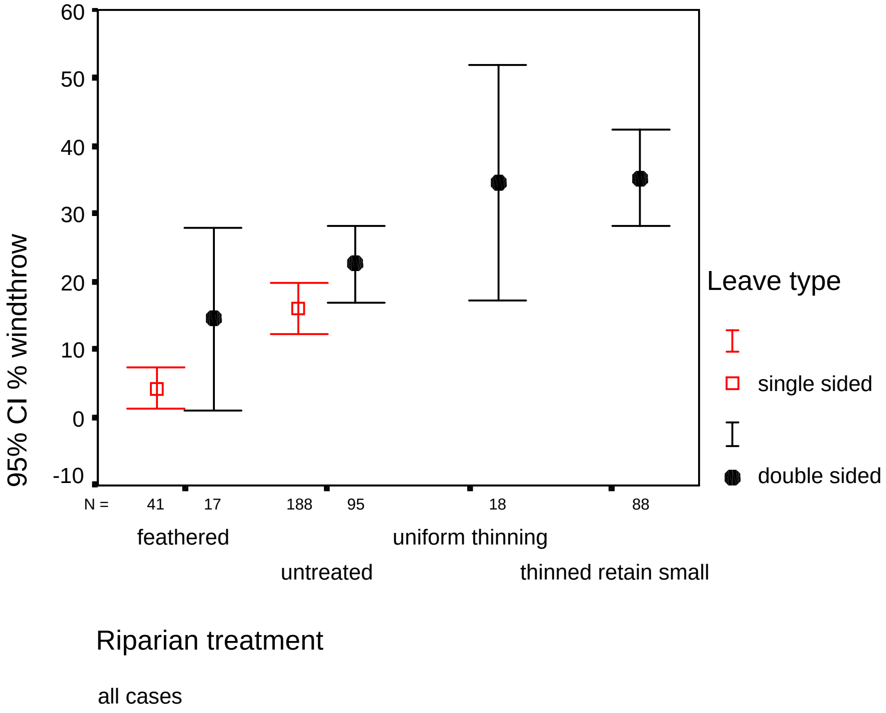


Figure 3 Windthrow distribution by leave type and treatment

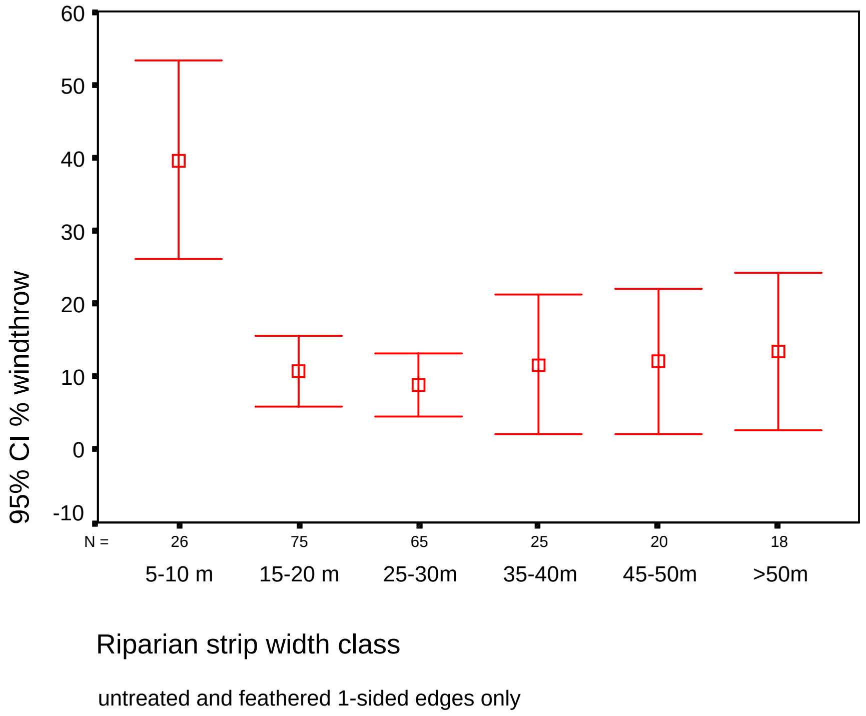


Figure 4 Windthrow versus width class for 1-sided strips

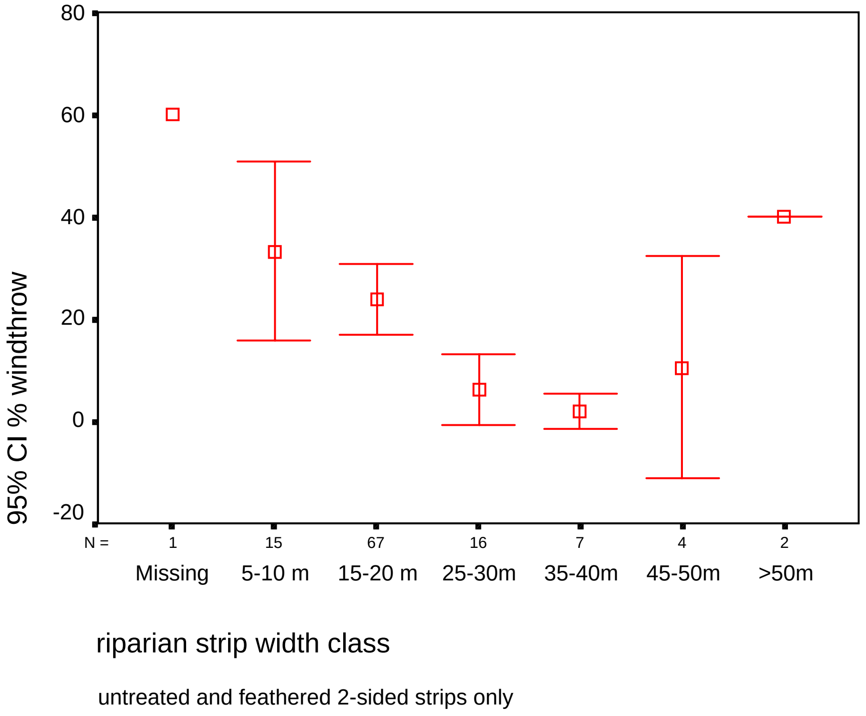


Figure 5 Windthrow versus width class for 2- sided strips

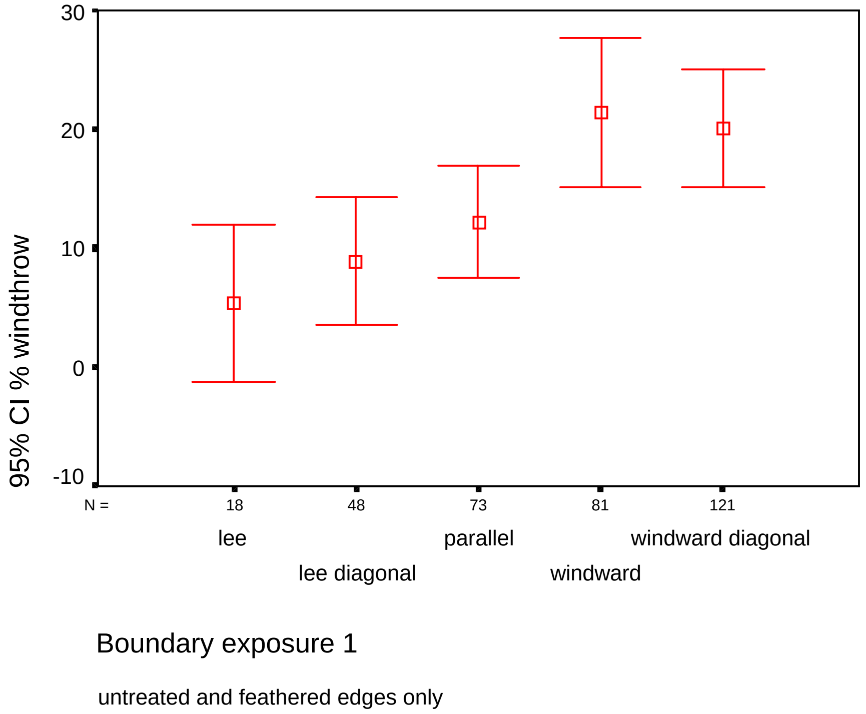


Figure 6 Windthrow distribution versus boundary exposure to wind

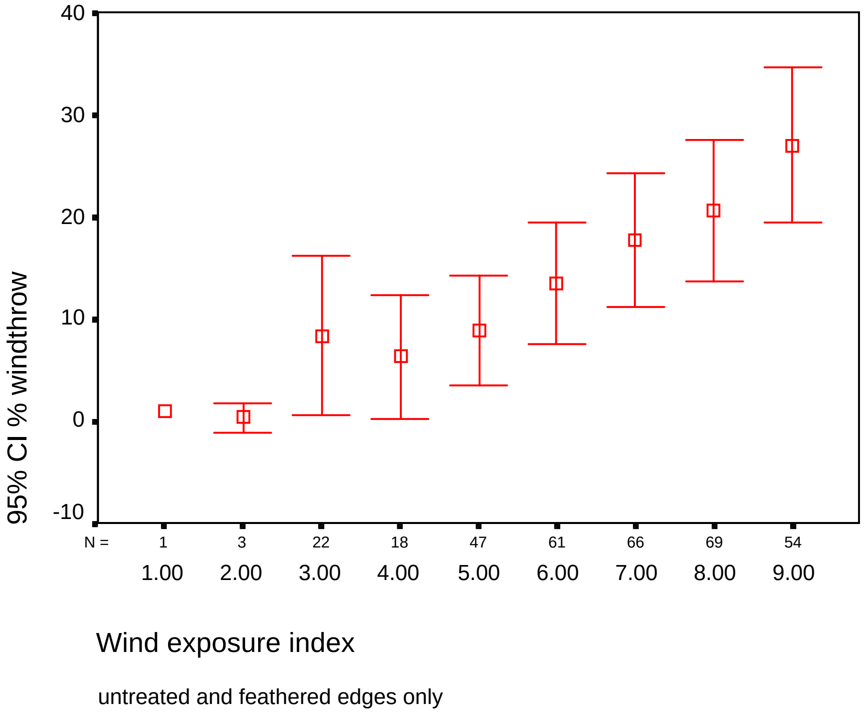


Figure 7 Windthrow distribution versus wind exposure index

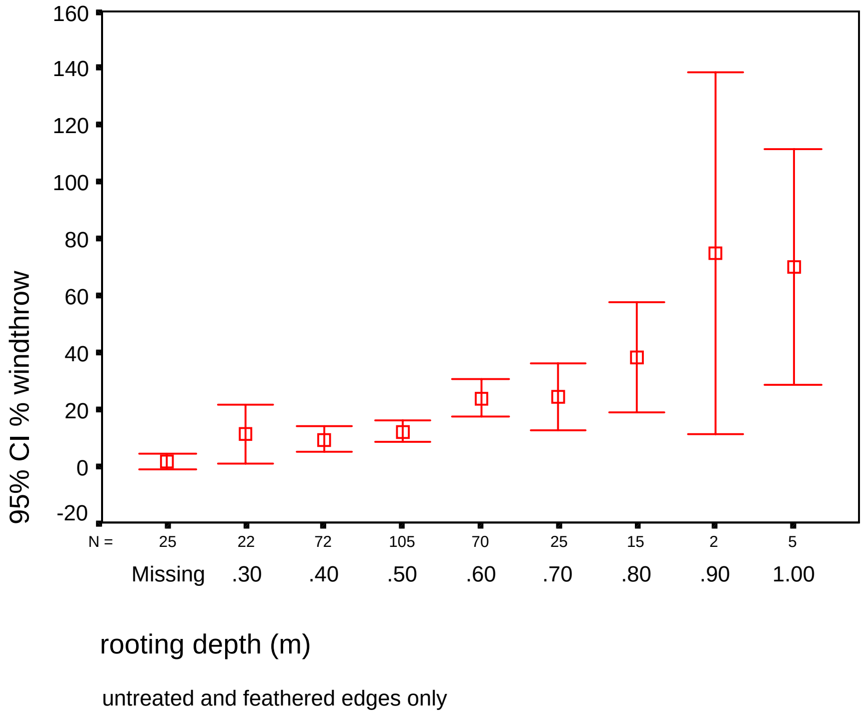


Figure 8 Windthrow distribution versus soil rooting depth

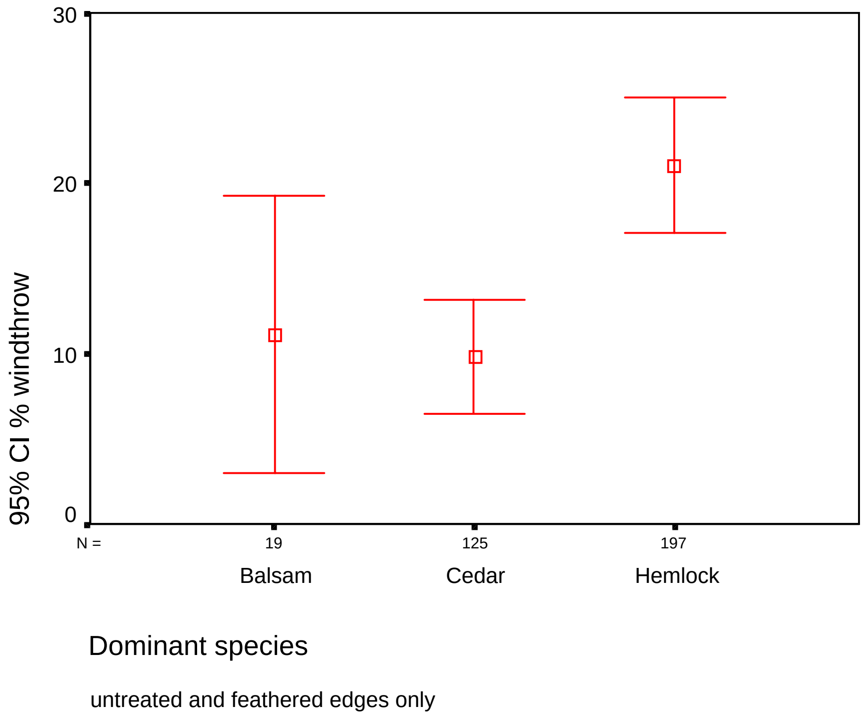
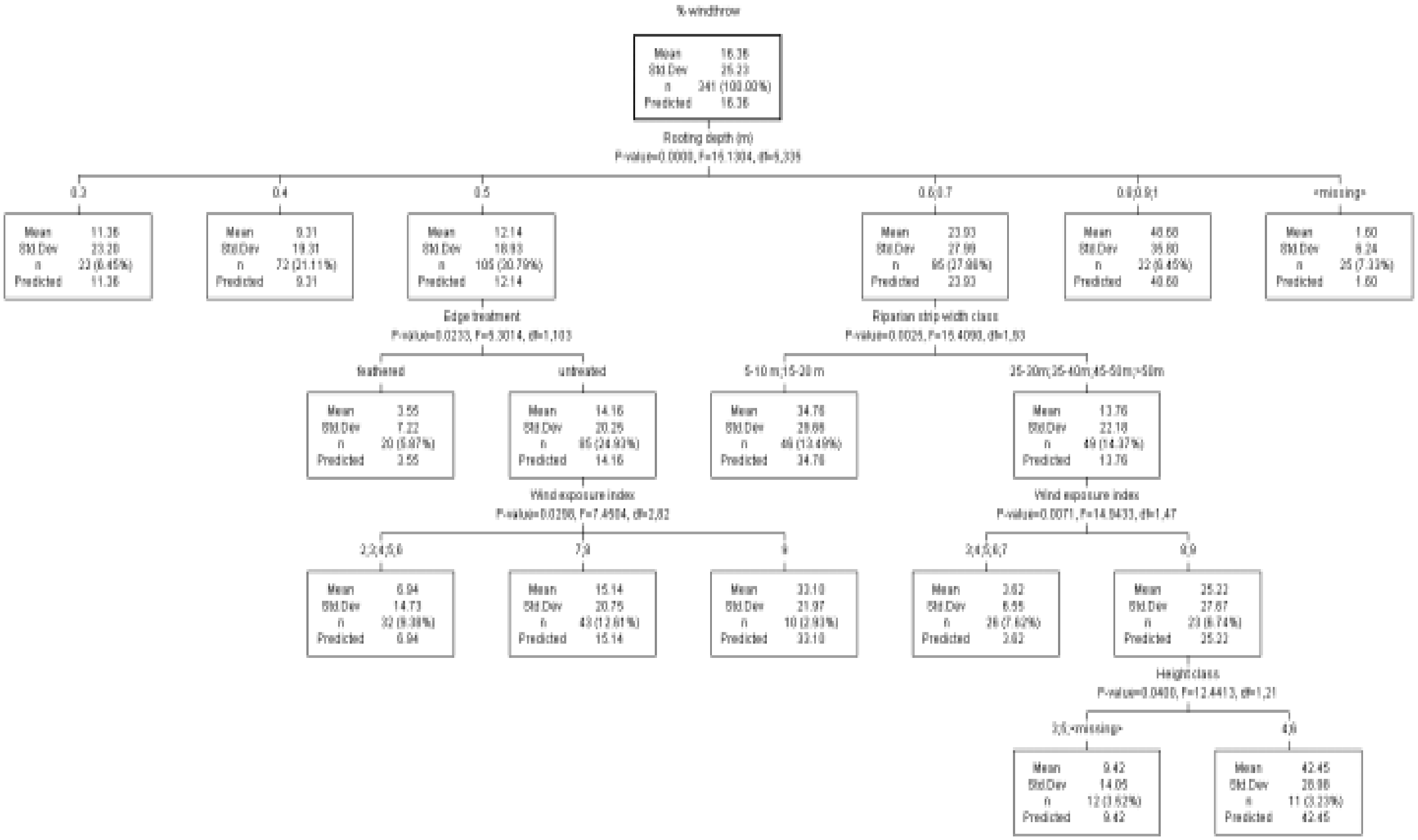


Figure 9 Windthrow distribution versus dominant trees species in riparian stands


% windthrow
Mean 16.36
Std.Dev 25.23
n 341 (100.00%)
Predicted 16.36
Rooting depth (m)
P-value=0.0000, F=15.1304, df=5,335
0.3
Mean 11.36
Std.Dev 23.20
n 22 (6.45%)
Predicted 11.36
0.4
Mean 9.31
Std.Dev 19.31
n 72 (21.11%)
Predicted 9.31
0.5
Mean 12.14
Std.Dev 18.93
n 105 (30.79%)
Predicted 12.14
0.6;0.7
Mean 23.93
Std.Dev 27.99
n 95 (27.86%)
Predicted 23.93
0.8;0.9;1
Mean 40.60
Std.Dev 35.80
n 22 (6.45%)
Predicted 40.60
<missing>
Mean 1.60
Std.Dev 6.24
n 25 (7.33%)
Predicted 1.60
Edge treatment
P-value=0.0233, F=9.3014, df=1,103
feathered
Mean 3.55
Std.Dev 7.22
n 20 (5.87%)
Predicted 3.55
untreated
Mean 14.16
Std.Dev 20.25
n 85 (24.93%)
Predicted 14.16
Wind exposure index
P-value=0.0298, F=7.4984, df=2,82
2;3;4;5;6
Mean 6.94
Std.Dev 14.73
n 32 (9.38%)
Predicted 6.94
7;8
Mean 15.14
Std.Dev 20.75
n 43 (12.61%)
Predicted 15.14
9
Mean 33.10
Std.Dev 21.97
n 10 (2.93%)
Predicted 33.10
Riparian strip width class
P-value=0.0026, F=15.4090, df=1,93
5-10 m;15-20 m
Mean 34.76
Std.Dev 29.66
n 46 (13.49%)
Predicted 34.76
25-30m;35-40m;45-50m;>50m
Mean 13.76
Std.Dev 22.18
n 49 (14.37%)
Predicted 13.76
Wind exposure index
P-value=0.0071, F=14.9433, df=1,47
3;4;5;6;7
Mean 3.62
Std.Dev 6.55
n 26 (7.62%)
Predicted 3.62
8;9
Mean 25.22
Std.Dev 27.67
n 23 (6.74%)
Predicted 25.22
Height class
P-value=0.0400, F=12.4413, df=1,21
3;5;<missing>
Mean 9.42
Std.Dev 14.05
n 12 (3.52%)
Predicted 9.42
4;6
Mean 42.45
Std.Dev 26.98
n 11 (3.23%)
Predicted 42.45

Do Spatial Patterns of Retained Canopy Trees after Partial Cutting Affect the Risk and Extent of Wind Damage?

