ASSESSING AND PROMOTING WINDFIRMNESS IN CONIFERS IN BRITISH COLUMBIA

by

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ABSTRACT

Windthrow is a natural disturbance agent which disrupts forest and stand level plans in British Columbia (BC). The objectives of this thesis were to: i) review the factors contributing to windthrow risk in BC, ii) investigate patterns of stem growth in conifers following thinning and consider their use for diagnosing windfirmness; and iii) present a diagnostic method of assessing windthrow risk suited to the heterogeneity of BC's forests.

Stem analysis was used to reconstruct the post-thinning stem growth patterns for 25 Sitka spruce (*Picea sitchensis* (Bong.) Carr.) from a coastal stand which was thinned in 1980, and 45 Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) from a stand on the interior plateau with 1978 and 1984 thinned portions. Both stands had very high initial densities and sample trees represented a range of stem slenderness in the thinned and control portions. Following thinning, height increment was temporarily reduced, radial increment increased and the allocation of radial increment became more basal in each of the three thinning treatments. The post-thinning stem slenderness curves were reverse-S in shape with initially more slender trees showing the greatest decline.

Critical turning moments of 36 Douglas-fir trees winched to failure were related to tree size. With a uniform wind profile over the crown length, critical wind speed declined with slenderness. The relationship between safety factor and slenderness varied between treatments depending on the attenuation of the within-canopy wind profile. The short term growth responses, their relationship with initial stem slenderness and the shape of the slenderness adjustment curves suggested a pattern of form re-equilibration following thinning. It appears that observation of the magnitude and duration of post-thinning stem form adjustment is a useful diagnostic tool for scheduling subsequent thinning entries in stands with high initial slenderness, and for identifying more vulnerable trees.

Forest managers in BC use a system of site and stand diagnosis during the preparation of stand level prescriptions. A diagnostic framework for windthrow risk is presented which can be incorporated into the prescription process. In this framework, the principle of acclimative growth is used in assessing the stand hazard and treatment risk components of windthrow risk. Recommendations are made for a comprehensive program of windthrow management.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol or Abbreviation	Units	Term; Synonyms Used in Text; *Definition*
BC		British Columbia
BCMOF		British Columbia Ministry of Forests
AAC	m3	Annual Allowable Cut; *total annual harvest volume from crown lands in BC*
AES		Atmospheric Environment Service
Topex		Topographic Exposure Score; *sum of angle to skyline in 8 cardinal directions, with negative angles=0*
CON		Control treatment - Sitka spruce or Douglas-fir Sites
THIN or J80		1980 thinning treatment - Sitka Spruce Site
J78		1978 thinning treatment - Douglas-fir Site
J84		1984 thinning treatment - Douglas-fir Site
DBH, dbh	cm	diameter breast height (at 1.3m up stem); diameter; *measured outside of bark*
HTINC	cm	annual height increment of stem; height growth; *leader extension in one year*
RVSA	cm	specific volume increment; ring thickness; radial increment; *current years ring volume/previous years bole surface area*
RV50		basal allocation; allocation; *ratio of ring volume in lower half of stem to ring volume in upper half*

RHTINC		relative height increment; *HTINC / 3 year pre-treatment mean HTINC*
RRVSA		relative radial increment; *RVSA / 3 year pre-treatment mean RVSA*
RRV50		relative longitudinal allocation; *RV50 / 3 year pre-treatment mean RV50*
HDR		height-diameter ratio; slenderness coefficient; slenderness; *total height / diameter at breast height*
HDRIB		height-diameter ratio inside bark; *total height / diameter at breast height inside bark*
TRVOL	cm^3	tree volume
U	m/s	horizontal wind speed
Ucrit	m/s	critical wind speed; *wind speed sufficient to cause uprooting or stem failure*
Uh	m/s	horizontal wind speed at top of canopy
Uz	m/s	horizontal wind speed at height 'z'
z	m	height above ground
α		attenuation coefficient; *a measure of the rate of decline of within-canopy wind speed with height*
Fd	N	drag force on tree crown; wind drag
Mw	N m	wind induced turning moment at base of tree
Mg	N m	gravity induced turning moment at base of tree

x_z	m	horizontal displacement of stem at height 'z'
Ma	N m	applied turning moment at base of tree; *turning moment acting on tree as a result of wind drag and self loading*
Mr	N m	resistive turning moment at base of tree; *resistance to bending due to bole, root, and root-soil strength*
Mc	N m	critical turning moment; *maximum turning moment which tree can withstand without failing*
SF		safety factor; *Mr/Ma*
SPH, sph	#/ha	stems per hectare
BA	m2/ha	stem basal area per hectare
HT	m (cm)	tree height
DBHtop	cm	diameter breast height for top height trees
Httop	m	tree height for top height trees
LCR		live crown ratio; *crown length / total height*
y		response variable (e.g. HTINC, RVSA, RV50)
y_t		response variable in year 't'
y_{t-1}		response variable in Year 't-1'
IHDR		height-diameter ratio inside bark at time of thinning; initial HDR, initial slenderness
IDIB	cm	diameter breast height inside bark at time of thinning; initial DIB, initial size
b0		y-intercept for linear regression

b1	slope of linear regression
p	probability value
R^2	coefficient of determination
Hw, Ss, Fd, Pl	western hemlock, Sitka spruce, Douglas-fir and lodgepole pine, respectively
CWH, IDF	Coastal Western Hemlock, and Interior Douglas-fir biogeoclimatic zones, respectively