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Abstract

Clearcutting has been the dominant silvicultural system in British Columbia. Wind damage has generally been considered a management issue only along the edges of clearcut units or after a catastrophic event. In response to a broader understanding of ecological relationships in forests and social pressure for change a variety of new silvicultural approaches are being considered or applied BC. As managed stands become more structurally complex, including continuous retention of canopy trees and management of multiple tree species with different life history characteristics, there will be more reliance on various types of models to predict future forest conditions at different scales. An important issue for complex stand management, and the development of predictive models, is how different spatial and temporal patterns of tree removal (or tree retention) affect wind damage risk and, ultimately, whether the extent of subsequent wind damage compromises current or future management objectives.

Wind damage is a natural liability in forest management and a certain amount of wind damage is acceptable, or even desirable, from an ecosystem perspective after partial cutting. The cutting pattern employed in partial cuts appears to be a critical element in windthrow susceptibility. 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. I will discuss potential approaches to empirically quantify the risk of wind damage and other agents of tree mortality in complex stands and how these studies can be linked to simulation models. Windthrow is but one of many potential agents of tree mortality, but it is often perceived as the greatest threat to implementation of complex stand management, thus the need to predict the extent and ecological implications of wind damage is great.

Introduction

In the past few years there has been a dramatic evolution in the management of British Columbia forests. Until recently, clearcutting without retention of residual trees was the dominant silvicultural system throughout British Columbia. Society's desire for a broader range of forest management options, combined with emerging concepts in the ecosystem and landscape ecology of both natural and managed forests have causing a reassessment of the dominance of clearcutting. We now see a variety of non-clearcut silvicultural systems and other partial cutting prescriptions that retain variable amounts of sub-canopy and canopy trees in space and time being applied or considered in BC forests.

When clearcutting was the dominant logging method tree mortality caused by wind events were considered an issue along the edges of the clearcut units or after a catastrophic wind event. An understanding of the underlying causes of wind damage is critical as our managed stands become more structurally complex, including continuous retention of canopy trees and management of multiple tree species with different life history characteristics. In this paper I will summarize the historical approaches to windthrow research in partially cut stands, review results from a recent silvicultural systems experiment in northwestern BC, and suggest new approaches to studying and predicting wind damage in structurally complex stands. I will pay particular emphasis to ways to characterize spatial and temporal heterogeneity in forest stands.

Wind damage in natural and partially cut stands

The extent of damage after a wind disturbance event in a forest stand 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. clearcutting), 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).

Early studies of wind damage in partially cut stands were generally *post hoc* studies established after a significant wind event (e.g., 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. Such studies were rarely designed experiments. Conclusions varied about the suitability of the various cutting methods. Unfortunately, direct comparison of wind damage in uncut stands and adjacent partially cut stands were 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 experiment (Lees 1964). Since these earlier studies, there has been an extended period during which few studies of wind damage after partial cutting in natural origin stands have been reported. In BC this drought of windthrow studies ended with the establishment of various silvicultural systems studies throughout the province in the early- to mid-1990's (Arnott and Beese 1997, Coates 1997, Huggard et al. 1999).

Windthrow at Date Creek

The Date Creek windthrow study (Coates 1997) was conducted two years after a large silvicultural systems study was established, in 1992, in the moist cold subzone of the Interior Cedar-Hemlock zone (ICHmc; Banner et al. 1993) of northwestern British Columbia. Forests in the area are wild fire origin stratified mixtures of coniferous and deciduous tree species. In mature stands (140 yr), western hemlock (*Tsuga heterophylla* Raf.) Sarg.) dominates; other species include western redcedar (*Thuja plicata* (Dougl. 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 (*P. sitchensis* (Bong.) Carr.) and perhaps Engelmann spruce (*P. 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+ yr) are dominated by western hemlock with varying amounts of western redcedar and some amabilis fir (*Abies amabilis* Dougl. ex Forbes). Amabilis fir abundance increases with elevation.

Windthrow was examined in replicated units of three treatments: (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. Two major wind events occurred in the two years before 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.

Partial cutting 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 the two years, 0.63 m^2 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 to 1.1% in unlogged areas. The 1.1% increase in damage in partial cut units was well below a 10% effect size considered large enough to warrant either management intervention or to deem the partial cutting treatments a failure. The greatest wind damage occurred in the old-growth stands. In the past six years windthrow continues to occur at low levels at Date Creek.

Although western hemlock was by far the most common tree species and had the greatest number of wind damaged stems (Table 1), hemlock was not the most wind-damage-prone species. Amabilis fir, trembling aspen and subalpine fir were the most susceptible species to windthrow. 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 1).

Table 1. Windthrow distribution by tree species, combined across all experimental blocks and treatment units.

Species	Windthrown stems tallied	Original Stand Density[a] (sph)	Windthrow Density[b] (sph)	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 treatents 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 percent of the original stand density was comprised of trembling aspen.

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 1). 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 to suggest that wind damaged individual species were different in terms of mean diameter, height or height:diameter ratio from the population of trees sampled in the cruise plots established right after logging (Table 2). Wind damaged hemlock trees appear to be smaller in diameter, but still fairly tall, resulting in a high height:diameter ratio compared to the general hemlock population. Wind damaged paper birch, although not significant (p=0.06), tended to have high height:diameter ratios (Table 2). The crown class distribution of wind-damaged trees by species was

Table 2. Tree characteristics from prism cruise plots established immediately after logging and from the windthrown trees, combined across all experimental blocks and treatment units. P-values are from a two sample t-test.

	Sample size (n)	Diameter (mean ± SE, cm)	Height (mean ± SE, m)	Height:Diameter Ratio	Crown Class[a]		
Species					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

[a] overstory, intermediate and suppressed - crowns occupy top, middle and bottom thirds of the canopy, respectively.

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

also quite similar to that of the population right after logging was completed (Table 2).

The effect of cutting pattern and scale of sampling

The cutting pattern employed in partial cuts appears to be a critical element in windthrow susceptibility. 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. At Date Creek trees were removed individually or in groups with a maximum opening size of 0.5 ha. Other studies that had similar levels and patterns of tree removal have also reported low levels of damage after partial cutting (Behre 1921, Kelly and Place 1950, McLintock 1954, Glew 1963, Lees 1964, Weetman and Algar 1976). Worthington (1953) found negligible damage around 0.5 to 1.6 ha openings, but severe damage around large clearcut boundaries in a western US study. Similarly, Glew (1963) reported little damage with single-tree selection but high damage in strip-cut areas. Wind damage is often significant in strip-cut areas because of the high edge to area ratio (Fleming and Grossfield 1983). In general, wind damage increases when tree removal rates are high (Lohmander and Helles 1987).

Windthrow is but one of many potential agents of tree mortality, but it is often perceived as the greatest threat to implementation of complex stand management, thus the need to predict the extent and ecological implications of wind damage is great. Most windthrow studies, including my Date Creek study that examined cutting treatments with considerable spatially variability, tend to report stand level wind damage response. Storm severity, stand attributes or certain tree characteristics are commonly invoked as causal agents of windthrow, but the explicit consideration of the possible interactions among storm severity, tree species, and various measures of local stand attributes (or neighbourhood) around damaged trees have rarely been examined experimentally.

We need to refine and extend our understanding of how wind damage risk is affected by fine-scale variation within stands. Canopy tree neighbourhoods have been shown to be fundamental units of forest ecosystems in which the spatial scale of the effective neighbourhood varies with the process under study. Experimental studies will be required to determine appropriate neighbourhood sizes for wind damage and to determine the important attributes of a canopy neighbourhood for wind damage prediction. It appears that a combination of storm severity, individual tree characteristics and neighbourhood measures can be used to predict windthrow risk in forests (Canham et al. 2001).

A neighbourhood approach to studying windthrow can be easily incorporated into spatially explicit individual tree forest dynamics models such as SORTIE. As managed stands become more structurally complex, including continuous retention of canopy trees and management of multiple tree species with different life history characteristics there will have to be more reliance on various types of models to predict future forest conditions at different scales. We need wind damage studies that can provide parameter values to models. Such studies need to be conducted in areas where multiple tree species are found across variable levels of tree retention. More refined studies of wind damage as a function of gradients of canopy influence combined with simulation models offer the best chance to evaluate how different proposed logging prescriptions will affect subsequent risk of wind damage and whether such damage will compromise current or future management objectives.

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Recent developments in windthrow research in Quebec

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Abstract

Windthrow hazard depends upon the interaction of numerous factors. Pertinent information can be gathered through a variety of approaches including : field monitoring of silvicultural trials, surveys after catastrophic blowdowns and comprehensive studies on the mechanisms involved. This paper presents results from three recent studies conducted in Eastern Canada. Empirical studies provide realistic data than can sometimes be difficult to generalize. Process-oriented studies provide a good understanding of the impact of different factors. However, they need to be validated with field studies. Our results show that it is of paramount importance to consider topographic exposure in assessing the risk of windthrow. Differences in species vulnerability have been observed in some cases, but not always. The assumed lower vulnerability of white spruce in comparison with balsam fir might be due to a different stem form. Our data on the effect of soil variables is rather inconsistant but research in progress should enable a better comparison. The British model ForestGales has been extended for some Eastern Canadian species. It provides an interesting tool to explore the impact of silvicultural strategies.

Introduction

The disturbance regime in Eastern Canadian boreal forests is largely dominated by fire and insect outbreaks. In this region, clearcutting and careful logging have been the preferred methods for harvesting mature even-aged stands. In such a context, windthrow is mostly associated with forested strips left alongside roads or waterbodies in order to mitigate the impacts of harvesting. This explains why very little research on windthrow has been conducted in Eastern Canada.

In recent years, the need to better integrate multiple uses of the forest brought a reduction in the size of clearcut areas, increasing the amount of exposed edges. Concurrently, recommendations have been made to increase the amount of mature trees or stands left after logging to provide a better habitat for wildlife. The need to increase the use of partial cutting has also been stressed (Franklin 1990;

Seymour and Hunter 1992). With these trends, wind-related damage is likely to become a primary preoccupation.

Windthrow hazard depends upon the interaction of numerous factors related to climate, topography, soil and stand characteristics. A certain variety of approaches are available to better understand the effect of each variable on windthrow occurrence. Field monitoring of windthrow in silvicultural experiments has been used for a long time. Surveys after catastrophic storms have also been used. More recently, the interest for process-oriented studies and modeling has increased. Each of these approaches has its own merits and drawbacks. They can be used alone or in conjunction.

Windthrow in riparian strips : a study combining field monitoring and a wind tunnel experiment

To assess the vulnerability of riparian buffer strips to windthrow, a field monitoring study and a wind tunnel experiment were conducted. The field study was conducted in mature balsam fir (Abies balsamea (L.) Mill.) stands, approximately 80 km north of Québec city, Canada (47°22'N 71°07'O). The study sites were selected in an attempt to minimize the variability in stand and site characteristics that could influence the vulnerability to windthrow. The field experiment consisted of 25 riparian sections (240 m section with a 80 m buffer zone at each end), corresponding to five treatments of different width (uncut control, 20 m, 40 m and 60 m strips) and thinning combinations (thinning or no thinning in 20 m strips).

A circular, 1:5000-scale terrain model representing a 10.7 km-diameter region was constructed and mounted on a turntable in a 2 m x 3 m wind tunnel. Wind speed was measured with pressure-based sensors for an array of incoming wind directions(Ruel et al. 1997; Ruel et al. 1998; Ruel 2000; Ruel et al. 2000a). Location of the sensors corresponds to most of the field plots to which were added some additional sensors to cover a wider range of topography. Other field study sites could not be included in the topographic model since they were located at some distance, in another cutting unit. A reference speed was obtained and used to compute overspeed ratios of measured speed over reference speed.

Windthrow percent after 5 years differed between species (χ^2=185.5 p=0.001). Mortality of balsam fir reached 19.6% of the number of stems, in comparison with 5.3, 11.1 and 4.0% respectively for white spruce (Picea glauca (Moench) Voss), black spruce (Picea mariana (Mill.) B.S.P.)and paper birch (Betula papyrifera Marsh.) . Balsam fir is considered more vulnerable to windthrow than many species because of its shallow rooting and its higher susceptibility to decay (McClintock 1954; Burns and Honkala 1990). Coates (1997) has also found that true firs were more vulnerable than spruces and paper birch.

Cumulative windthrow increased steadily during the first three years (Figure 1). Between three and five years after cutting, the annual mortality decreased, leading to a certain stabilization of the cumulative mortality. It increased again between five and seven years due to an unusual wind event. Mortality after 5 years was not affected by treatment although there was a tendency for control strips to be less damaged than other treatments and for 40 m strips to be less impacted than 20 m strips. An analysis of covariance was performed for part of a valley oriented NNW-SSE where most of the plots are located, using overspeed values for winds blowing from the W as a covariate. Eleven strips representing the three different widths for unthinned strips were included. The effect of strip width then became non significant and there remained no tendency for 40 m strips to differ from other strip widths. In fact, the highest damage occured in two adjacent strips (a 20 m and a 60 m strip) which had the highest overspeed ratios. Hence, the greater wind exposure of those two stands made them more vulnerable leading to a somewhat lower mortality in 40 m strips in comparison with 20 m strips. Treatment effect was still not significant after 7 and 9 years, showing the same tendencies observed after 5 years. Cumulative mortality was very variable. For instance, maximum mortality was 77% for one 20 m unthinned strip but remained below 7% for a control and a 40 m strip.

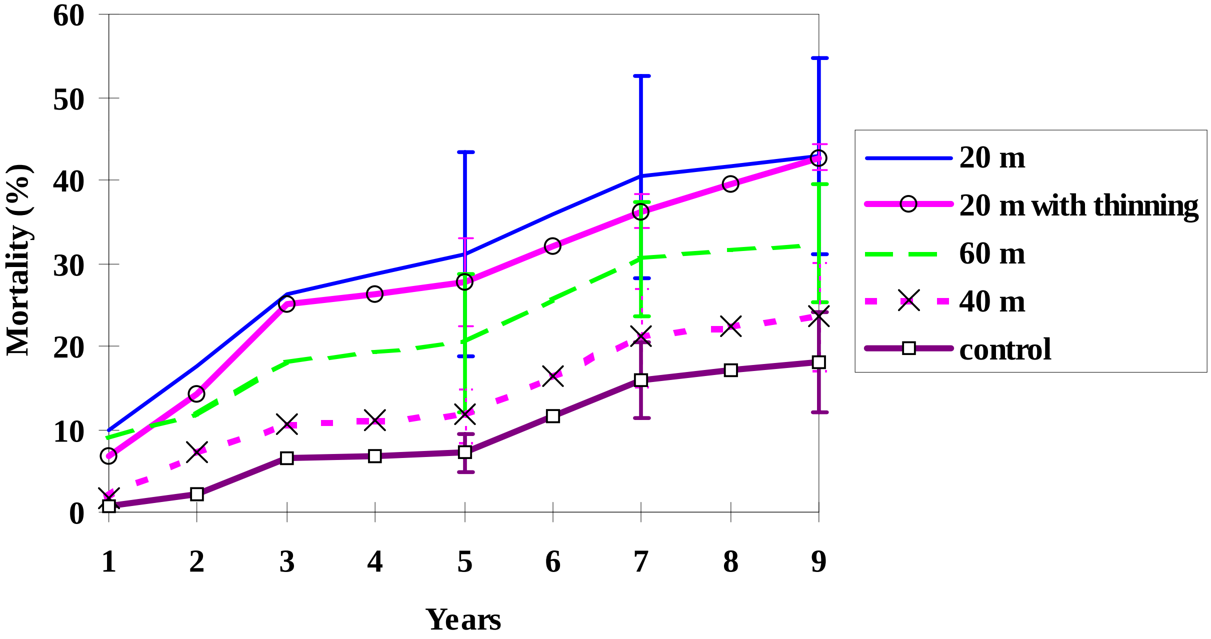

Figure 1. Evolution of windthrow in riparian buffer strips

Looking at a catastrophic windthrow : combining maps and a numerical wind flow model

In November 1994 a severe storm hit two regions of Québec, damaging 175 000 m^3 in the Charlevoix region and 525 000 m^3 in the Gaspé peninsula. The storm was reconstituted at different scales by using the MC2 model developed by Environment Canada. This model evaluates wind speed in cascades of increasing resolution and decreasing area, using data from the previous step as input. Three steps were used, the last one using a grid of 500 m. Windthrown areas were mapped from aerial photos at the scale 1:15000 and overlayed with wind speed data and forest types maps(Ruel and Benoit 1999).

The Charlevoix region was mostly affected by winds blowing from NW at speeds reaching 55-65 km h^{-1}. High wind speeds were estimated on hilltops but not in a valley in line with these winds where an important part of the windthrow is located. No consistent effect of wind speed on windthrow could be demonstrated for this region. In the Gaspé peninsula, wind speed was lower and its effect on windthrow percent was not significant.

For wind speeds between 28-37 km h^{-1}, pure balsam fir stands were more heavily damaged in comparison with spruce-fir stands (p=0.0316). For winds reaching 37-46 km h^{-1}, 70 years old pure balsam fir stands were more damaged than fir-birch stands of the same age (p=0.0001). In fir stands growing on deep tills, an increase of damage with age was seen for all wind speeds combined. Stands reaching 70 years were more damaged than 50 years old stands (p=0.001). Older or uneven-aged stands were not damaged more than 70 years old stands (p>0.05). For 70 years old balsam fir stands, deep tills were more damaged than shallow ones (p<0.001).