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CHAPTER 1 - INTRODUCTION

1.1 Problem Statement

Windthrow is a natural disturbance agent in British Columbia's (BC's) forests that frequently influences the outcome of silviculture prescriptions and the achievement of the desired stand conditions. While damaging wind events are common in many areas of BC, provincial statistics are not routinely compiled or published. Damage estimates derived from a BC Ministry of Forests census of windthrow in 1992 indicated that a volume of timber equivalent to 4.2% of BC's annual allowable cut was windthrown in one year. Windthrow results from complex interactions of climatic, edaphic, stand, and management factors. While the mechanics, general ecology and principles for reducing windthrow are documented in the international literature, management of windthrow in BC has been hampered by the lack of systematic documentation of damage, and lack of a risk assessment approach suited to the diversity of BC's forests and the skills of forest managers. Identification of windthrow as a 'forest health factor' in the BC Forest Practices Code and a requirement for stand level assessment of windthrow risk in silviculture prescriptions has provided impetus for development of windthrow assessment tools and new management strategies.

From a biological standpoint, windthrow is a problem of tree acclimation to periodic peak wind loads. Short return period peak winds rarely damage healthy open grown trees, whereas they often damage trees along stand edges recently exposed by harvesting, or within stands opened up by thinning. A relationship between stocking and windfirmness has been reported in the literature. The terms 'acclimative' or 'adaptive' growth are commonly used to refer to the short term growth responses of trees following changes in wind or mechanical loading.

However the long term pattern of tree growth responses following a change in loading, and the potential diagnostic value of these growth patterns for assessing windfirmness have not been evaluated.

1.2 Objectives

The objectives of this thesis were to: i) review the factors contributing to windthrow risk in BC; ii) investigate post-thinning growth patterns in trees with different initial taper for evidence of acclimative growth, and to consider the utility of these patterns for diagnosis of windfirmness; iii) identify the components of a comprehensive approach to windthrow management and present an assessment method suited for current use in BC.

1.3 Approach to the Problem

The thesis commences with a review of the windthrow literature in Chapter 2. The review focuses on the mechanics and ecology of windthrow, consistent trends and inconsistencies in risk factors identified in local studies, and tree acclimative responses to wind loading.

Chapter 3 investigates the post-thinning tree growth responses of trees from stands with high pre-treatment densities for evidence of acclimative growth, and for long term effects on stem slenderness. Twenty-five Sitka spruce (*Picea sitchensis* (Bong.) Carr) trees were obtained in 1993 from the 1980 thinned and un-thinned portions of a 47-year-old Sitka spruce-western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) stand in the Queen Charlotte Islands. Forty-five Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) trees were obtained in 1994 from 1978 thinned, 1984 thinned and un-thinned portions of a 52-year-old Douglas-fir stand near 100 Mile House. Both stands had very high mean tree slenderness (ratio of mean tree height:mean tree breast height diameter (HDR)) prior to thinning. Current crown attributes were measured. Stem analysis was used to reconstruct past stem form. Thirty-six of the Douglas-fir trees were winched over prior to collection of stem samples in order to determine the critical turning moment. The principal research questions investigated were: i) were the longitudinal and radial growth patterns in the years following spacing consistent with short term responses to mechanical or wind loading reported in the literature, ii) how did the growth responses change in the years following thinning and what was their combined effect on stem slenderness, iii) how did the growth responses vary with initial slenderness from year to year?

The components of a comprehensive program for windthrow assessment and management in BC are discussed in Chapter 4. Systematic assessment of windthrow risk is a key component of this program. Existing windthrow assessment approaches are reviewed and a diagnostic approach to windthrow assessment designed for general use by BC forest managers is introduced. The assessment of stand hazard in the diagnostic approach is based on the premise that open grown trees acclimate to routine wind loads.

This research makes a number of contributions including: i) demonstration of the patterns of height increment, radial increment and longitudinal allocation following thinning in very high density stands, their contribution to form adjustment, and how they vary with initial slenderness; ii) identification of height-diameter ratio adjustment as a means of diagnosing tree re-equilibration with post thinning wind loads; iii) introduction of a new diagnostic framework for windthrow risk evaluation.