In the Gaspé peninsula, pure balsam fir stands were not damaged more than fir-spruce or spruce-fir stands (p>0.05). However, 50 years old balsam fir stands were less damaged than 70 years old stands (p=0.0052), which in turn were less damaged than 90 years old stands (p=0.0489). Shallow tills were more impacted than deep tills (p=0.0001). Similarly, windthrow proportion is higher on talus debris (p=0.0294) whereas bedrock does not differ from deep till (p>0.05). Here, the effect of surface material is compared for one specific wind speed since some surface deposits were rarely associated with the other wind speeds.

Looking at the mechanics of windthrow

Both studies that have been presented enable us to draw conclusions about the effect of some variables. Both studies show important wind speed variations related with topography so that its effect should be considered when trying to deal with the risk of windthrow. No conclusion can be drawn about the effect of soil variables since the buffer strip study was specifically designed to minimize soil variations and conclusions from the catastrophic windthrow study differ between regions. Balsam fir seems more vulnerable than associated species but again conflicting results have been obtained for the two regions in the catastrophic windthrow study. Vulnerability of balsam fir to windthrow increases with age but the exact age at which this increase occurs cannot be determined precisely from our results.

A better knowledge of the effect of the different factors can be reached through a mechanistic approach. First, we need to understand the behaviour of the causal agent. A general map describing variations in mean wind speed across Canada can be used to understand regional variations in vulnerability to windthrow. However, we must also take into account the local effect of topography on wind speed. Numerical wind flow models can be useful but usually describe a single wind event. Morever, their capacity to behave correctly at a fine resolution might not be adequate if we consider the results from the catastrophic windthrow study and the correlations obtained with the wind tunnel study for a similar incoming wind direction (Table 1). Civil engineering models, such as Strongblow, can provide reliable indicators of wind exposure. However, their design is more adapted to point estimation and their use over broad areas could become tedious. Topographic indices of wind exposure (Topex and distance-limited Topex) have been shown to correlate well with average wind speed and also with wind tunnel results. Basically, those indices work with the horizontal angle made by the topography around a point. They could be calculated automatically over broad areas and thus could serve as the basis for a risk minimizing strategy. Mapping of topographic units could also be an alternative since many similarities were observed between a map of topographic units and one of distance-limited Topex.

Given the knowledge of the wind speed acting acting at a location, one must be able to assess how likely this wind speed is to cause damage. The resistance of standing trees to overturning or breakage has been estimated with winching studies since the sixties(Fraser and Gardiner 1967). Our first work with this approach compared resistance to stem breakage between stems with and without defects (Silva et al. 1998). It was able to demonstrate that some defects were associated with a loss of mechanical resistance, even though the level of decay did not differ between defective and externally sound stems.

Our next step was to compare overturning resistance in relation to species and soils. Even if both balsam fir and white spruce can be considered vulnerable to windthrow, the latter was less damaged in the buffer strip study and is generally tought to be less vulnerable. A little over 40 trees by species were selected on mesic soils in stands were both species were growing together in sufficient numbers. Hence, resistance to overturning can be compared directly, without confounding soil and wind exposure effects (Ruel et al. 2000b).

Results show that white spruce is more resistant to overturning than balsam fir of a same height (Figure 2). However, better regressions with critical turning moment are obtained using stem weight. Using this variable, no difference remains between species (Figure 3). These apparently conflicting results can be explained by differences in stem form. For a given height, spruce will have a greater DBH and hence a higher stem mass. A similar work has been conducted on mesic soils with lateral drainage (seepage). Analysis of results is not completed yet. When this research is completed, we will have a good understanding of resistance to overturning for those two species on the productive sites where partial cutting is likely to be applied.

Table 1. Comparison between different methods of estimating wind exposure.

Method	Correlation coefficient (r)
Topex	-0.83***
Distance-limited Topex	-0.92***
Strongblow	0.91***
MC2 (strong winds)	0.71***
MC2 (moderate winds)	-0.21
MC2 (low wind speed)	0.11

*** significant at p=0.001

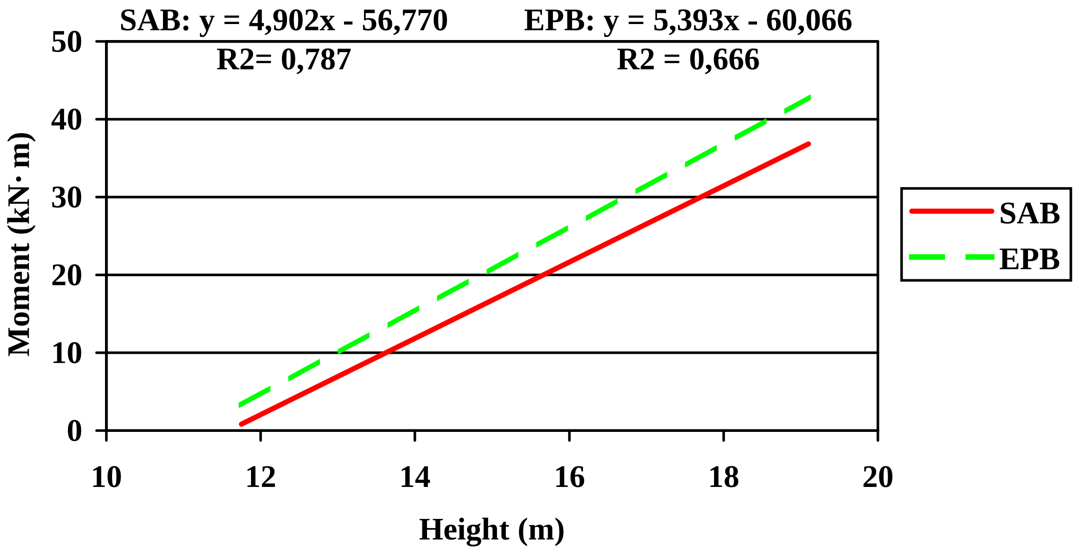

Figure 2. Relationship between height and critical turning moment for balsam fir (SAB) and white spruce (EPB)

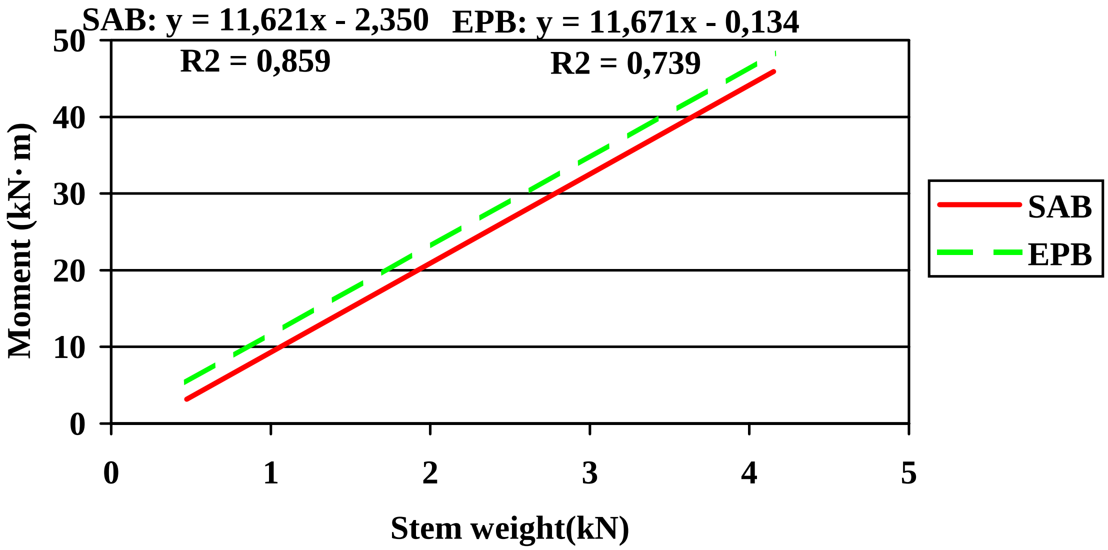

Figure 3. Relationship between stem weight and critical turning moment for balsam fir (SAB) and white spruce (EPB)

Even though this knowledge of resistance to overturning is interesting in itself, it can become more useful when integrated with additional process-based knowledge. The British ForestGales model provides a basis for integration. This model integrates knowledge derived from over 30 years of research in many disciplines. First, it calculates a critical wind speed for overturning. Then, it estimates the annual probability that this wind speed is exceeded, incorporating the effect of regional variations of wind speed and topography. Results from winching studies provide many of the necessary relationships to adapt the model for additional species. Thus, our own data on white spruce and balsam fir were included in a new version of the model (ForetVent). The model was also extended to other species based on available published results or similar species.

Simulations using published empirical yield tables for balsam fir were conducted. They demonstrated that the evolution of windthrow risk will depend on site productivity and wind exposure. With a mean wind speed of 10 km/h (site class I), the risk of windthrow in untreated stands would remain low up to 75 years (Figure 4). On severely exposed sites (mean wind speed = 15 km/h; Site class I), risk would already be high at age 40 (Figure 5). In fact one can suspect that other species would replace fir on those sites or that trees would adapt a stunted form. Not surprisingly, the same thinning treatment will give different results in both situations. With a mean wind speed of 10 km/h, a return period of 15 years (annual probability of 0.0666) would not be exceeded after a 25% thinning unless the stand has reached age 60. With higher thinning intensities, this return period would be reached at any age. This type of wind exposure would correspond to a mid-slope position in the area where the buffer strip study was conducted. At the bottom of valleys, thinning could be applied to a greater age without incurring high risks.

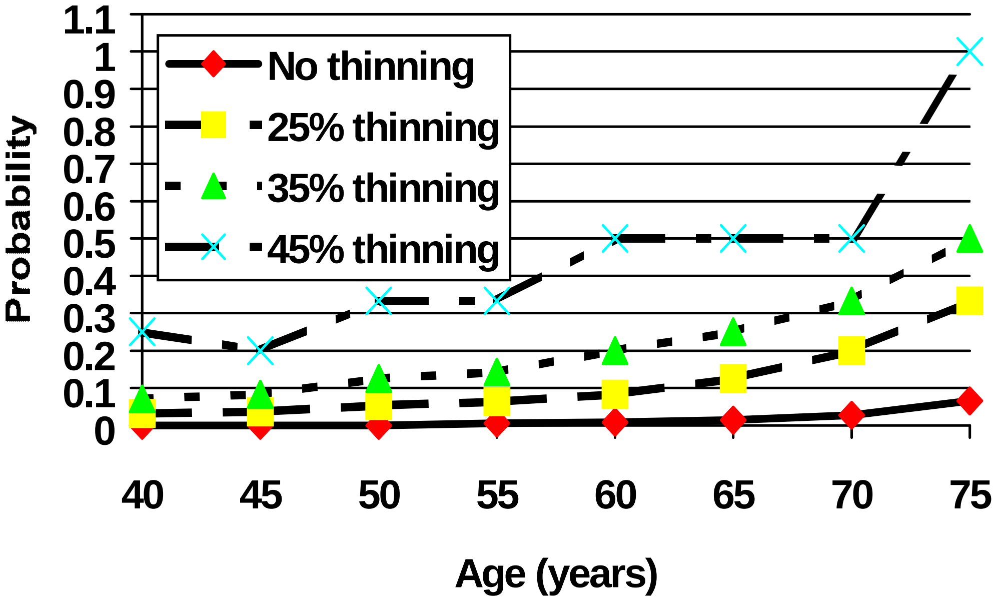

Figure 4. Windthrow risk after thinning balsam fir on site class I (mean wind speed=10 km/h)

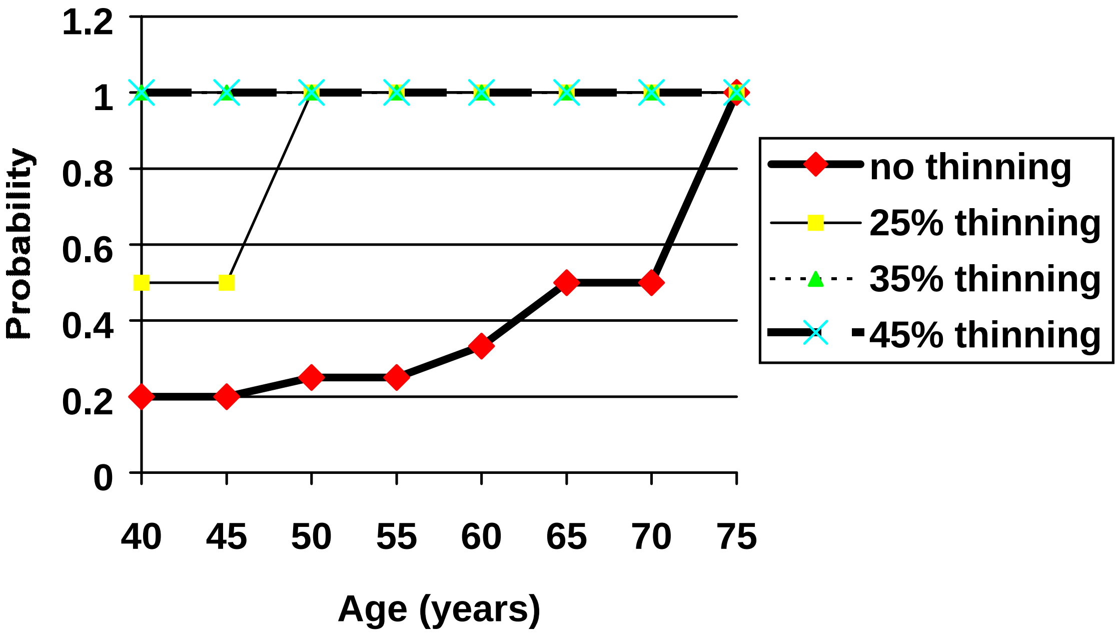

Figure 5. Risk of windthrow after thinning balsam fir on site class I (mean wind speed=15 km/h)

Conclusion

Many methods can be used to gather pertinent information on vulnerability to windthrow. Each one has its own strengths and weaknesses. Field monitoring provides realistic results but obtaining observations for a sufficient number of samples over a significant period of time can become costly. Results are often variable and difficult to generalize. Surveys after storms can provide realistic results within a short time at a relatively low cost. However, generalization of results can be hampered by the particular nature of the storm. For instance, if the storm is strong enough, the critical wind speed for all species can be exceeded so that no species-related effects are found. At the opposite, if the critical wind speed for the least resistant species is not reached no difference between species will be found. Process-oriented models provide an opportunity to integrate results from many sources and disciplines. They can then be generalized more easily. However, these models have not been validated through field monitoring in our conditions.

We are currently working to improve the data for eastern Canadian species. We are looking at the effect of precommercial thinning on rooting and resistance to overturning for balsam fir. We also plan to add data for jack pine and black spruce, comparing both species on the same site and one species on different sites. We would also like to study the impact of cutover dispersion on the amount of windthrow. This, coupled with the use of permanent sample plots would provide an opportunity for assessing the general behaviour of the model.

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Wind Tunnel Modelling Of Partial Cuts And Cutblock Edges For Windthrow

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Abstract

In British Columbia, pressure from environmental groups and recognition of alternate forest values are forcing industry to consider a wider variety of forest management methods other than the traditional ones that produced large clearcuts. Some of these alternate methods result in many smaller clearings with extensive edges or require that a low density of trees be left standing in the harvested areas. Two aspects that must be considered when deciding upon such silvicultural scenarios are the microclimates experienced by the seedlings that will form the next generation of trees and the stability of the trees left standing against windthrow. Both of these are strongly influenced by wind speed and turbulence patterns that exist within the resulting complex forest/clearing configurations. This paper describes a project that we have been carrying out since 1992 that was designed to answer such questions by studying the fundamental physics governing turbulent flow in complex forest/clearing configurations. The study methods include using scale models in a large wind tunnel, making field measurements at the Sicamous Creek Silvicultural Systems Research Area near Kamloops, and numerical modelling, although only some of the wind tunnel and field measurements are described herein. It is shown that the wind tunnel measurements of wind speed and turbulence are in good agreement with field measurements and that a custom-made strain-gauge balance can successfully measure the drag of the wind on trees at selected locations within complex forest/clearing configurations in the wind tunnel. The data from this study is extensive and further analysis is required to fully realize its scientific value and potential in helping forest managers.

Introduction

Forest harvesting strategies currently in practice or being considered in British Columbia range from clearcutting to single-tree and group selection methods. To date, clearcutting of very large blocks has been the method of choice but the

Forest Practices Code of BC puts upper limits on cut-block area. Pressures from environmental groups, recognition of the negative effects of traditional methods of forest removal, and the need to consider ecological, recreation, wildlife, watershed, fishery, and aesthetic factors in forest management are forcing the industry to consider other options, including single-tree and group selections.

Two major aspects that must be considered in choosing amongst management scenarios are the microclimates experienced by planted tree seedlings and blowdown of timber. Successful forest regeneration in large clearcuts is difficult, especially at the higher elevations now being harvested routinely in British Columbia, in large part because of the harsh microclimates in cleared areas. It is expected that regeneration will be better in smaller clearings and partially cut areas that more closely mimic natural forest conditions. Major factors governing microclimate are wind speed and turbulence, which depend strongly on clearing size, shape, orientation, and topography, and which vary spatially in clearings and partially cut areas in a complex way. Blowdown of trees along cutblock edges is a recognized chronic problem in the forest industry in BC, costing millions of dollars annually. Immediately following harvest, trees along cutblock edges are not yet adapted to the higher wind speed and turbulence levels that typically occur in the cleared areas. This problem may be more acute with smaller cutblocks and partial cutting because the total length of edges will increase, although lower wind speed and turbulence in the smaller blocks should compensate. Wind forces on edge trees for different clearing size, shape, orientation, and topography are still unknown. Both steady forces arising from mean wind speed and dynamic forces associated with turbulence have been implicated in the blowdown process.

It is nearly impossible to make systematic, cost-effective, and timely field measurements of wind speed, turbulence, and forces on trees for various clearcut configurations. However, using scaled-down model forests and clearings in a laboratory wind tunnel is comparatively inexpensive and convenient, and allows systematic investigation of clearing size, shape, and orientation, with varying topography. The use of wind tunnels to design aircraft, buildings, and bridges is well known. The science of fluid dynamics has established criteria that wind tunnel models must satisfy so that measurements on the model will be applicable to the real world, although field verification is still required ultimately.

The Biometeorology/Soil Physics group in the Faculty of Agricultural Sciences at the University of British Columbia has been studying the effects of clearing size and shape and varying topography in the UBC Department of Mechanical Engineering large blow-through wind tunnel since spring 1992 (Chen et al., 1995). Funding was initially from a Science Council of BC Research and Technology grant during 1992-1995, aided by a series of contracts during 1991-1996 from the BC Ministry of Forests, and then followed by a grant from the Forest Renewal of British Columbia Research Program during 1996-2000. Currently, project support is from a National Scientific and Engineering Research Council Research Grant.