CHAPTER 2 - LITERATURE REVIEW[1]

2.1 Windthrow Occurrence, Impacts and Management in British Columbia

2.1.1 Extent of Forest Resource and Responsibilities for Management

2.1.1.1 Biogeoclimatic Zones

British Columbia (BC) is a geographically diverse province with a total land area of 948 600 square kilometers. The province is divided into five physiographic regions (Valentine et al. 1978): the Coast Mountains and Islands, the Interior Plateau, the Columbia Mountains and Southern Rockies, the Northern and Central Plateaus and Mountains, and the Great Plains. Since the mid-1970's BC's forests have been managed within an ecosystem classification and interpretation framework. The classification system is based, with some modifications, on the work of Krajina (1965, 1973) and incorporates climate, soil and vegetation data. Twelve forested biogeoclimatic zones are recognized, each characterized by a distinct climax forest community on zonal sites where soil conditions reflect regional climate.

2.1.1.2 Land Ownership and Tenure

The provincial government owns 95 percent of BC's estimated 47.4 million ha of productive forest land (Watts 1983). The BC Ministry of Forests (BCMOF) administers six Forest Regions (Figure 2.1) each of which are further sub-divided into Forest Districts. Cutting rights to crown timber are held by forest products companies under various forms of tenure. These include volume based Forest Licences, and area based Tree Farm Licences. Licensees are responsible for harvesting and reforestation under BCMOF supervision.

[1] Modified sections from this chapter are published as Chapter 25 in Wind and Trees. Cambridge University Press (S.J. Mitchell 1995a)

2.1.1.3 Utilization

BC's timber inventory is dominated by previously unmanaged mature and over-mature age classes. The annual allowable cut (AAC) from Crown Land in 1992 was 74.4 million cubic meters, this declined to 60 million cubic meters in 1998 due to withdrawals from the forest land base and increased retention of reserve areas within areas available for harvest. While the majority of the area harvested annually in BC is clearcut (BCMOF 1992), partial cutting is well established in the dry Douglas-fir and western larch forest types of the southern interior (De Long 1991), and is being extended to other forest types. The proportion of the area partially cut is expected to increase as the industry responds to public demands for increased emphasis on biodiversity and aesthetics (Canadian Pulp and Paper Association 1992). To date commercial thinning is localized and provides a very small amount of timber. This is expected to change if the economics of harvesting and manufacturing small logs improves (J.L. Mitchell 1996). In 1990, the Research Branch of the Ministry of Forests established the Silviculture Systems Program to investigate alternatives to conventional clearcutting. This program funds research, development, demonstration and extension of partial cutting systems in each Forest Region.