The objectives of this paper are as follows:

1. To show that the wind tunnel represents field measurements adequately. This is not obvious because it is not possible to fully meet all required fluid-dynamic scaling criteria in the wind tunnel (Reynolds numbers are too low), the geometric scaling is never perfect (tree branch and leaf architectures are not correct; the wind tunnel height is too small compared to the scaled boundary-layer height), and there are well-known limitations to the accuracy of the hot-wire probes (Bruun, 1995; Jorgensen, 1971). There are few, if any, direct comparisons between wind tunnel and field measurements in the literature and none as detailed as those that we have accomplished.
2. To show that our unique custom-made strain-gauge balance can properly measure drag on strategically located model trees in the wind tunnel. This allows direct measurement of the windthrow potential of various forest/clearing configurations.

Methods

Wind Tunnel Experiments

The UBC Mechanical Engineering wind tunnel is an open-return blow-through type, 25 m long, 1.5 m high, and 2.4 m wide. An equilibrated turbulent boundary typical of the atmosphere was produced using a combination of vertical spires (Counihan, 1969), transverse boards, and wooden blocks placed successively downwind from the inlet to a total length of about 7 m, as shown in Figure 1. Any treatments studied were placed downwind of these roughness elements. Model trees were made from artificial Christmas tree branches up to 15 cm in length and with the plastic needle strips trimmed to appropriate conical shapes (Figure 2). The trees are 15 cm high with a nearly uniform “leaf'” (plastic strip) area distribution above the 1.5 cm height above the floor, below which all strips had been removed. The trees were firmly installed into plywood boards drilled with evenly spaced holes so that successive downwind rows were staggered. The wind tunnel trees are 50-100 times smaller than their real-world counterparts.

Figure 1: Downstream view of the UBC Mechanical Engineering wind tunnel with Counihan spires in the foreground, followed immediately by the various wooden roughness elements and then the model forest.

Figure 2: The 15 cm high model trees made from artificial Christmas tree branching used in the wind tunnel experiments.

Instantaneous measurements of the wind speeds in 3 orthogonal directions (along the tunnel, laterally, and upwards) at various locations of interest were made using a tri-axial fibre-film, hot-wire probe (Dantec Measurement Technology, Denmark). Total diameter of each nickel-plated quartz wire is 75 microns and the active sensing length is 1.35 mm, with the active portions of all three wires contained within a sphere 3 mm in diameter (Figure 3). The probe only measures wind speeds correctly when the instantaneous wind vector is directed downwind at an angle less than about 35^o from the wind tunnel center-line; otherwise the speeds are rectified (upwind flows, which should be negative, are reported as positive) and may be in error. We sampled for 20 s at 500 Hz so as to capture all relevant turbulent fluctuations. Mean air temperature for each 20 s run was measured near the probe using a chromel/constantan thermocouple and was used in the calculation of wind speeds from the measured voltages. The probe was mounted on a traversing system, which was moved to any desired location by remote control while the wind tunnel was operating at a steady flow rate.

Figure 3: The Dantec tri-axial hot-wire probe mounted horizontally in the wind tunnel. Wind would be flowing from right to left during the measurements.

All data were acquired, low-pass filtered, digitized, and stored on the hard drive of a computer in real time, with final archiving of the raw data to backup magnetic tape and CD-ROM occurring after completion of each set of runs.

We measured the drag and bending moment on a tree at selected locations with our custom-made two-stage strain-gauge balance, shown in Figure 4. This required raising the plywood floorboards the whole length of the wind tunnel by 15 cm to accommodate the balance, which is mounted on the bottom of a floorboard with the tree attached through a hole in it. While we were able to measure mean values of drag and bending moment successfully with this balance we were unsuccessful at measuring the turbulent fluctuations of these as originally planned because the lowest resonant frequency of the balance was in the range of the dominant frequencies of these fluctuations.

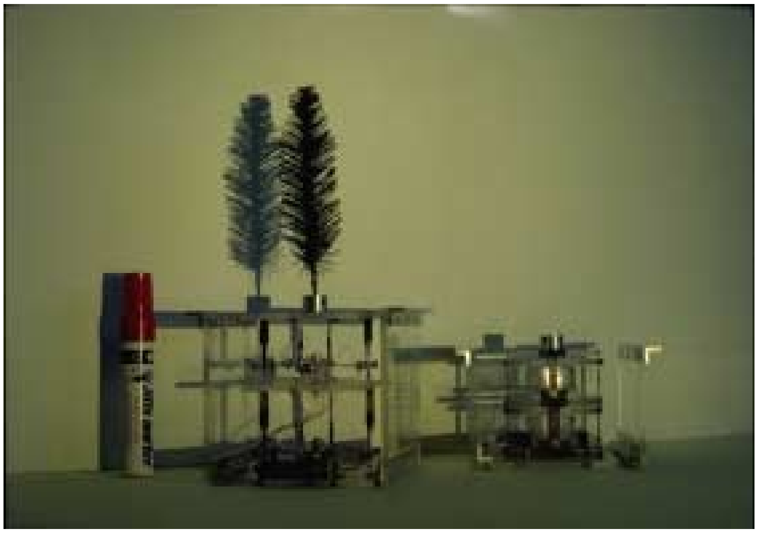

Figure 4: Custom-made two-stage strain-gauge balance with a model tree installed. An earlier prototype is shown on the right.

Field Experiments

Field experiments during the project were carried out at the Sicamous Creek Silvicultural Systems Research Area in the B.C. Southern Interior. The site is in the (high elevation) Engelmann Spruce Subalpine Fir (ESSF) biogeoclimatic zone in the Kamloops Forest Region. Experiments were done in the summer and fall of 1995 (Novak et al., 1997), 1996, and 1997. The Sicamous Creek project is studying new options for forest management in the high elevation BC Interior using operational-scale plots. Included are (nominally) 10, 1, and 0.1 ha nearly square clearings located in 3 plots spread across the site. The latter two sizes were set in a near-checkerboard pattern containing many clearings (9 and 60 clearings, respectively, in the plots we used). This was not possible for the 10-ha plots, because of their size, although they are more or less surrounded by the smaller-clearing plots in most directions. The weather in 1995 was very favourable with minimal rainfall, many relatively warm clear days, and with the wind often from the west. In this paper we only present measurements made at the 10 ha site during 1995.

The B5 10 ha clearing is nearly square (334 m by 326 m) with its sides oriented about 10^o from true north. Surrounding trees were estimated to be 30 m tall and the clearing is located on a 12% north-facing slope with contours running roughly east to west (Figure 5). In 1995, a transect of 6 evenly spaced stations was established in the (nominally) east to west direction perpendicular to sides of the clearing and through its centre. Stations were numbered from 1 to 6 going from west to east along the transect. Half-hour average horizontal wind speed and direction were measured simultaneously at the 8 m height at these stations with R.M. Young anemometers (Figure 6). Other micrometeorological measurements made in 1995 are not used in this paper. All monitoring was with Campbell Scientific data loggers and storage units.

Figure 5: Areal view facing west of the B5 10 ha clearing at the Sicamous Creek Silvicultural Systems Research Area.

Figure 6: R.M. Young anemometers mounted at 8 m height in the B5 10 ha clearing.

In addition to our own field experiments we compared our wind tunnel results to measurements made by other research groups by digitizing their data directly from published graphs in scientific journals. These studies are described at the appropriate points in the text below.

Results and Discussion

Wind and Turbulence

A fundamental objective was to verify that the wind tunnel measurements match similar measurements made in the field. This has been accomplished for a number of forest/clearing configurations. Figure 7 shows the wind tunnel model of what is conceptually the simplest possible configuration, that of a uniform forest (we considered different tree densities, achieved by whole-tree pruning). We were able to compare our wind tunnel results to measurements made by Green et al. (1995), who studied wind and turbulence in thinned field plots of Sitka spruce located near Edinburgh, Scotland. Figure 8 show that agreement is reasonably good for the 2nd order moments of the turbulence statistics in these stands (3rd and 4th order moments, i.e., skewness and kurtosis, not shown, are in similar good agreement). Although a uniform canopy is a simple configuration conceptually, it is most demanding for measurements of turbulence because of the high turbulence intensities (greater than 0.3) that typically exist within canopies, especially at higher tree densities. Some of the differences shown between the wind tunnel and field are ascribed to the fact that the vertical leaf area distributions for the two canopies were different, that for the wind tunnel being nearly uniform while that for the Sitka spruce being triangular, with the greatest concentration of foliage at about 1/3 tree height. The good agreement overall, and especially for higher-order statistics, is somewhat surprising given the limitations of the tri-axial probe in high intensity turbulence (i.e., the fairly narrow cone of directions in which it measures properly and the inability to measure reverse flows). We believe that the reason is because turbulence statistics within the canopy are dominated by "sweeps", which are gusts of fast moving air that penetrate from above the trees. These gusts are responsible for most of the momentum transfer within and just above the canopy. During these critical events, the wind is within 10^o of the horizontal and so the tri-axial probe can measure them properly. The uniform thinning study is described fully in Novak et al. (2000).

Figure 7: Looking upwind in the wind tunnel configured with a uniform model forest.

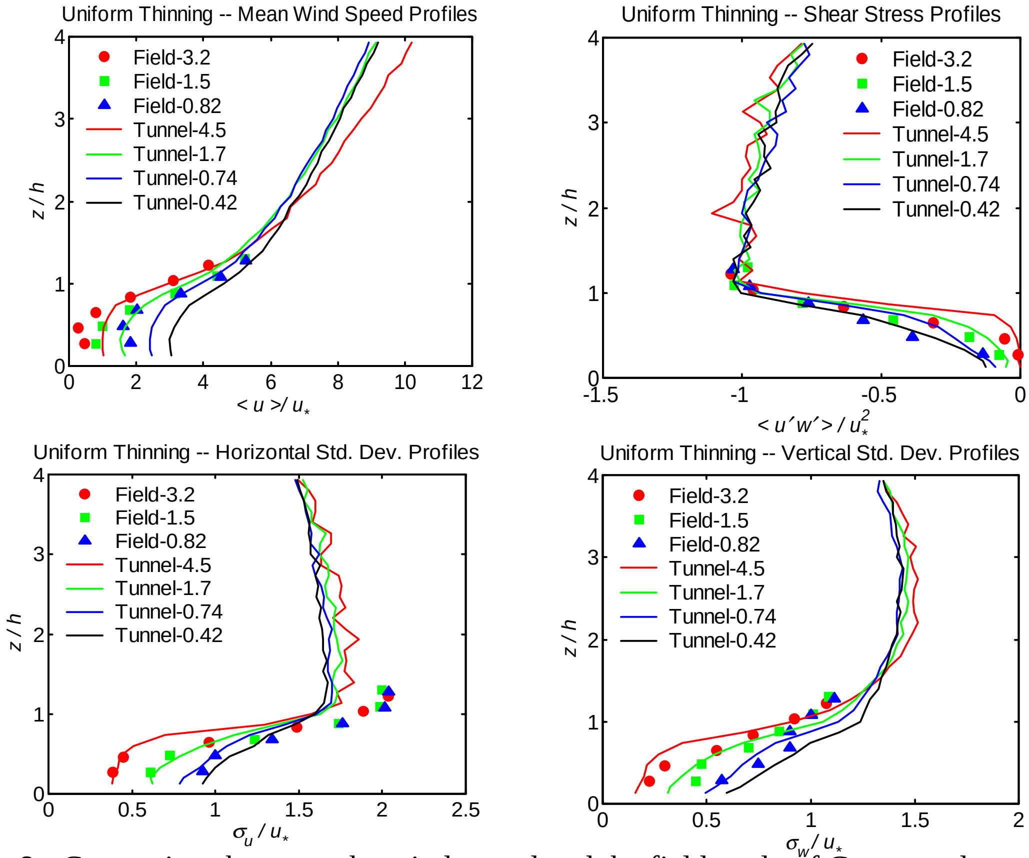

Figure 8: Comparison between the wind tunnel and the field study of Green et al. (1995) for vertical profiles of some basic turbulence statistics in uniformly thinned forests. Profiles are mean wind speed, *u*, mean shear stress, *u*'*w*', and standard deviations of horizontal, σ_u, and vertical, σ_w, wind speed all normalized by the friction velocity, u_*. Numbers in the legends are leaf area indices.

Figure 9 shows the simplest wind tunnel model of the Sicamous Creek B5 10 ha clearing (i.e., smooth and flat) and compares mean wind speeds measured along the east-west transect at the 8 m height (just under 30% of tree height) in the field in 1995 with those at the same scaled heights within the wind tunnel model. The field measurements shown are those for which half-hourly average wind directions at all 6 stations were simultaneously within 15° of the transect direction and the wind speed at the most downwind station exceeded 1 m s^{-1}. All wind speeds were normalized to the most downwind station. Clearly, the wind speed profile across the field clearing is a function of whether the wind blows from the east or west. The wind tunnel profiles roughly agree with the field profiles, especially for the Sicamous East profile.

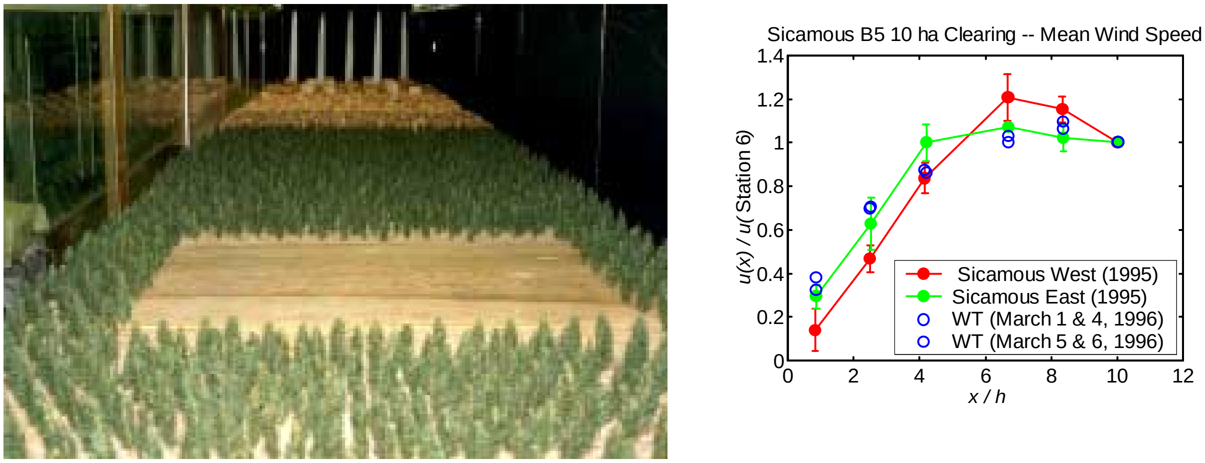

Figure 9: View upwind of the simplest wind tunnel model of the B5 10 ha clearing at the Sicamous Creek Silvicultural Systems Research Area and comparison between wind tunnel and field mean wind speed profiles along the east-west transect at the 8 m height in the field (4 cm height in the wind tunnel). The Sicamous East and West profiles refer to field measurements with the winds blowing from the east and west directions, respectively. The variable x/h is the distance from the upwind edge normalized by tree height.

Figure 10 shows the wind tunnel model of the 10 ha clearing with the floor of the clearing raised to match the topographic profile that we surveyed in the field for the wind blowing from the west. This survey showed that the 4th station from the west edge was near the highest point in the transect, being about 3 m higher than the west edge and 4 m higher than the east edge. Evidently, incorporating these elevation changes in the wind tunnel greatly improves the agreement with the field measurements for the Sicamous West profile. This good agreement suggests that the decrease of wind speed near the downwind edge ($x/h > 7$) for this profile is due to the change in surface topography rather than a "wall drag" effect of the downwind edge. For $x/h < 4$, wind speeds in the wind tunnel are still overestimated which is attributed to rectification errors with the tri-axial probe. The same overestimate is seen in the profiles of mean wind speed in Figure 8 well within the canopy, because the flow in the clearing just downwind of the upwind edge is similar to that within a forest canopy. Unfortunately, we did not reverse the direction of the elevated clearing floor, which would have allowed proper comparison with the Sicamous East profile shown in the figures. We intend to do that case later this year.

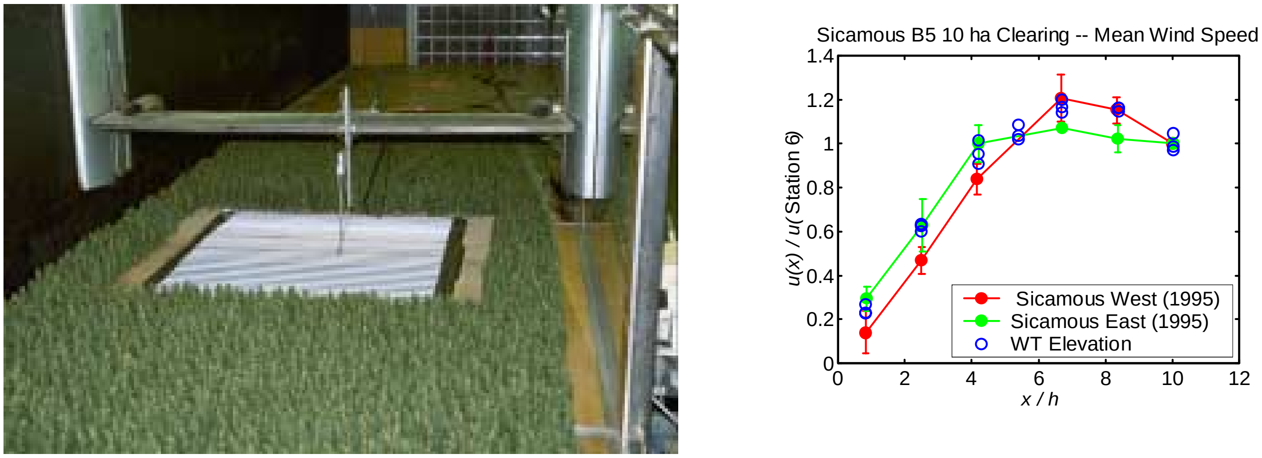

Figure 10: View upwind of the simplest wind tunnel model of the B5 10 ha clearing at the Sicamous Creek Silvicultural Systems Research Area and comparison between wind tunnel and field mean wind speed profiles along the east-west transect at the 8 m height in the field (4 cm height in the wind tunnel). The Sicamous East and West profiles refer to field measurements with the winds blowing from the east and west directions, respectively. The variable x/h is the distance from the upwind edge normalized by tree height.