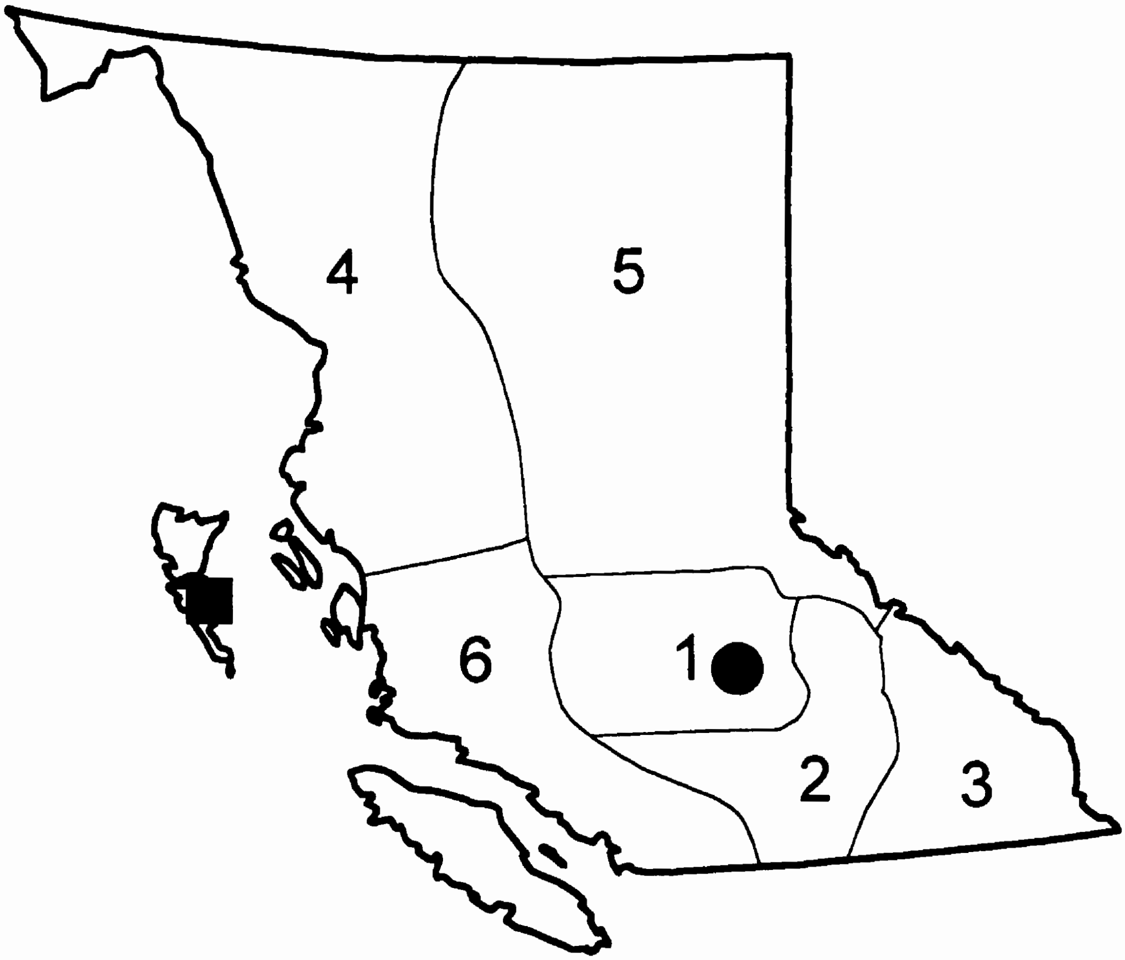


Figure 2.1: Map of British Columbia showing the Forest Regions and study sites: 1 Cariboo, 2 Kamloops, 3 Nelson, 4 Prince Rupert, 5 Prince George, 6 Vancouver. Location of Sitka spruce study site (■), and Douglas-fir study site (●).

2.1.2 Impacts and Occurrence of Windthrow in BC

2.1.2.1 Impacts of Windthrow

Windthrow is a natural disturbance agent in forest ecosystems (Schaetzl et al. 1989). Mergen (1954) reported that the U.S. Forest Service estimated timber losses caused by wind damage to exceed the annual loss from fire, accounting for 2.5% of the annual drain on timber resources. In a 7-year study in southeast Alaska, Hutchison and LaBau (1975) found that windthrow was responsible for 26% of the annual tree mortality. Windthrow contributes to turnover of forest soils and variability in soil microtopography and microsites (Cremeans and Kalisz 1988), and influences the structure and distribution of stands in windy environments such as the northwest coast (e.g. Nowacki and Kramer 1998).

Major categories of impacts include economic losses, increased risk of damage to timber, ecological damage, and aesthetic impacts. Negative impacts occur when wind damage conflicts with forest or stand level management objectives (e.g. Benskin 1975). Disruption of forest level plans includes revision of harvest boundaries, loss of corridors and buffers, reconstruction of access, modification of schedules and remobilization, reduction of forested area. Disruption of stand level plans includes damage to boundary trees and increase in opening size, and loss of within block reserve trees (Figure 2.2).

There have been few studies in BC into the site level impacts of windthrow. Tripp et al. (1992) note that out of their sample of 20 stream-side reserve strips within Vancouver Island cutblocks harvested between 1988 and 1992, 19 had windthrow with an average percentage of blowdown of 18.9%, of which 16.2% was in-stream. Tripp et al. describe these percentages as 'fairly low' implying that they are acceptable, and recommend that in-stream windthrow be left in place unless it can be shown to have a negative impact on fish productivity. Carr and Wright (1992) identify windthrow triggering as the probable cause of two land slides out of 49 observed erosion sites in their disturbance inventory of the partially logged Shomar Creek drainage in the Queen Charlotte Islands.

2.1.2.2 Documentation of Windthrow in BC

Statistics on major sources of damage to BC forests such as insect damage, wildfire, root-decay and mistletoe are collated and summarized by the BCMOF in their annual reports (e.g. BCMOF 1992). Wind damage occurrence is not routinely compiled or reported in BC, and no published estimates of the level of damage are available. There is no formal system for monitoring or collecting statistics on annual windthrow losses across the province and province wide statistics of windthrow occurrence are not compiled (J. Henigman BCMOF, Victoria, personal communication 1998). Individual companies and forest districts carry out annual windthrow surveys, typically in late winter or spring, to document and plan salvage of damage from winter storms. Where special salvage permits are issued for windthrow recovery, volumes could be determined from stumpage receipts, however this would represent only a portion of total windthrow salvaged. In coastal BC edge windthrow is often included in second pass cut blocks and is not tallied separately from undamaged volume. There is no systematic documentation of unsalvaged windthrow or of the proportion of greenwood in salvage volumes.

Figure 2.2: Example of windthrow along a recently harvested clearcut boundary in a second growth Douglas-fir stand in coastal BC.

2.1.3 BCMOF 1992 Windthrow Census

2.1.3.1 Objectives and Methods of Census

In August 1992 the BCMOF conducted a province wide census of wind damage and salvage. Each Forest Region was sent a memo containing a questionnaire on windthrow occurrence and salvage (Appendix A - Table A.1). The Regions passed the questionnaire along to each Forest District to complete, and the Districts compiled answers from ministry and local licensees. The data were largely obtained through aerial and ground reconnaissance and represent the best estimates of local licensee and ministry staff. A few districts that traditionally had low windthrow occurrence and which did not conduct district wide surveys, provided current year estimates based on typical levels of damage in previous years. The respondents' comments provide insights into factors constraining windthrow management and attitudes towards windthrow (Appendix A - Table A.2). The results of the census were not published by the BCMOF. District and Regional summaries were provided to the author by John Howe, Timber Administration Officer, BCMOF Vancouver Forest Region.