We have field measurements of turbulence in the Sicamous Creek 10 ha clearing but the analysis is incomplete, although preliminary indications are that the standard deviation of vertical wind speed, σ_w, measured with Campbell Scientific 1-d sonic anemometers, is, after suitable normalization, in excellent agreement with the wind tunnel for various locations in the clearing. Gash (1986) reported comprehensive wind and turbulence measurements made at a forest/heath interface in Great Britain using 3-d sonic anemometers. We modelled the flow from forest to heath in the wind tunnel (we assumed that the heath, which consisted mostly of heather, was perfectly smooth) and made measurements downwind of the forest to the same distance that Gash did. Figures 11 and 12 compare the wind tunnel and field measurements at about 1/3 tree height for both mean wind speed as well as turbulent statistics (friction velocity, u_*, from which the horizontal drag on the canopy is calculated as ρu_*^2, where $\rho = 1.23$ kg m^{-3} is the density of air, and the standard deviations of horizontal and vertical wind speed fluctuations). All have been normalized to measurements made above the upwind forest (which consisted of a mixture of Scots pine and European larch trees with an average height of 10 m). With the exception of σ_w, agreement is excellent between the field and wind tunnel. We speculate that the disagreement for σ_w may be due to differences in morphology between the modelled and real trees, which apparently affected the developed part of the wake zone more than its initial part, which is just downwind of the quiet zone (agreement was good for the first 2 field measurement stations, $x/h < 11$, but not for $x/h > 11$). To be able to achieve $x/h > 70$, we used the rectangular wooden blocks only to model the extensive upwind forest, and these were less porous to air flow in the upper half of the canopy than the field trees (although this would have also been true if we had been able to use our model trees upwind of the model heath). These figures (and others not shown) show that Gash's first upwind measurement, which was at about $x/h = 5$ (the effective distance varied slightly with wind direction), was just outside the quiet zone (i.e., just in the wake zone). The wind tunnel measurements encompassed the quiet and wake zones fully.

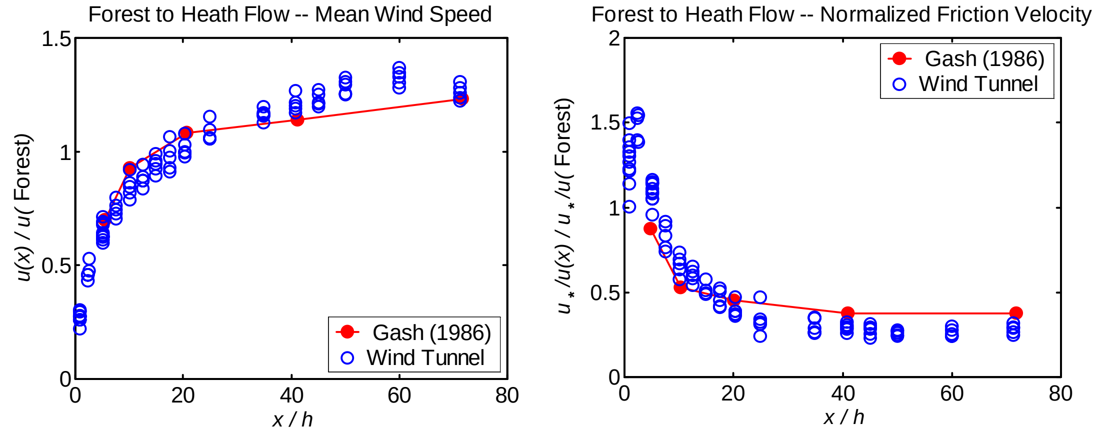

Figure 11: Comparison between wind tunnel and Gash (1986) field values of normalized mean wind speed, u, and friction velocity, u_*, measured at the 3.5 m height (6 cm height in the wind tunnel) above a heath downwind of a forest.

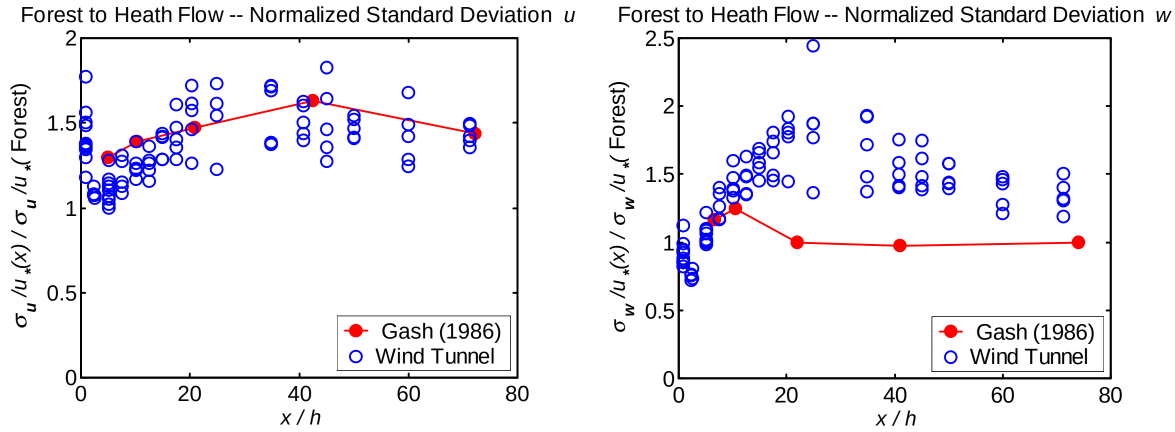

Figure 12: Comparison between wind tunnel and Gash (1986) field values of normalized standard deviation of the horizontal, σ_u, and vertical, σ_w, wind speed measured at the 3.5 m height (6 cm height in the wind tunnel) above a heath downwind of a forest.

Strain-Gauge Balance

We have used our two-stage strain-gauge balance to measure the drag and bending moment on trees at selected locations in a number of forest/clearing configurations. Besides these direct measurements, the balance is useful in testing and calibrating formulas to calculate drag and bending moment from measured wind speed and turbulence. Such formulas are critical in modelling wind and turbulence using numerical solutions of the basic equations governing turbulent fluid flow. Much of our early wind tunnel measurements were done before the balance was built and it would be useful to be able to make drag/bending moment calculations for them. The present balance is incapable of measuring fluctuations in drag and moment arm because of its slow response time.

One of the most stringent tests of the balance is to measure drag in a uniform forest, such as in the thinning study described above. This is very demanding because the drag per tree is low compared to that experienced by a tree at an exposed forest edge. In 1998, we measured drag in uniformly thinned model forests (20 and 55 trees m^{-2}) with the balance and found that agreement with the surface shear stress at the top of the canopy (which is drag per unit horizontal area; see Figure 8) after multiplying the drag per tree from the balance by the number of trees per m^2 was within 20% at both densities. Note that because the shear stress in the wind tunnel varies little with tree density, the drag per tree increases dramatically with thinning, being 11 times greater for the lowest density (31 trees m^2 with a leaf area index of 0.42) compared with the highest density (333 trees m^2 with a leaf area index of 4.5) in the uniform thinning study. But because the displacement height, which according to Thom (1971) is the moment arm of the drag, decreases with increased thinning, the mean bending moment on a tree (which ultimately causes windthrow) only increases by a factor of 8 between these two treatments.

The standard aerodynamic formula for drag, *D*, is given by:

$$D = 1/2\, \rho\, C_d\, A_f\, u\,|u| = 1/2\, \rho\, C_d\, A_f\, [\langle u\,|u|\rangle + (u\,|u|)'],$$

where C_d is the drag coefficient, A_f is the frontal (horizontally projected) leaf area of the tree, and *u* is the horizontal wind speed, with $|u|$ being its magnitude (*u* is normally positive in the downwind direction but can be negative when the flow direction is reversed because of some turbulent fluctuation; the tri-axial probe rectifies such reverse flows and yields, incorrectly, $u > 0$ only). The < > brackets refer to the mean part and the prime refers to the fluctuating part due to turbulence. In general for turbulent flow, C_d is relatively constant with wind speed which gives the formula its usefulness for prediction.

Figure 13 shows wind tunnel measurements of wind speed and drag and associated statistics calculated with the above formula using tri-axial probe measurements of wind speed and turbulence. The wind speed in the formula was from a height of 7 cm (0.47 tree heights), 3.5 cm (0.23 tree heights) in front of the downwind edge of cleared strips of various widths. The strips were oriented perpendicular to the flow and spanned the full breadth of the wind tunnel. The 7 cm height used for the calculation (with the 1993 wind speed data) is equal to the moment arm measured with the tree balance in 1998 (the moment arm did not vary greatly with location and configuration). We used $C_d = 1.04$ and $A_f = 0.0043$ m^2, the latter based on video images of 7 sample trees. The mean wind speed at 7 cm height, and the drag values measured with the balance in 1998 are also shown in the figure. Because we operated the wind tunnel at a higher overall speed in 1998 (to maximize balance signal), the 1998 mean wind and drag measurements were normalized to the 1993 measurements for comparison. This was done, by multiplying all the 1998 mean wind speeds by 0.63 and all the 1998 mean drags measured by the balance by $0.63^2 = 0.40$ (since the above formula shows that drag depends on the square of the wind speed). The normalizing factor of 0.63 and the $C_d = 1.04$ were found by matching (on an overall basis) the 1993 and 1998 wind speeds and drags shown in Figure 13. The wind speeds then show nearly identical variation with strip width. The measured and calculated drags also match well, which demonstrates the reasonableness of the drag formula, with C_d being relatively insensitive to wind speed and configuration, and that the balance works properly (the reason for the decline in drag at the widest strip width in 1998 is not known). The $C_d = 1.04$ differs from $C_d = 0.88$ found by placing the 7 sample trees in isolation in laminar flow in the wind tunnel.

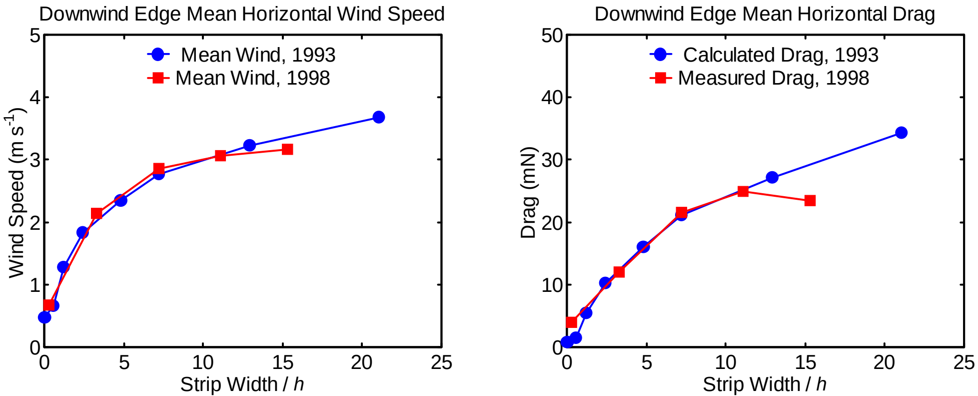

Figure 13: The variation with strip width of mean wind speed, and calculated and measured drag, at the downwind edges of clearings oriented perpendicular to the flow. The wind speeds were measured at the 7 cm height just upwind of the downwind edge in 1993 and 1998, with the 1998 speeds normalized by multiplying by 0.63, as described in the text. The drag for 1993 is calculated using the formula given in the text and the drag measured in 1998 with the two-stage balance is normalized by multiplying by $0.63^2 = 0.40$, as described in the text.

This is consistent with our measurements that showed that drag depends upon configuration to some extent, e.g., we found that drag on a tree in a single row of trees transverse to a turbulent flow increased as the density of trees in the rows increased and was higher than for an isolated tree in the same flow. It should be noted that analysis of the 1998 results is as yet incomplete. A more exact analysis will use the 1998 wind speed data to calculate the drag with the above formula; this will be done in the near future.

Figure 14 shows that the maximum instantaneous drag exceeds the mean drag by at least a factor of 5, with the ratio increasing as strip width decreases. This is also illustrated by the standard deviation of the drag fluctuations. Although these increase with increasing strip width, the ratio to the mean drag decreases with increasing strip width. The fluctuations in drag, which are due to turbulence, especially large gusts, are important in the windthrow process because they lead to greater loading on a tree than would be inferred from the mean wind speed and because the constant swaying of the tree probably weakens the roots.

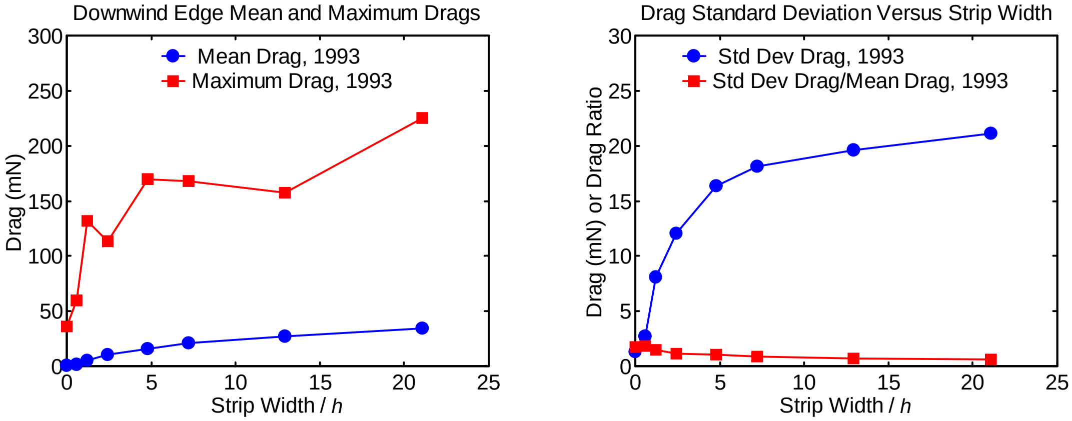

Figure 14: The variation with strip width of mean and maximum instantaneous drag and the standard deviation of the drag at the downwind edge of clearings perpendicular to the flow, all based on the 1993 wind speed and turbulence measurements.

Concluding Remarks

Since 1992, we have used the large UBC wind tunnel to study a large and diverse number of forest/clearing configurations. The results presented herein demonstrate that the wind and turbulence measurements made in these studies realistically describe what occurs at the full scale in the real world. Furthermore we have shown that our strain-gauge balance can properly measure mean drag on a tree at any location of interest in one of these configurations and so should allow us to determine their windthrow potential. The standard aerodynamic drag formula appears to be in good agreement with the drag measured by the balance. Analysis of all of our wind tunnel and field data is as yet incomplete. In the next few years we expect to fully utilize all of this data, and carry out additional new measurements, with a view towards better understanding windthrow and microclimate in harvested forests.

Acknowledgements

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The Mechanical Behavior of Trees under Wind Loading: Influence of Crown Properties and Structure.

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Abstract

Basic structural mechanics theory is reviewed and is applied to show that the dynamic response of a tree to an arbitrary wind loading can be predicted using a knowledge of natural frequency (*f*) and damping ratio (#1). Analysis of available data showed that natural frequency was linearly related to DBH/H^2. Differences were found between tree genera, with pines (*Pinus* spp.) having lower natural frequencies than spruces (*Picea* spp.) or Douglas-fir (*Pseudotsuga menziesii*). Successive removal of branches from the base of the crown increased the natural frequency of a tree; the greatest change occurring with removal of the uppermost part of the crown. This result coupled with the observed increase in the ratio of the stem-only to whole-tree natural frequencies with increasing DBH/H^2 indicates that crown structure, and, in particular, the distribution of crown mass is very important in determining the mechanical behavior of trees.

Pruning as a silvicultural treatment to reduce the risk of wind damage may be of limited value if only branches at the crown base are removed. The relative wind speed in this region is low and it appears that at least 40% of the crown must be removed before there is a significant change in the tree mechanical behavior.

Introduction

Damage from wind storms is a problem in forests in may parts of the world (Quine and Gardiner, 1991; Everham, 1995). In response to this damage a number of authors have developed classification schemes to address the risk of wind damage (Quine, 1995). Many of these schemes have a strong empirical basis and provide only a qualitative assessment of risk (i.e., low, medium, high etc.). More quantitative assessments of risk, and the investigation of the effects of both individual tree characteristics and stand structure on this risk, can be achieved using mechanistic models which attempt to model the processes that cause wind damage. A major component of these mechanistic models is a sub-model which predicts the response of a tree to a particular wind load. The simplest models treat the applied wind load acting on a tree as a static force (i.e., invariant with respect to time) and use engineering beam theory to determine the deflection from the vertical, the maximum turning moment at the base of the tree, as well as the vertical distribution of stresses within the tree. Although understanding the static behavior of trees provides a good basis for understanding their overall behavior, it is a simplification of reality. Trees are dynamic systems and their behavior varies with time. The response of a tree is frequency dependent with the tree responding most to wind gusts at frequencies close to its resonant frequency and its harmonics (Gardiner, 1992). In these situations the dynamic effects are likely to increase the bending of stems and hence the load on the root system (Milne, 1991).

There are two approaches to quantifying the dynamic properties of a tree from wind storm data (Milne, 1991). The first approach requires both the randomness of the wind and the response of the tree to be investigated. Alternatively, if we have information on the dynamic properties of trees then it is possible to characterize their motion in response to any known applied force through standard engineering methods.

In this report, these standard engineering methods are discussed and their data inputs described. Previous studies that have attempted to model these parameters based on tree size variables are reviewed and some preliminary results from an experiment to investigate the effect of crown structure on tree behavior under wind loading are presented.

Fundamental Structural Dynamics Principles

While the motion of a tree under wind loading may appear to be completely random, it is in fact possible to analyze it as a linear combination of periodic motions. More specifically, the motion of a tree under wind loading can be analyzed by superposing periodic motions that can be described by simple trigonometric functions (i.e., sine and cosine waves).

All periodic motions can be described by a few basic characteristics, the most important of which are amplitude (y); period (T) and frequency (f). Period is the time to required to complete one cycle of motion. For simple harmonic motion, amplitude is defined as maximum displacement from the rest position. Frequency is the inverse of period, i.e., the number of repetitive cycles which occur during a unit time:

$$f = 1/\mathrm{T} \qquad [1]$$

The motion of a tree that is displaced and then allowed to oscillate corresponds to damped free-vibration. Here the amplitude of vibration does not remain constant but decreases with time. This reduction is due to the friction of the support system and to the internal friction of the vibrating material, called damping (Bodig and Jayne, 1993). The equation of motion for a tree under these conditions is:

$$m\frac{d^2y}{dt^2}+c\frac{dy}{dt}+ky=0 \qquad [2]$$

where m is the mass of the tree, c is the damping constant of the tree and k is the stiffness of the tree. Solving equation [2] to get the time history of tree displacement, y(t) yields:

$$y(t)=\rho e^{-\xi\omega t}\sin(\omega_d t+\phi) \qquad [3]$$

where, #2 is a function of the initial velocity and displacement conditions of the tree, #3 is the natural circular frequency of the tree (#4), #1 is the damping ratio, #5 is the damped natural circular frequency (#6) and #7 is a phase shift which is also a function of the initial velocity and displacement conditions of the tree.

From equation [3] it can be seen that the time dependent behavior of a tree can be fully described through a knowledge of the natural frequency and damping ratio. This is also true for the case where the tree is subjected to a sinusoidal excitation of amplitude #8 and frequency #9 (i.e., #10). Here the equation of motion is:

$$m\frac{d^2y}{dt^2}+c\frac{dy}{dt}+ky=F_o\sin\Omega t \qquad [4]$$

and its steady-state solution is:

$$y(t)=\frac{1}{\sqrt{(1-\beta^2)^2-(2\xi\beta)^2}}\frac{F_o}{k}\sin(\Omega t-\phi) \qquad [5]$$

where #11 (i.e., the ratio of the excitation frequency #9 to the natural frequency #3). If we focus on the first part of equation [5], then we can define the transfer function:

$$\left|H(\omega)\right|=\frac{1}{\sqrt{(1-\beta^2)^2-(2\xi\beta)^2}} \qquad [6]$$

The physical interpretation of this function is that it is the ratio of the dynamic and static responses of the system to a given force. It is also often referred to as the dynamic magnification factor. A plot of this function versus #12 is given in Figure 1. From this it is apparent that the dynamic magnification factor increases markedly when the excitation frequency and the natural frequency of the tree are similar. When the natural frequency and excitation frequency coincide (i.e., #12 = 1), a situation called resonance occurs. With inadequate damping the sway deflections and the resulting stresses can be very large (Wood, 1995).

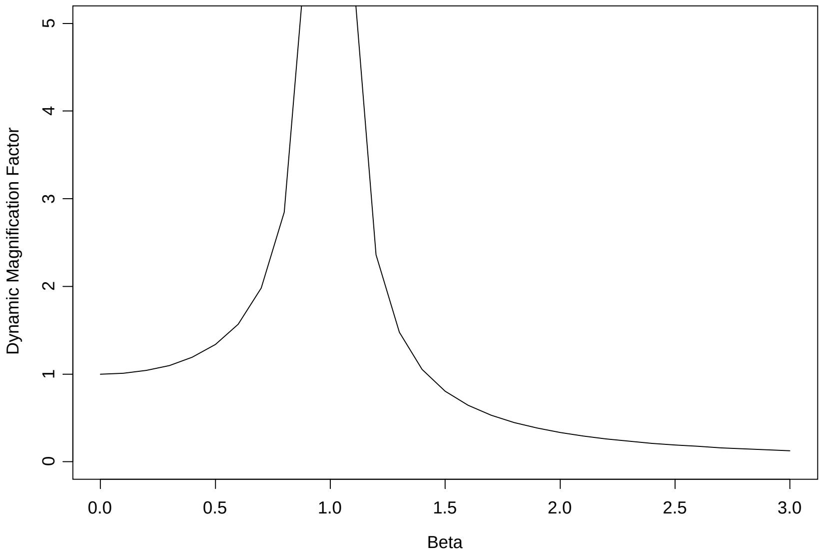

Figure 1. Variation of dynamic magnification factor with frequency. Damping ratio #1 = 0.05.

Predicting Natural Frequency from Tree Characteristics

Estimates of the natural sway period and damping can be obtained from sway tests in which a tree is forced to sway with an attached rope and then released and allowed to adopt its natural frequency. These tests are obviously time consuming and it would be ideal if sway period and damping could be predicted from commonly measured tree attributes such as height, diameter at breast height (DBH), stem volume, crown length and crown width.

Previous studies investigating the natural sway frequencies of trees are relatively sparse. One of the earliest studies was made by Sugden (1962). He stated that the period (T) of a weightless beam fixed at one end, with mass (M) concentrated on it at a distance (L) from the fixed end could be expressed by the formula:

$$T \propto ML^{2} \qquad [7]$$

While he found that this equation was appropriate for predicting the sway period of a bamboo rod with a weight attached to it, Sudgen (1962) noted that a tree can not be considered as a weightless beam because it has its mass distributed along its length. However, he does point out that, in general, tree sway period decreases as diameter increases (height and branch weight remaining constant) and increases as height increases (all else remaining constant).

More recently Gardiner (1992) and Milne (1991) have used the Rayleigh method to develop an approximate theoretical relationship for *f*. The underlying concept of the Rayleigh method is the principle of conservation of energy; the energy in a freely vibrating system must remain constant if no damping forces act to absorb it (Clough and Penzien, 1993). Thus, the maximum kinetic energy (K_{max}), which occurs as the tree sways through the rest position, must equal the change in gravitational potential energy (U_{max}), which occurs between the rest condition and the limit of displacement (Milne, 1991). Solving these equations, Gardiner (1992) developed the following relationship for natural frequency:

$$f \propto \frac{d_L\sqrt{\frac{E}{\rho}}}{L^2} \qquad [8]$$

where #13 is basal diameter, #14 is Young's modulus of elasticity and #2 is wood density. If the ratio of Young's modulus to density is approximately constant then [8] can be simplified to:

$$f \propto \frac{d_L}{L^2} \qquad [9]$$

If it further assumed that basal diameter is proportional to DBH then the latter can be substituted into equation [9].

Available data on frequency from studies performed by other authors (Sugden, 1962; Mayhead, 1973; Mayhead et al., 1975; Milne, 1991; Gardiner, 1992; Flesch and Wilson, 1999) as well as from a study on nine Douglas-fir (*Pseudostuga menziesii*, Mirb. Franco) trees in the Oregon Coast Range were plotted against DBH/H^2 (Figure 2). Despite a concentration of data points at values of DBH/H^2 less than 0.20, a strong linear relationship was found between DBH/H^2 and *f* (r^2 = 0.814).

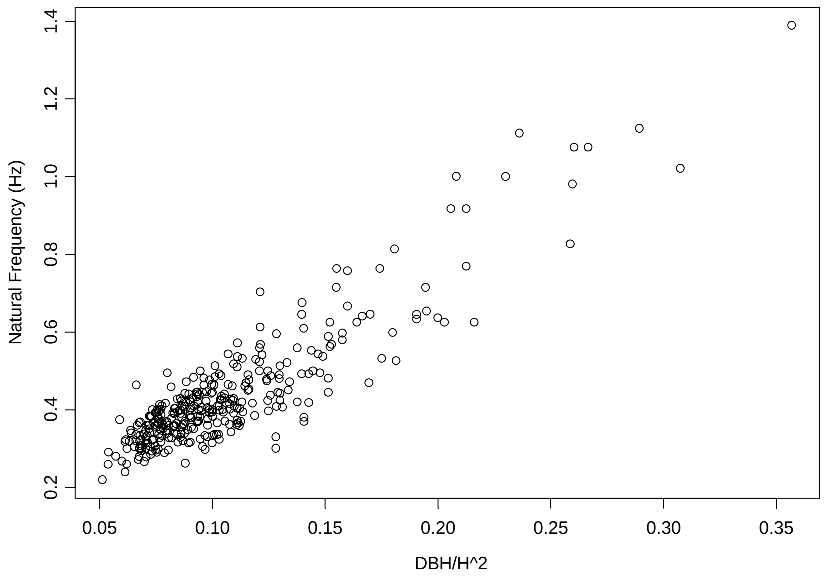

Figure 2. Relationship between natural frequency and DBH/H^2 for all available data from previous studies and from a study on Douglas-fir in the Oregon Coast Range.

Species differences were investigated by grouping trees according to genus (Figure 3). After accounting for DBH/H^2, the natural frequency of pines (red pine (*Pinus resinosa* Ait.), Lodgepole pine (*Pinus contorta*), Corsican pine (*Pinus nigra*) and Scots pine (*Pinus sylvestris*)) was significantly lower than for spruces (Sitka spruce (*Picea sitchensis* Bong Carr), Norway spruce (*Picea abies* L.) and white spruce (*Picea glauca*); $p < 0.001$). No significant difference was found between the spruces and Douglas-fir ($p = 0.3022$).

Mayhead (1973) did not test for differences in sway period between species but suggested that if they did exist then they might be due to differences in factors such as branch form and flexibility, length of canopy and form factor.

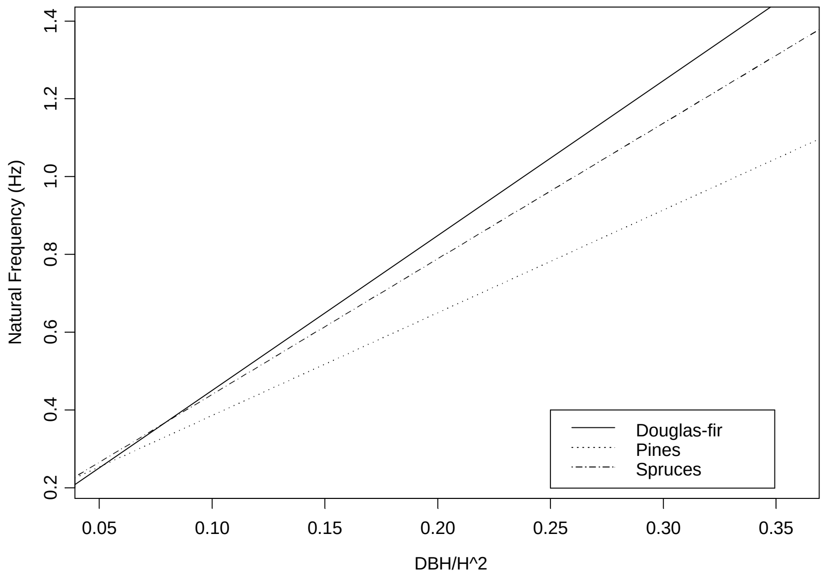

Figure 3. Differences in the natural frequency between trees from the pine, spruce and Douglas-fir genera.

Effect of Crown Removal

Sugden (1962) noted that the heavier the crown of a tree, or the higher its center of mass, the lower the natural frequency. This has been confirmed by Milne (1991) and Gardiner (1992) who found that sway periods of whole trees are greater than for the same trees with the branches removed. A plot of their data, collected from 16 Sitka spruce trees, along with data collected from 6 red pine trees by Sugden (1962) and from 9 Douglas-fir trees is shown in Figure 4. It is clear that the difference in natural frequency between the whole tree and the stem only increases with increasing DBH/H^2. The ratio of the stem-only to whole-tree natural frequencies also increases with increasing DBH/H^2 (Figure 5).

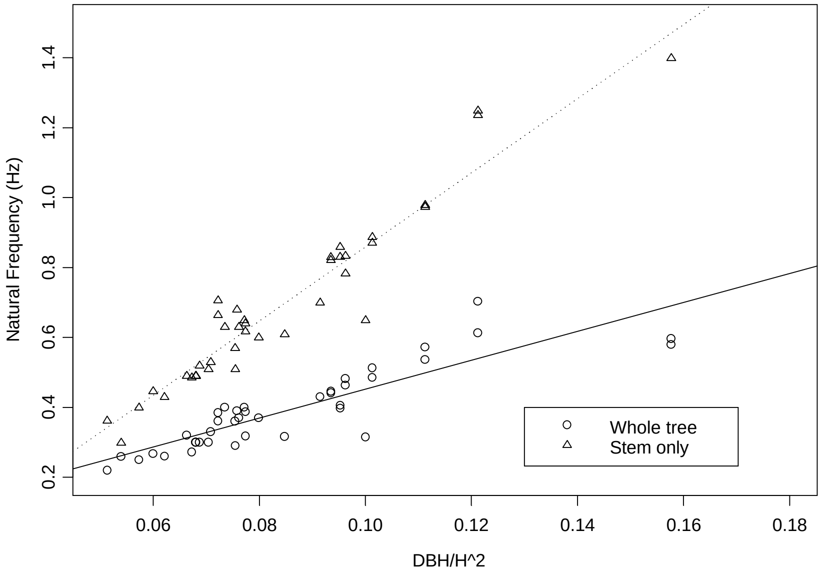

Figure 4. Comparison of natural frequency between the stem only and the whole tree for 16 Sitka spruce, 6 red pine and 9 Douglas-fir trees.

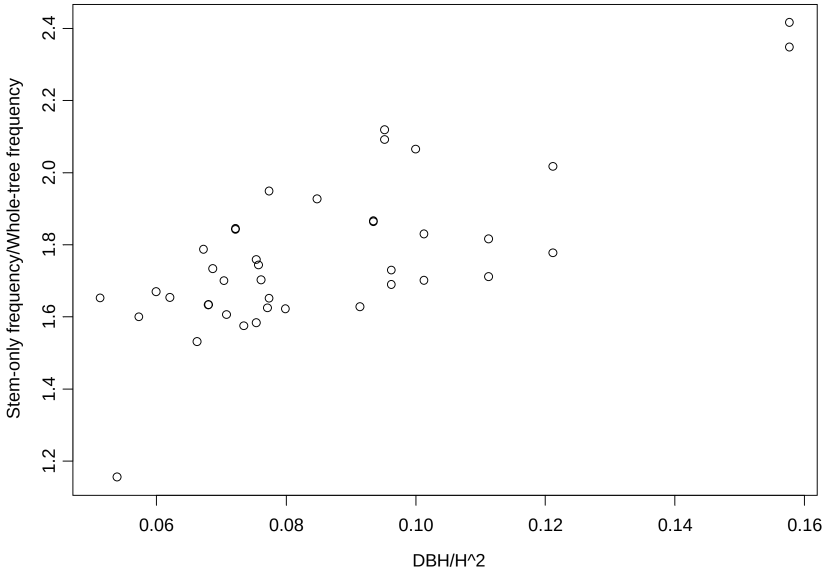

Figure 5. Ratio of stem-only (i.e., all branches removed) natural frequency to whole-tree natural frequency for 16 Sitka spruce, 6 red pine and 9 Douglas-fir trees.

For unpruned trees, a larger value of DBH/H^2 implies a greater crown length and crown mass. This would act to attenuate the slope of the relationship between whole-tree natural frequency and DBH/H^2 and could explain the increase in the ratio of the stem-only to whole-tree natural frequencies with increasing DBH/H^2. For those trees where data existed, significant linear relationships were found between branch mass and DBH/H^2 (Figure 6). The increase in branch mass with increasing DBH/H^2 is much greater for the red pine trees measured by Sugden (1962) than for the Sitka spruce trees measured by Gardiner (1992) and Milne (1991).

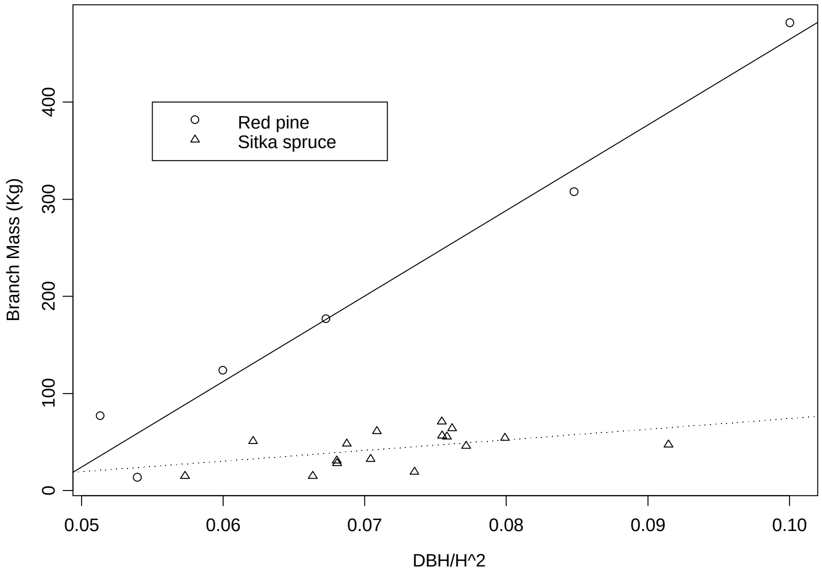

Figure 6. Relationship between branch mass (Kg) and DBH/H^2 for red pine and Sitka spruce trees.

The effect of crown structure on the mechanical behavior of trees was investigated through an experiment, conducted in the Oregon Coast Range, which involved successive removal of approximately one-third, two-thirds, and the entire crown length on 9 Douglas-fir trees, and measurement of their corresponding natural frequency.

Preliminary results indicate that the largest change in natural frequency occurs due to the removal of the uppermost portion of the crown (Figure 7). A similar result was found in maritime pine (*Pinus pinaster* Ait.) by Guitard and Castera (1995). For the data from the Oregon Coast Range, finite element models will be constructed from measured branch mass distributions and then applied to determine whether the change in natural frequency is simply due to a change in the mass distribution of the tree.

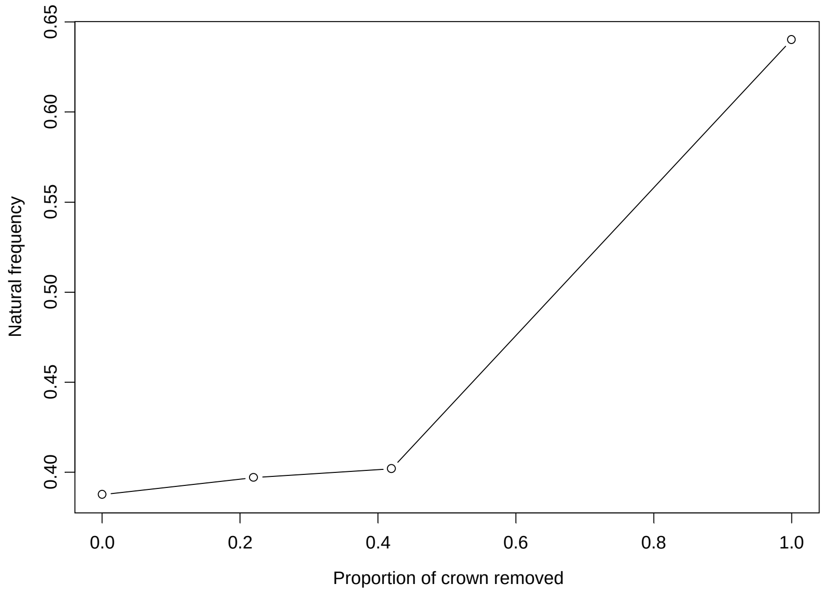

Figure 7. Relationship between the natural frequency of a Douglas-fir tree and the proportion (by length) of crown removed.

These results are important from a practical standpoint as they indicate that pruning of a tree from the crown-base upwards may have very little effect on the behavior of the tree under wind loading. The wind speed profile within a stand is generally exponential in nature (i.e., wind speed increases exponentially with height above ground) and therefore the relative wind speed acting on bottom part of the crown is low. Removal of this part of the crown will therefore only afford a slight reduction in both the wind load acting on the tree and the natural sway frequency of the tree.

Conclusions

Reliable estimates of the natural frequency of whole trees can be obtained from measurements of height and DBH. This means that dynamic models of behavior under wind loading can be constructed for trees within a stand using information commonly available in stand records. These models can then be used to predict the effect of various silvicultural regimes on the behavior of trees under wind loading. Further work is required to investigate the effect of the distribution of crown mass on the mechanical behavior of trees and their response to wind loading.

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Section 4. Techniques for Reducing Damage

Edge Windfirming Treatments in Coastal British Columbia

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Abstract

The effectiveness of pruning, topping and edge feathering for reducing damage to newly exposed cutblock boundaries was tested in coastal BC. Damage in untreated controls one year after exposure by harvesting ranged from 0 to 85% of stems. Helicopter-based pruning and manual topping techniques reduced damage by 40% in comparison with controls. Crown modification treatments did not increase direct tree mortality in the first 3 years after treatment. Edge feathering reduced damage in some stands and increased it in others.