2.1.3.2 Results of Census

The total volume of non-viable windthrow, mean patch size of non-viable windthrow and year 1 and 2 planned salvage volumes are summarized by Region in Table 2.1. Windthrow was considered commercially 'viable' if it was accessible, could be salvaged at a profit, and if salvage would not conflict with other resource management objectives. 'Green' timber volume refers to undamaged timber included within salvage permits. These values are expressed as proportions of total damage in Table 2.2. The proportion of Regional AAC affected by windthrow, fire and insects is summarized in Table 2.3 along with the contribution of each Region to provincial AAC.

Table 2.1: Summary of volumes and patch sizes reported in BCMOF 1992 windthrow census.

Region	Regional AAC 1992 (m^3)	Non-viable windthrow[1] (m^3)	Mean size non-viable patches (ha)[2]	Planned salvage yr1 (m^3)[3]	Planned salvage yr2 (m^3)[3]
Cariboo	8 415 000	10 000	0.25	465 729	93 585
Kamloops	8 027 000	162 150	2	1 160 834	282 045
Nelson	6 487 000	117 400	1.5	640 898	270 986
Pr.George	18 520 000	66 500	0.5	403 873	55 048
Pr.Rupert	9 256 000	242 000	5	166 800	57 500
Vancouver	23 741 000	526 725	2	1 162 974	1 214 197
Province	74 446 000	1 124 775	1.9	4 001 108	1 973 361

[1] Non-viable windthrow will not be salvaged due to low profitability or conflict between harvesting and non-timber management objectives.

[2] The mean size of contiguous areas (patches) of windthrow which were not viable for salvage.

[3] Due to seasonal harvesting constraints, access construction and administrative delays, some of the viable windthrow reported will not be salvaged until the second year after detection.

Table 2.2 : Regional and provincial summaries of non-viable, green and first year salvage as proportion of annual allowable cut.

Region	Non-Viable[1] (%)	Green[2] (%)	Plan 1st Year[3] (%)
Cariboo	2	20	83
Kamloops	10	25	80
Nelson	11	38	70
Pr.George	13	14	88
Pr.Rupert	52	47	74
Vancouver	18	56	49
Province	16	41	67

[1] Proportion of wind damaged volume which is non-viable. [2] Proportion of green timber in salvage volume. [3] Proportion of salvage volume planned for harvest in first year.

Table 2.3: Proportion of Regional and Provincial annual allowable cut affected by windthrow, fire and insects.

Region	Regional AAC	Non-Viable	Viable Year 1	Windthrow	Wildfire [1]	Insect [1]
	% Prov AAC	% of Regional AAC				
Cariboo	11	0.1	4.4	4.5	1.5	1.3
Kamloops	11	1.6	10.9	12.5	0.4	12.0
Nelson	9	1.3	6.1	7.4	0.3	6.3
Pr.George	25	0.3	1.9	2.2	9.7	11.3
Pr.Rupert	12	1.9	0.9	2.8	4.1	0.7
Vancouver	32	1.1	2.2	3.3	5.8	0.1
		% of Provincial AAC [2]				
Province	100	1.0	3.2	4.2	5.0	4.9

[1]From BCMOF 1990-91 Annual Report Tables E-4 and E-6 (BCMOF 1992).
[2]Provincial averages determined from regional values weighted by regional cut.

2.1.3.2.1 Volume Affected by Wind Damage

The following assumptions were made in interpreting volumes of windthrow reported in the census: i) windthrow reported is current and potentially viable (e.g. not old decayed material); ii) it represents a pool with annual inputs of new windthrow, outputs of salvaged windthrow, and a component of non-viable windthrow; iii) annual salvage kept pace with new inputs. Given these assumptions, the annual salvage volume was taken to indicate one years worth of viable windthrow. The planned salvage in year 1 of the harvest plan was 4 001 108 m^3 (Table 2.1). This represented 67% of the volume planned for salvage in years 1 and 2 (Table 2.2). Of the volume scheduled for salvage 41% was green, leaving 59% as wind damaged (Table 2.2). Wind damaged volume scheduled for harvest in year 1 was therefore 2 360 653 m^3, a volume equivalent to 3.2% of the annual allowable cut. The total non-viable windthrow reported was

1 124 775 m^3. Using the same assumption as above, that 67% of this volume represents current years damage, there was 753 599 m^3 of current non-viable damage, equivalent to 1% of the annual allowable cut.

Combining year 1 salvage windthrow and year 1 non-viable windthrow yielded a damaged volume of 3 114 253 m^3, which was equivalent to 4.2% of the provincial AAC (Table 2.3). The Kamloops and Nelson Regions had the highest levels of damage, reporting damaged volumes equivalent to 12.5 and 7.4 percent of their respective regional AAC's. These high proportions reflected damage caused by a major storm in October 1991 in the southern interior of the province. The Prince George and Prince Rupert Regions reported the lowest proportions of wind damaged timber. Provincial figures for timber damaged by wildfire and insects obtained from the BCMOF Annual Report for 1990-91 (BCMOF 1992) indicated volumes equivalent to 5.0 and 4.9 percent of provincial AAC respectively.

2.1.3.2.2 Windthrow Viability and Salvage

The proportion of windthrow considered commercially viable (Table 2.2) varied from Region to Region as did minimum viable patch size. Respondents indicated that easier access and increased risk of bark beetle outbreaks contributed to smaller minimum patch sizes in the Cariboo and Prince George Regions. Reasons cited for the non-viability of windthrow included stands with a low proportion of damage, isolated patches with high access or mobilization costs, inoperable areas, areas which were unavailable due to unresolved integrated resource management or community issues, areas detected too late where the timber had deteriorated, and fringe damage adjacent to regenerating areas where salvage would cause unacceptable damage to the young stands (Appendix A - Table A.2).

Salvage was generally completed within one year of detection. The highest proportion of first year salvage was in the Prince George and Cariboo Regions. Respondents indicated that this was motivated by desire to salvage wood prior to deterioration and before bark beetle flight. More difficult access, more complex integrated resource management issues, and prolonged negotiations over valuation were reasons cited for slower salvage in the Prince Rupert and Vancouver Regions. In some Regions, salvage was delayed until sites or access were snow free. The Quesnel District reported that little deterioration of wood quality (staining or bark loss) had occurred during the two years it took to complete salvage of the 1990 wind storm damage.

In many cases a portion of green standing timber was harvested along with the windthrown timber. The highest proportions of green wood were included in the Vancouver Region, and the lowest in the Prince George and Cariboo Region (Table 2.2). Most Regions indicated that windthrow salvage areas were clearcut. Standing green timber was removed for operational and safety reasons, to enable establishment of windfirm boundaries, or to avoid isolation of small patches of timber.

2.1.3.3 Limitations and Implications of Census Results

The census data is included in this thesis to provide an indication of the magnitude of the windthrow problem, and illustrate some basic issues in windthrow management in BC. The census figures were rough estimates of volume damaged, based primarily on aerial and roadside reconnaissance. Losses of trees dispersed within standing timber were not included. The census was carried out subsequent to major wind storms in May of 1990 in the central interior and October 1991 in southeast BC, and likely reflected higher than normal levels of damage in those regions. Accepting these limitations, windthrow was of the same order of magnitude as damage by wildfire and insects, affecting significant volumes of timber in each Region, one quarter of which was not planned for salvage. While additional years data are needed to verify the average yearly damage, the census results indicate that a more systematic approach to windthrow documentation, risk assessment and management is warranted.

2.2 Mechanics and Ecology of Windthrow

2.2.1 Windthrow Defined

2.2.1.1 Windthrow and Windsnap

Windthrow occurs when the wind load acting on a tree exceeds the anchoring ability of the root-soil system and the tree uproots. Windsnap is a special case of windthrow in which the stem fails (Mayer 1987; Shaetzl et al. 1989). Stem breakage normally initiates from compression failures in the leeward side of the stem. Conifers injured in this way but without complete breakage form scar tissue and compression wood over the failures and are prone to further wind damage (Mergen 1954). Putz et al. (1983) studying windthrow and windsnap in a multi-storied forest in Panama found that snapped trees were smaller, had less taper, lower moduli of rupture and elasticity, and less dense wood than windthrown trees, but no consistency was found in height of breakage. Mattheck and Bethge (1990) found that buttressing reduced the risk of failure by delamination at the root collar. Mattheck et al. (1995) found that trees with central stem decay were likely to fail once the ratio of sound perimeter thickness to stem radius was less than 32%. The term windthrow is also used synonymously with the term 'blowdown' as a general term to describe all forms of tree uprooting and breakage by wind.

2.2.1.2 Endemic and Catastrophic Damage

Miller (1985) distinguishes between catastrophic windthrow and endemic windthrow in Britain. Endemic windthrow occurs during annual winter gales and damages susceptible plantations each year throughout upland Britain. Catastrophic windthrow occurs during windstorms with long recurrence intervals and causes severe localized damage to both open grown and stand grown trees along the storm path. Mayer (1987) indicates that uprooting is more common during endemic events and that the proportion of stem breakage is higher in catastrophic events. Studying damage in riparian reserves on Vancouver Island, Moore (1977) found that windthrow was more the result of trees that had long been protected from the full force of the wind, suddenly being exposed, than of excessively strong or freak winds. Because of its frequent recurrence and wider extent, windthrow risk assessment has traditionally focused on prediction of damage from endemic winds (Miller 1985).