Introduction

Wind is a natural disturbance agent in forests and contributes to both forest and stream productivity (Grizzel and Wolff, 1998). Endemic windthrow refers to damage caused by routinely occurring peak winds. It often initiates at abrupt or unstable boundaries resulting from forest management practices. Windthrow is a serious threat to managed forests because it results in loss of timber yield, landscape quality and wildlife habitat (Quine et al, 1995). This is of particularly concern in Coastal British Columbia which experiences chronic windthrow losses. Windthrow losses are largely unquantified, however the U.S Forest Service estimated annual losses equivalent to 2.5% of the annual drain on timber (Mergen 1954). The BC Forest Service found damage equivalent to 4% of the annual allowable cut in a survey conducted in 1992 (Mitchell, 1995).

Windthrow has a negative impact when the damage interferes with the achievement of management objectives at the forest or stand level. Wind damaged trees lose commercial value rapidly and salvage operations are often costly. Grizzel and Wolff (1998) found that wind damage in small stream riparian buffers in Northwest Washington was highly variable, affecting on average 33 percent of the buffer trees. Even when wind damage does not result in a direct physical affect on the stream, it may compromise some of the intended functions of the buffer, e.g. shade, water quality, bank stability, and enhance others, e.g. large woody debris recruitment and sediment storage.

Recent changes to forest practices in BC have have served to increase the amount of cut block edge open to the influence of winds thereby increasing the risk of endemic windthrow. In response, a number of management techniques have been developed and applied to manage windthrow risk. Windthrow management typically begins with a stand level assessment of windthrow risk (e.g. Stathers et al., 1994; Mitchell, 1998). Measures to reduce damage to acceptable levels include moving boundaries to more windfirm types, realigning boundaries with damaging wind direction, edge thinning or 'feathering', and crown modification of reserve or boundary trees (e.g. Ruel, 1995; Quine et al., 1995). Modification of tree crowns is a method commonly used to control windthrow of individual trees in suburban areas and along utility lines. Thinning or feathering of the stand edge along clearcut areas to remove trees considered vulnerable to windthrow is occasionally done operationally primarily along streamside corridors or protective buffers in unstable terrain.

In 1992, the Ministry of Forests in co-operation with Weyerhaeuser Company Limited (formerly MacMillan Bloedel Ltd.) established a windthrow edge management study in the Akan Creek drainage of northern Vancouver Island. In 1994, a second windthrow edge treatment study was set up in the riparian area of the Keogh River on the north end of Vancouver Island with the assistance of Western Forest Products Ltd. Each of these early studies tested windfirming techniques in a single stand type with small treatment units. Early results indicated that edge treatments reduced wind damage only slightly relative to the intensity of treatments applied. However, the wind damage in the two edge study sites was low in all treatment units and the effectiveness of the treatments had therefore not been thoroughly tested (Mitchell, 1997).

The current study tested the operational efficiency of two stand edge treatments, and their effectiveness for the reduction of windthrow in a variety of stand types and locations in coastal BC. Crown modification by topping or pruning reduces the sail area of the trees along the clearcut edge by approximately one third. Edge feathering involves the removal of trees along the stand edge, with the objective of leaving the most windfirm trees standing. Short and longer term effects of treatments on tree mortality were recorded, and the site, stand and tree factors which contributed to damage vulnerability were assessed.

Methods

The study sites included in this report are located in wind exposed locations of coastal BC. The Insular Mountains dominate the regional landscape of study sites located in the southern half of Vancouver Island. The study sites located in the northern half of Vancouver Island and the Queen Charlotte Islands are influenced by a complex network of islands and gentle to moderate sloping inlets (Holland, 1976). The study sites encompass a diverse array of geological features including sedimentary and volcanic clastic bedrock which can be locally folded, sheared and metamorphosed. Virtually all study sites are dominated by podzolic soils with inclusions of organic complexes.

All sites are strongly influenced by Pacific Ocean with mild wet winters and cool moist summers. Most of the study sites experience high annual rainfall ranging from 100 cm to 500 cm. Seasonal snow during the winter is typically rare, with short term accumulations on some of the higher elevation and inland sites. Peak southerly winds are typically associated with Pacific low pressure systems between October and March and are usually accompanied by high rainfall.

Most of the study sites are located in the submontane very wet maritime variant of the Coast Western Hemolock biogeoclimatic zone (Green and Klinka, 1994). Abundant rainfall and mild temperatures make these forest types very productive with mean annual increments ranging from 3.5 to >6.4 m^3/ha/yr. The majority of the study sites were located in mature forests with a lesser number of sites located in second growth forest (southern Vancouver Island sites). Sites are typically dominated by western hemlock, (Hw) amabilis fir (Ba), and western red cedar (Cw) although several other species are also common.

Implementation of the study required co-operation of forest licensees to carry out windthrow management techniques. Study sites in cutblocks proposed for harvesting were identified through invitations of interest. Candidate study sites had to be located in areas of known windthrow concern. In most cases, the windthrow hazard had already been assessed as 'moderate' to 'high' using the assessment process described in Stathers et al. (1994), and direct windthrow management techniques were prescribed, or were under consideration. Sites had to have relatively uniform terrain and stand conditions. The proposed cutblock boundary had to be located in a relatively straight line, perpendicular to prevailing storm winds. Preference was given to study sites that could used for demonstration and extension activities. The study included 15 study sites as indicated in Figure 1.

Treatment units (TU's) were established along windward cutblock or riparian management area edges in openings greater than 5 tree lengths wide. TU's were approximately 100 meters long by 30 meters deep. In most cases, they were separated by a 20-30 meter untreated buffer (Figure 2). Within the 15 study sites, 38 treated units and 22 untreated control units were established. Because of the size of the study, physical cutblock size constraints and operational constraint involved, it was impossible to establish replicate treatments in every study site. On average, 3 treated and one control units were established in each study site, randomly assigned to the available TU's.

All standing and down trees greater than 15cm DBH and 3m tall within each TU were tagged and mapped. Individual trees were located, using a base line or “hub” co-ordinate system, in relation to the cutblock boundary. Stand level data collection included the number of stems surveyed, size of treatment unit, type of edge, original survey date, topographic position at various scales, elevation, slope, aspect, orientation of prevailing wind as well as site series and soil profile information. Individual tree data collection included species, DBH, crown class, pathology indicators, general vigour observations, current status, crown and total tree height, and direction and degree of lean. For windthrown trees azimuth bearing, rooting radius and depth and direction were also recorded. TU's contained an average of 115 stems, for a total of 8642 mapped stems.

Applied treatments were based on techniques gaining acceptance in coastal British Columbia forest operations. These included feathering, topping and pruning. In edge feathering (thinning), the original stand along the edge of a cutblock is thinned to help dissipate and reduce the applied windforce as well as to retain trees with greater resistance to the applied wind forces (Figure 3). In this study, the edge feathering variants removed 15-90% of the trees within a each TU. Treatments were completed and funded by the associated licensee partner. In all cases, manual falling was used. Timber was removed by either ground based harvesting equipment, e.g. hoe-forwarder, or cable yarding, e.g. grapple yarder or live skyline methods. Three variants were tested (Table 1).

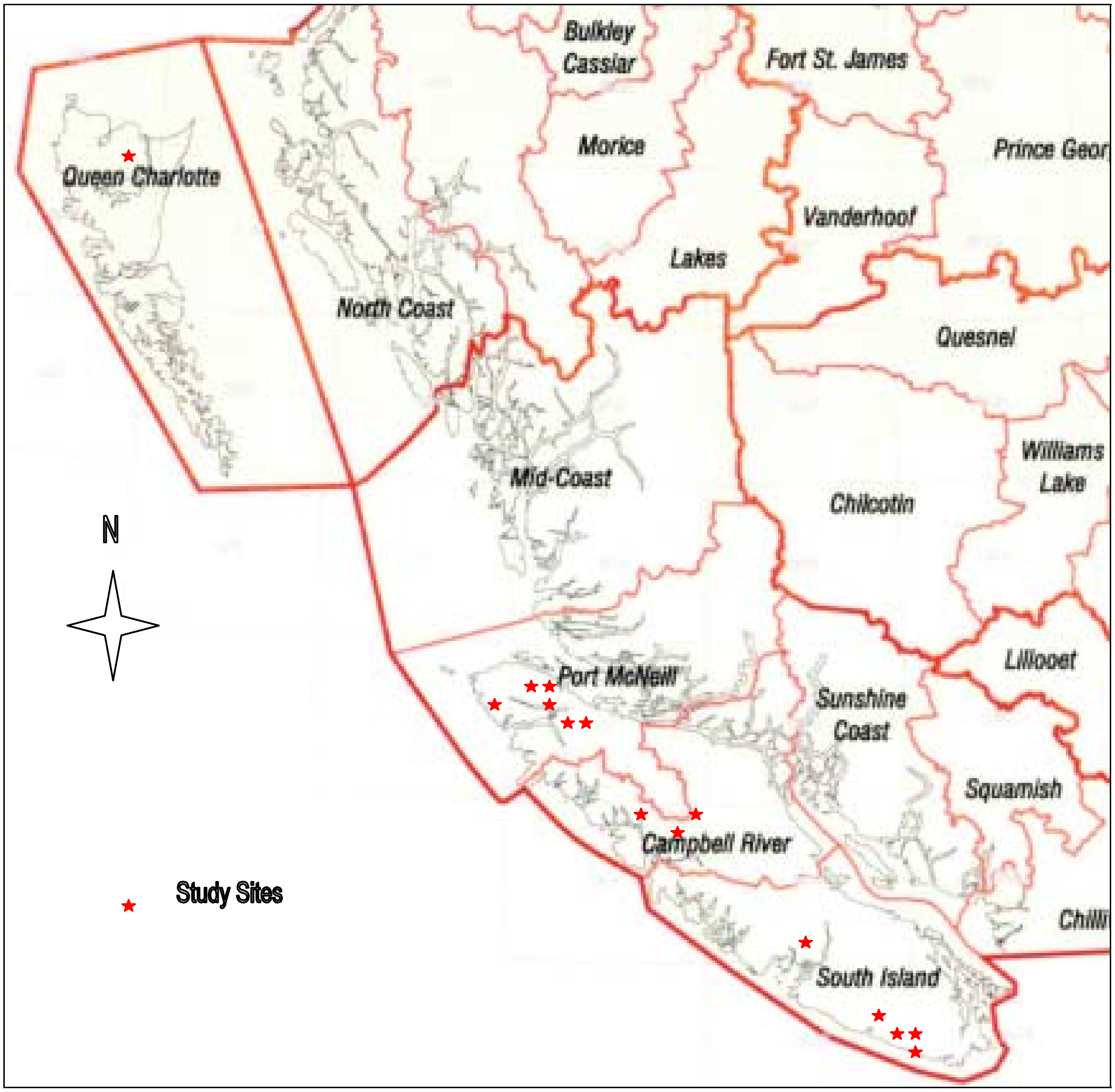

Figure 1. Location map of study sites within each Forest District.

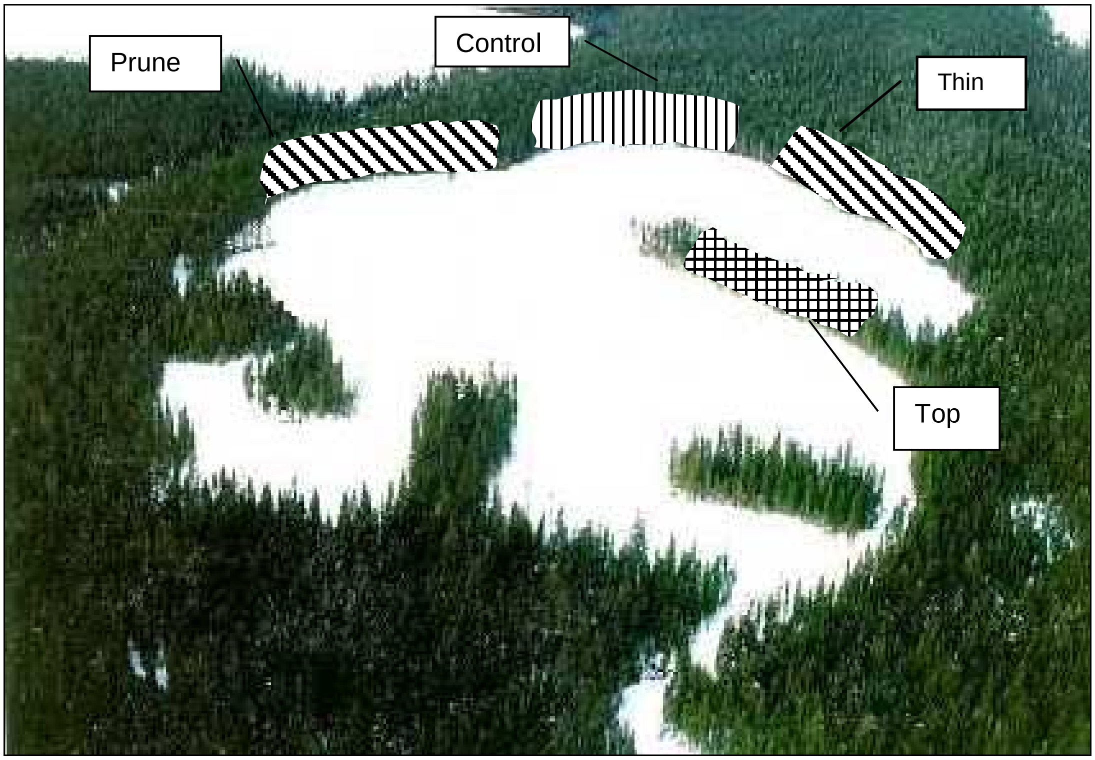

Figure 2. Example treatment and control unit layout pattern.

Table 1. Description of edge feathering variants.

Variant	Description
uniform retention	trees were retained in a uniform distribution throughout the treatment unit preserving the original stand profile as much as possible
serrated edge	created a geometric zig-zag pattern with points centred behind a windthrow resistant tree (sometimes created by topping or pruning)
super dominant	up to 30% of the largest dominant trees with the highest windthrow resistance features were retained (veteran or wolf trees with crowns significantly higher than the average stand canopy)

Figure 3. Example of edge feathering retaining most wind resistant stems.

In the crown modification treatments, the objective was to remove 30% of the crown. Topping involved cutting the stem of the tree whereas pruning involves removal of branches at or near the bole of the tree but otherwise leaving a live leader. All topping treatments were completed manually using tree climbing crews. Workers specializing in this work would climb selected trees and cut the stems using a chainsaw (Figures 4 to 6). Treatments were only applied to dominant and codominant trees. Three variants were tested (Table 2).

Table 2. Description of crown modification variants.

Variant	Description
Leading edge	only those trees where more than 50% of the crown sail area was exposed to storm force wind, i.e. not hidden behind another tree -> usually only 1-2 tree crowns deep into the stand
50% distribution	every other tree was topped or pruned throughout the entire treatment unit
100% distribution	all dominant and codominant trees were topped or pruned throughout the entire treatment unit

Figure 4. Specialized tree topping worker climbing a stem.

Figure 5. Tree topping in action.

Figure 6. Complete tree topping treatment within example treatment unit.

Pruning treatments were completed using cutting devices suspended below a helicopter to prune the tree. One helicopter firm used a pruning shear equipped with weights that was lowered down the side of the tree to shear branches from the stem (Figures 7 and 8).

Figure 7. Pruning shear used in year two of the study.

Figure 8. Pruning shear used in year one of the study.

The other helicopter firm used a “heli-saw” designed with continuously running, multiple circular saw blades in a tandom configuration (Figures 9-11). Combination treatments involving edge feathering and either topping or pruning of residual trees were also tested.

Figure 9. Heli-saw used in year two of the study.

Figure 10. Heli-saw used in year two of the study.

Figure 11. Example product of pruning application.

The application of treatments and variants was governed by the availability of TU's within each block. Each cutblock contains a control TU, but it was not possible to have every treatment in every block. Because of the large size of the study, it was not possible to implement all treatments in one field season. The earliest blocks were treated in 1996. The latest blocks were treated in 1999.

While treatments were delayed in some instances, treatments were applied prior to the onset of winter storms, i.e. on or before the end of October.

Following the implementation of treatments, TU's were inspected to confirm treatment application. Trees removed in thinning treatments were identified. Trees topped and pruned were identified and residual height of topped trees was recorded. Using this information, tree status was updated. Following each winter storm season, a follow-up survey was conducted in all study units to update pathology indicators, tree status, and record rooting and tree lean information where windthrow damage had occurred. All data was entered into an Excel spread sheet format consistent with data compiled during year one and two operations. Data was compiled and analyzed using SAS statistical software (SAS 1994). The general linear models procedure was used to test overall differences between treatment methods. Contingency tables were used for analysis of damage patterns for individual treatment and stand variables. To account for the varying levels of damage in control units from block to block, damage was expressed as a percentage of that in the controls. Recognizing that exposure time is more important than calendar year, the results were analyzed by the number of years since treatment.

Results

The damage in the untreated control units during the first year after harvest ranged from 0 to 85 % of initial live stems, with a mean of 31% and a median of 26%. For most Blocks, damage in controls was heaviest in the first year after treatment (e.g. Figure 12). Trees which had existing lean during initial measurement were 3 more times likely to uproot than standing live trees during the first winter. Of the trees which commenced leaning during the first winter, only 30% were uprooted in second winter. Healthy stems were less likely to be damaged than stems with scars, rotten branches, and in the case of hemlock - mistletoe.

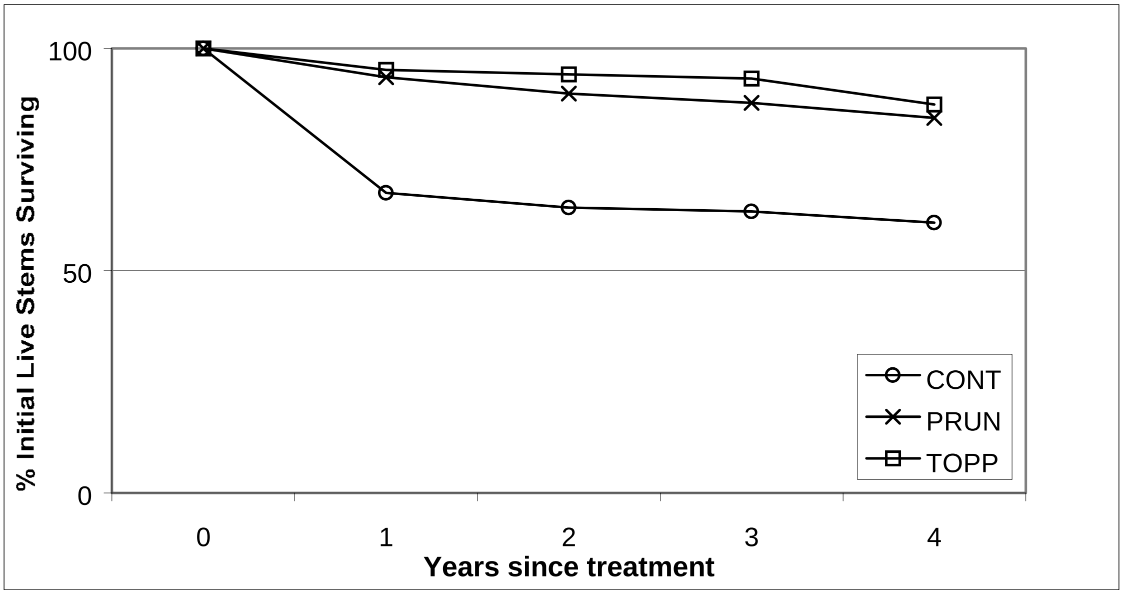

Figure 12. Example of trend in surviving stems by year (Block 928).