2.2.2 Mechanics of Windthrow

2.2.2.1 Critical Turning Moment

The 'moment' of a force about a given point provides a measure of the tendency of the force to cause a body to rotate about the point. It is the product of the force and the length of the lever or 'moment arm' to the point of rotation. Tree failure occurs when applied moments exceed resistive moments. The critical turning moment is the maximum turning moment that the root-soil anchorage or stem section can resist without failing (Figure 2.3). The strength of a stem section is determined by stem dimension, shape, elasticity and strength in compression (Mergen 1954). The strength of root anchorage is determined by root architecture, root strength in extension and compression, root-soil cohesion and soil cohesion. The strength of the root-soil anchorage may decline during windthrow events as trees rock back and forth, particularly when soils are saturated (Coutts 1983). Critical turning moments measured with static winching experiments have been found to be proportional to tree mass (e.g. Fraser 1962), and to stem diameter at breast height cubed (e.g. Blackburn et al. 1988). The relationship with stem diameter cubed is expected, as the strength of a cylinder in bending is proportional to radius cubed.

2.2.2.2 Critical Wind Speed

The critical wind speed is the wind speed that is sufficiently strong to cause tree failure. It is determined by the balance between applied moment and resistive moments and is the wind speed at critical turning moment. The applied moment is determined by the wind speed profile, the crown profile, crown drag coefficient, gusting and damping (Blackburn et al. 1988) (Figure 2.3). Wind drag on tree crowns has been measured empirically by placing crowns or branches in wind tunnels (Mayhead et al. 1975), and by simultaneous measurement of wind speed and tree deflection (Papesch 1977). Researchers commonly estimate crown drag from wind speed profiles, crown projected area and crown drag coefficients (e.g. Smith et al. 1987; Fredericksen et al. 1993).

2.2.2.3 Probability of Critical Wind Speed

The probability of winds of critical speed occurring at a given location can be determined through analysis of climate records where appropriate records are available (e.g. Murphy and Jackson 1997). The annual probability of windthrow for a given site is the inverse of the return period of the critical wind speed. However, stations with long term records are often located at airports, communities or lighthouses. In forest settings in BC, there are often no nearby stations. There are a variety of approaches for estimating local wind regimes and these are discussed below.

2.2.3 Ecology of Windthrow

2.2.3.1 Pattern

The extent and severity of windthrow in forests varies in space and time as function of climatic, topographic, stand and soil features. Windthrow occurs where high winds act on vulnerable stands. Local wind regime is determined by the interaction of regional climate and local topography. Stand vulnerability is determined by stand age, composition and structure, by the characteristics of the soil in which the trees are rooted, and by treatment history. In the following sections, wind characteristics and the wind regime experienced in BC are reviewed. The contributions of site, stand and management factors to stand vulnerability are then discussed.

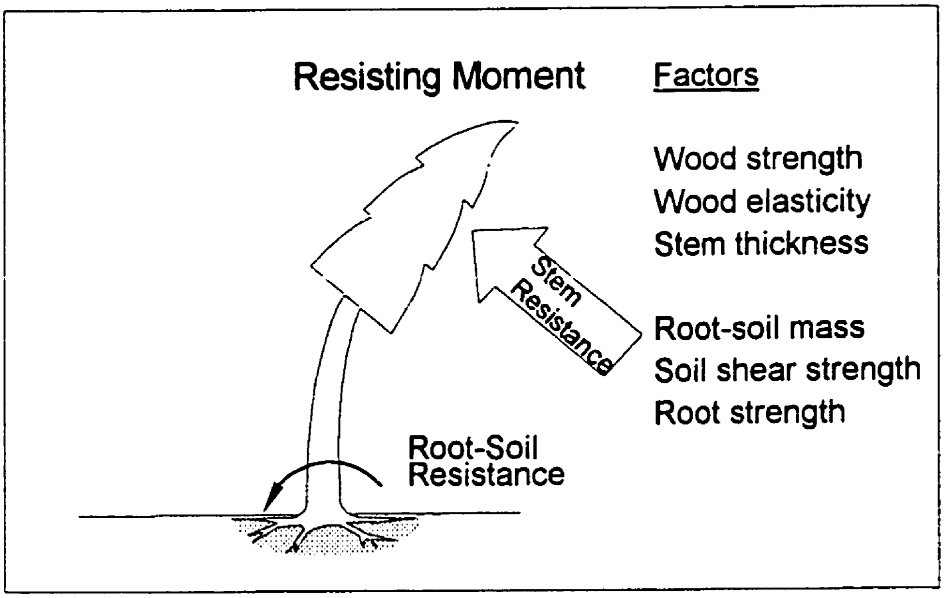


Figure 2.3: Factors affecting the resistance to wind and gravitational forces acting on a tree.