For all control TU's pooled, Ba and Hw had similar levels of damage (25%) followed by Cw (14%). Hw/Ba stands were more vulnerable to damage than Hw or Hw/Cw stands. Analysis of the vulnerability of species by TU indicated that within mixed species stands Ba was more susceptible, Cw less susceptible and Hw neutral compared to their co-mixtures. The minor species, which included Sitka spruce, Douglas-fir, red alder and bitter cherry were less susceptible than their co-mixtures (Table 3). For control TU's pooled, uprooted stems were larger in diameter, taller, and less slender with larger live crowns than standing stems. However, analysis of vulnerability within TU's indicated that in the majority of stands, the damaged stems were smaller and more slender than undamaged stems (Table 4).

Table 3. Susceptibility of species within mixed species stands.

Ratio[1]	Hw	Cw/Cy	Ba	Ss	Fd	Decid
				Number of TU's		
> 1.05	10	4	8	1	0	1
0.95-1.05	4	0	3	0	0	0
< 0.95	7	12	3	3	6	4
Mean Ratio	1.02	0.68	1.10	0.40	0.00	0.81

[1] Ratio= % of stems of species damaged / % of total stems damaged in TU

Table 4. Susceptibility to damage by tree size within stands.

Ratio[1]	DBH	HT	HDR	LCR
	Number of TU's			
> 1.05	5	6	9	7
0.95-1.05	4	5	7	8
< 0.95	10	8	1	4
Mean Ratio	0.90	0.99	1.10	1.01

[1] Ratio= mean dimension of damaged trees / mean dimension of undamaged trees in TU

The analysis of mean damage levels using the general linear models procedure indicated that for the study as a whole pruning, topping and combination treatments reduced damage compared to untreated stands, while feathering did not. Evaluation of block by block results indicated that in all but one block, pruning reduced damage in year 1 compared to controls. The same was true for topping (Figure 13). Topping or pruning 100% of overstory stems reduced damage more than treating only 50%. Leading edge pruning was as effective as other forms of pruning in the 2 blocks where it was tried. In pruning or topping treatments where 50% the overstory trees were left untreated, damage was 5 times higher for non-pruned and 13 times higher for non-topped trees. Pruning and topping did not increase standing stem mortality in years 1-3, but a small increase in standing mortality was observed in year 4 in some topped treatments.

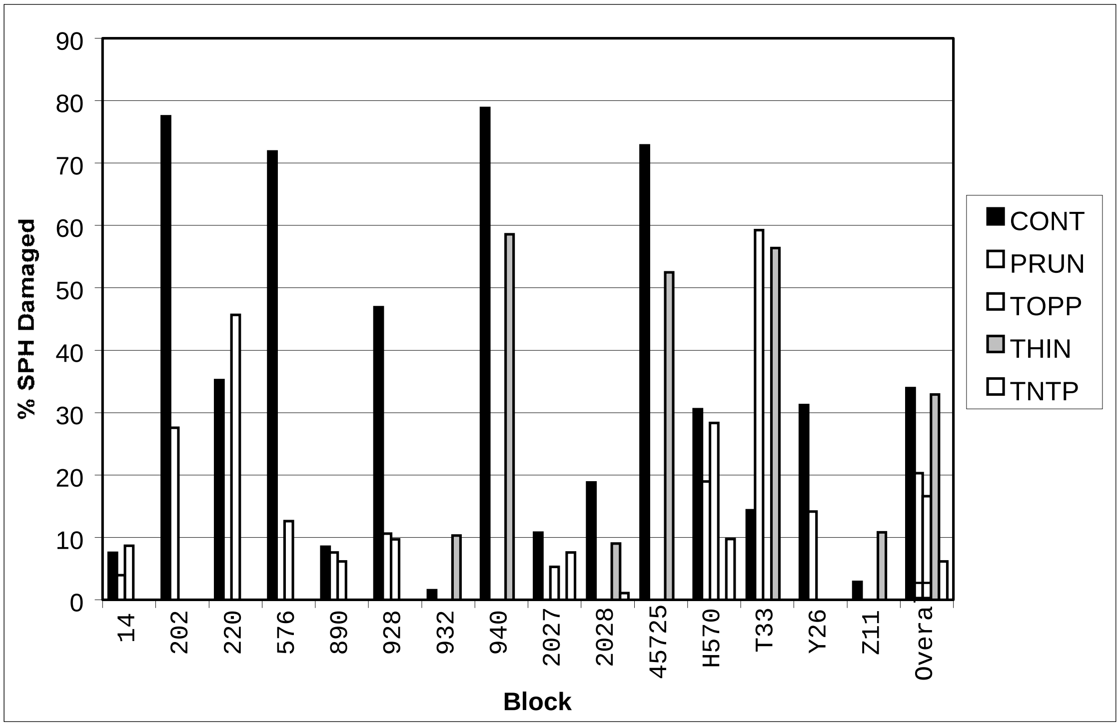

Figure 13. Percent of stems damaged in each block by treatment type in year 1.

Feathering reduced damage compared to controls in 3 blocks and increased it in 3 blocks (Figure 14). All of the feathered TU's which had damage higher than controls were in Ba/Hw types. Two of the three TU's which had less damage than controls were in Hw/Cw types, the other was in a Ba/Hw type. There were no other obvious differences in stocking or mean tree size trends in these feathered edges. There were no consistent trends in the effectiveness of different feathering types.

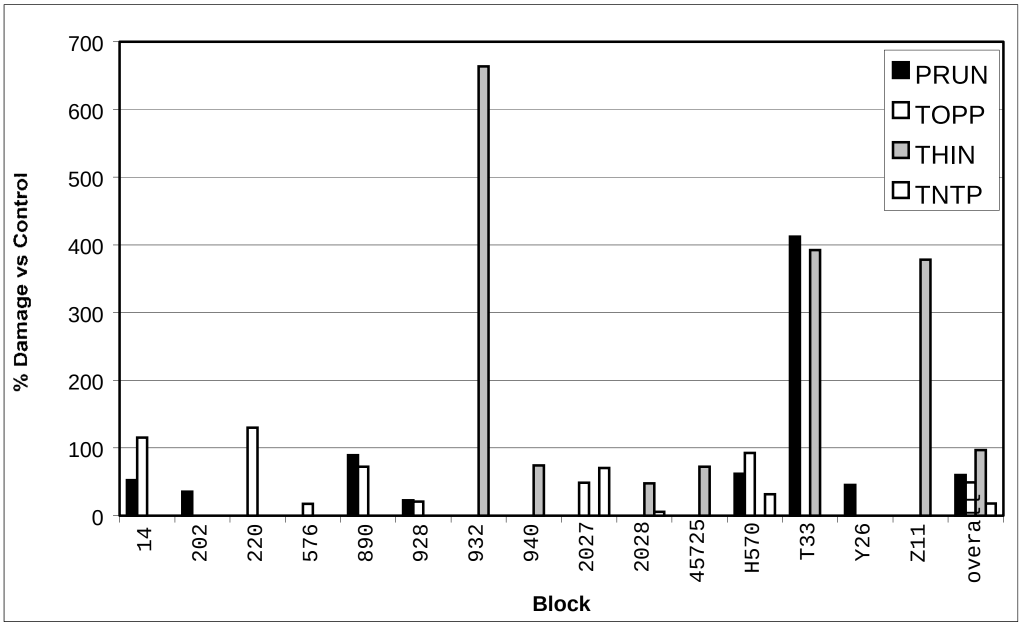

Figure 14. Ratio of damage in treatment versus control for each block by treatment type in year 1.

In this study, the helicopter-based pruning techniques were faster and less expensive per tree than manual topping techniques (Table 5). Of the two helicopter techniques, the heli-saw was faster. In this study, the heli-saw effectiveness was less affected by branch size than that of the pruning shear.

Table 5. Productivity and cost of crown modification techniques.

	Trees/hour	Cost/tree ($)
Manual Topping	1.3-1.9	46-54
Aerial Pruning - Shear	9-37	23-91
Aerial Pruning - Saw	12-44	19-68

Discussion

The limitations of the experimental design necessitate some caution in interpreting the results of the study, however some strong trends emerge. As in other studies, cedar was more windfirm than hemlock and amabilis-fir (e.g. Ruth 1976, Moore 1977, Harris 1989). Reports on the relationship between tree size and vulnerability vary in the literature. While differences in stand structure may account for some of the discrepancy, the method of analyzing results can also influence the outcome. It has been widely observed that taller stands are more vulnerable to damage (e.g. Moore 1977, Holmes 1985, Harris 1989) . This being the case, lumping trees from all sampled stands together for analysis will mask the within-stand patterns of vulnerability. In this study, no within-stand differences in vulnerability by height class were observed, but smaller diameter, more slender trees were more vulnerable. This is consistent with the findings of Cremer et al. (1982), and patterns of tree acclimation by dominance class (Mitchell, 2000).

Damage varies more from location to location, than from treatment to treatment within a given location, indicating that biophysical factors have a greater effect on vulnerability than treatments. Crown modification treatments substantially reduce but do not prevent damage. Increasing the percentage of overstory trees modified at the leading stand edge reduces damage, but it is not clear how far into the stand crown modification should extend. To-date direct mortality from the treatments is minimal, but mortality may increase in time. The mixed results from edge feathering treatments likely reflect the narrow range of tree stability in uniform stands, and indicate the need for further investigation of this treatment before it is recommended for wide application.

The helicopter and manual crown modification techniques are practical and cost efficient when applied in locations where endemic windthrow is expected to cause undesirable impacts. Treatment of newly exposed edges prior to storm winds is crucial to the effectiveness of crown modification. Techniques evolved during the period of the study and continue to develop. Manual tree climbers now rappel from tree to tree, reducing climbing and descent cycle times. This can substantially increase productivity and reduce unit costs. The helicopter techniques are faster and enable rapid treatment of freshly exposed boundaries. The heli-saw is more effective than the heli-shear in mature stands with larger branches. Newly developed helicopter-based topping devices are now in use in second growth stands.

Conclusion

Crown modification reduces damage to newly exposed cutblock boundaries when treatments are completed prior to storm winds. Helicopter based pruning and manual topping are similar in their effectiveness. Edge feathering is not consistently effective and further work needs to be done to identify where and how to apply this treatment. Biophysical factors have a greater influence on vulnerability than treatments, therefore edge modification treatments should be preceded by careful assessment and cutblock layout.

Acknowledgements

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Summary of Break-out Discussions

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At the conclusion of the workshop, presenters and attendees combined to form small breakout groups to synthesize the results of research presented at the workshop, consider revisions to management practices, and identify directions for future research. To focus discussions, participants were given a set of 'leading questions'. Each small group then presented their responses to the workshop as a whole. A summary of the responses is given below.

1. Synthesis of research results

What are the common themes in studies presented here?

- Wind and windthrow are complex. This complexity increases in irregular terrain. Damage patterns are not always obvious in small samples.
- Study results reflect local interactions of ecological and management conditions. Be cautious in applying results from one area to another.
- Most damage occurs in the first 1-2 years after harvest, however, damage is higher in years with stronger than normal winds.
- There are some species trends (e.g. redcedar dominated stands were less vulnerable to damage than hemlock dominated stands in several studies).
- Tapered trees, super-dominants, and veterans are less vulnerable to damage. When analyzing species and tree form trends, differentiate between within-stand and between-stand differences (e.g. tall stands are often more vulnerable than short stands, but tall, tapered trees within stands may be less vulnerable than other trees in the same stand).
- When documenting windthrow in partial cuts, in patches, or along cutblock boundaries, the level of damage should be compared to the background level of damage in equivalent non-harvested stands.
- Levels of damage reported in these studies are similar for different silviculture systems at a given location.
- Windthrow has not resulted in 'failed' prescriptions in any of the silviculture system trials reported here. In other words, the windthrow which occurred has not caused unacceptable impacts.
- Crown modification treatments are operationally feasible and reduce damage levels

What inconsistencies are there in the results of studies presented here?

- The relative vulnerability of different species varied from study to study.
- Higher damage on deeper soils noted in the northern Vancouver Island studies is inconsistent with the usual observation of increasing stability of deeper soils. Shallow soils in the study areas are dominated by short, open cedar dominated stands in which trees are well acclimated to wind. Deeper soils support higher density taller hemlock dominated stands in which individual trees are less acclimated to wind.
- Level of damage varies from region to region. Most of the interior BC studies reported low levels of damage. Higher levels of damage were found on northern Vancouver Island.
- Study protocols and methods of reporting results varied. Studies of damage should include site and stand descriptions and report damage as percent of stems in a given class (species, size, site etc) which are damaged.
- There is inconsistency in the use of the term windthrow risk. Some authors use 'windthrow risk' to refer to the probability of a given level of damage, and use the term 'windthrow impacts' to refer to the consequences of a given level of damage. Others use 'windthrow risk' to refer to the interaction of probability of a given level of damage and consequences (e.g. windthrow risk is 'high' if there is low damage probability but significant consequences, or if there is a high level of damage but lower consequences).

Do any of these results challenge past understandings of windthrow?

- Alternative silviculture systems have not resulted in "everything falling down” as was expected.
- The unexpected relationship between soil depth and damage on northern Vancouver Island, highlights the importance of analyzing the separate components of windthrow risk (e.g. stand, soils, topography, management actions).
- Open grown trees can be stable even on low strength soil materials. Analysis of tree and stand vulnerability to damage requires consideration of both the biology of acclimation and the mechanics of wind loading and resistance.

To what degree is wind damage affecting forest level plans, and stand level prescriptions?

- The annual volume losses reported in most studies are smaller than anticipated.
- Cumulative damage may become significant over time.

- In most studies, damage is not significantly impacting forest level plans or stand level prescriptions.
- The threshold level for acceptable damage may be higher than anticipated. However, the impact of windthrow on non-timber values needs further investigation.
- Damage to clearcut boundaries and riparian reserves is significant in the northern Vancouver Island studies and is affecting forest level and stand level objectives.
- There are various categories of losses including: gross volume damaged, volume damaged in excess of that accounted for by Operational Adjustsment Factors (OAFs), volume not-recovered by salvage etc.
- Second growth stands are vulnerable to windthrow.
- There is no province-wide system for documenting or reporting windthrow losses.
- More knowledge of stand level risk factors is already leading to better prescriptions.

2. Recommendations for management.

(Note: these recommendations reflect the results of studies presented at the workshop and are intended to enhance or clarify the more comprehensive list in Section 6 of the Windthrow Handbook for BC Forests.)

How much windthrow is too much?

- It depends on stand and forest level management objectives, and the consequences of damage on these objectives.
- Some consequences are easy to predict (e.g. bark beetles), while others (e.g. public perception) are harder. More work needs to be done on ecological impacts.
- Windthrow is a natural process. Consider ecological role of coarse woody debris and soil turnover.
- Need to know background level of damage in unmanaged stands, volume affected and size distribution of patches.
- Depends on ease of salvage, and the consequences of salvage on management objectives.

- Need to incorporate acceptable level of damage (‘tolerance’) into prescriptions.

What types of trees are the most windthrow resistant? (in partial cuts, along boundaries)

- Superdominants and veterans are more resistant than dominants and codominants. Differences are subtle within uniform canopied stands.
- Mature/old growth cedar, Douglas-fir are more windfirm than hemlock and *abies*, but differences in species resistance varies with site and stand conditions.
- Dispersed trees are more vulnerable than grouped trees.
- The best strategy is to examine damage by tree class on a site by site basis.

What management techniques are most effective at reducing wind damage?

- Crown modification is effective, but long term (>4 year) effects on tree health are still unknown and treatments must be complete before the first strong winds.
- Identify depth of penetration of damage into reserves/boundaries and increase reserve group size to increase ratio of interior to edge.
- Align groups parallel to the wind direction, and round corners of reserve groups.
- Use veterans and superdominants for dispersed reserves where possible.
- Increase shelter provided by upwind timber by keeping openings less than 5 tree lengths wide, and parallel to the wind direction.

What salvage strategies are best for reducing future windthrow risk?

- Partially salvage boundaries to leave natural feathering.
- Retain leaners and trees with broken crowns where possible.
- Minimize ground disturbance near trees to be retained.
- Keep access open to facilitate salvage.

How should stands be managed in long term to reduce future windthrow risk?

- Build database of local/regional windthrow patterns.
- Use computer models based on good empirical data and an understanding of biological and mechanical processes.

- Anticipate and adapt to future forest/social conditions.
- Incorporate windthrow risk into prescription design.
- Be cautious of over-prescribing expensive crown modification treatments.

3. Directions for future research.

How can we make windthrow risk assessment more quantitative?

- Identify key components of windthrow risk which need further study.
- Have coordinated team of researchers working on the problem.
- Use easily obtained inputs in models. Take advantage of current data collection processes (engineering, cruising, prescription). Incorporate wind records and evidence of past windthrow.
- Use empirical or mechanistic models to provide quantitative predictions of damage likelihood and severity under different management scenarios.
- Have a single, easily interpretable model output which is relevant to operational forestry.
- Work at regional, local, stand, and tree levels.
- Build landscape scale maps of windthrow hazard using GIS software.
- Test model portability and validate in new areas.
- Provide simple, useful tools for stand-level diagnosis and prescription design.
- Set-up a feedback process so the outcomes of management are used to refine models.

What major topic areas need further investigation?

- Background level of windthrow from endemic and catastrophic events in unmanaged stands.
- Quantify recovered and non-recovered losses from endemic and catastrophic events in managed and unmanaged stands.
- Ecological role of windthrow in unmanaged stands.
- Impacts of windthrow on riparian reserves, biodiversity, slope stability etc.
- Develop risk models which unify ecological and physical principles.
- Use of remote sensing for damage detection and mapping.
- Indicators of individual tree vulnerability.

- Rooting properties of different soils.
- Tree growth rates and wind resistance.
- Effects of fertilization.
- Vulnerability of stands with different structures and composition.
- Reserve design.
- Edge design and treatment.
- Windthrow management and salvage strategies for riparian reserves.
- Long term effects of crown modification.
- Windthrow and bark beetle dynamics.
- Windthrow and fungal pathogens.
- Wind vs. snow damage vulnerability.
- Windthrow and other natural disturbance processes.
- Windflow over terrain, within openings and within stands.

What opportunities are there for collaborative projects?

- Incorporate knowledge from urban forestry/arboriculture.
- Link with windthrow research groups elsewhere e.g. Quebec, UK, New Zealand, Scandinavia.
- Build interdisciplinary research team.
- E-mail list/newsletter.
- Annual meeting with field tour in different parts of the province.
- Seek strategic funding.

List of Participants

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