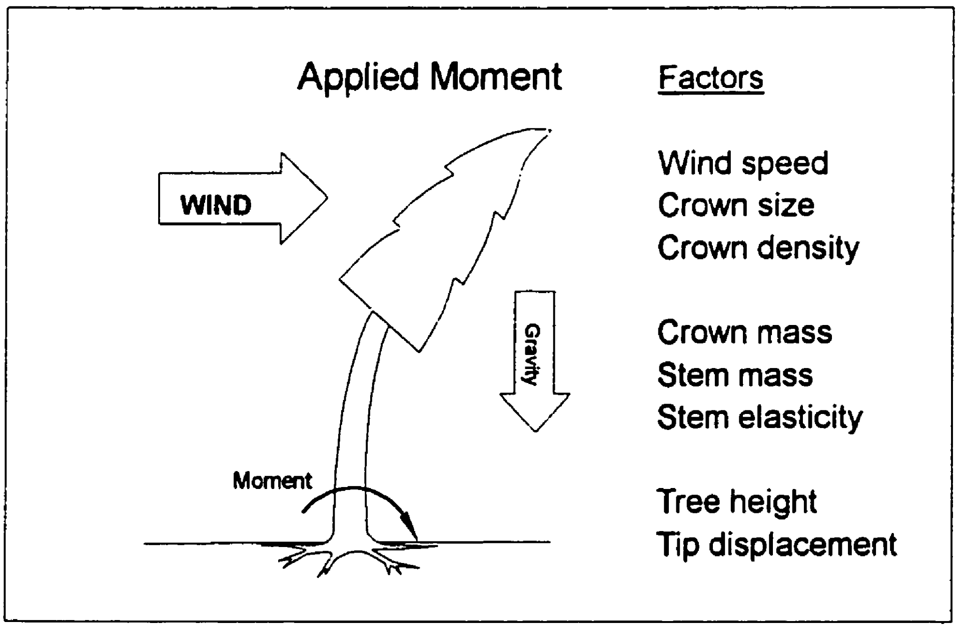


Figure 2.4: Factors affecting the wind and gravitational forces acting on a tree.

2.2.3.2 Wind Characteristics

2.2.3.2.1 Sources of Peak Winds

Grace (1977) distinguishes between 'free atmospheric' and 'surface' winds. In the free atmosphere, winds are driven by the large scale distribution of atmospheric pressure. Surface winds are modified by topography and low-level surface flow is modified by surface roughness.

Two basic measures are used in discussing wind speeds in the literature. The 'hourly mean wind speed' is normally based on 1-5 minute integration periods averaged over the hour, or on hourly wind run. 'Gusts' are instantaneous peaks for which the integration periods are in the order of 3 seconds and depend on the sensitivity of the instrument. In BC the Atmospheric Environment Service (AES) of Environment Canada maintains climate stations and collates station data throughout the province. The BCMOF collates data from forest fire weather stations, but few of these stations are monitored year round and wind speed is recorded only at noon each day. As a consequence these stations are not useful for windthrow risk assessment. Many AES weather stations do not record wind continuously. The reported 'hourly mean wind' is actually a 1-2 minute reading taken on the hour and the 'gust' is the peak instantaneous reading that occurred during the 15 minutes prior to the hour (E. Coatta AES Vancouver, personal communication 1992). Wind directions are recorded in 8 directions and refer to the direction from which the wind is blowing.

2.2.3.2.2 Wind Storm Periodicity

The probability that trees at a given site will experience winds strong enough to cause damage is determined by the periodicity of peak mean winds and gusts. Calculating the return period of peak winds is a form of extreme value analysis. Analysis of an observed sample of peak winds allows generalizations about the likely frequency of recurrence for events as large as have been recorded, and potentially extrapolations to the likely frequency of events not yet recorded (Flesch and Wilson 1993). The most common model for fitting extreme value distributions is the exponential or 'Gumbel' distribution, and the dataset must meet three requirements: the variable to be examined is a random statistical value; there is no time trend in the data; and individual extreme values are independent. The variable of interest is the annual peak hourly wind or annual peak gust. Return period analysis is generally restricted to stations with at least 20 years of data (Flesch and Wilson 1993; Murphy and Jackson 1997)

2.2.3.2.3 BC Wind and Precipitation Regime

Environment Canada has climate stations throughout BC located primarily at airports and coastal light stations. These sites and details of data collected at each site are listed in the Climatological Station Catalogue (Environment Canada 1989). Wind data for selected sites are summarized in the BC Climate Normals (Environment Canada 1993), and compiled in CD-ROM format in the Canadian Monthly Climate Data and 1961-1990 Climate Normals (Environment Canada 1994).

Some basic relationships between mean wind speed, maximum recorded hourly mean wind speed and maximum recorded gust speed for BC stations are demonstrated in the scattergram shown in Figure 2.5. Bearing in mind that the length of record varies from station to station, there is a positive linear relationship between mean wind speed and maximum hourly mean wind speed. This indicates that locations with higher day to day winds also have higher periodic peak winds. The peak gusts are approximately 50% higher than the peak hourly mean winds which is consistent with the findings of Oliver and Mayhead (1974) in Britain, Smith et al. (1987) in north-central Ontario, and Harris (1989) in Alaska. Wind speeds are much higher at coastal stations than at interior stations.

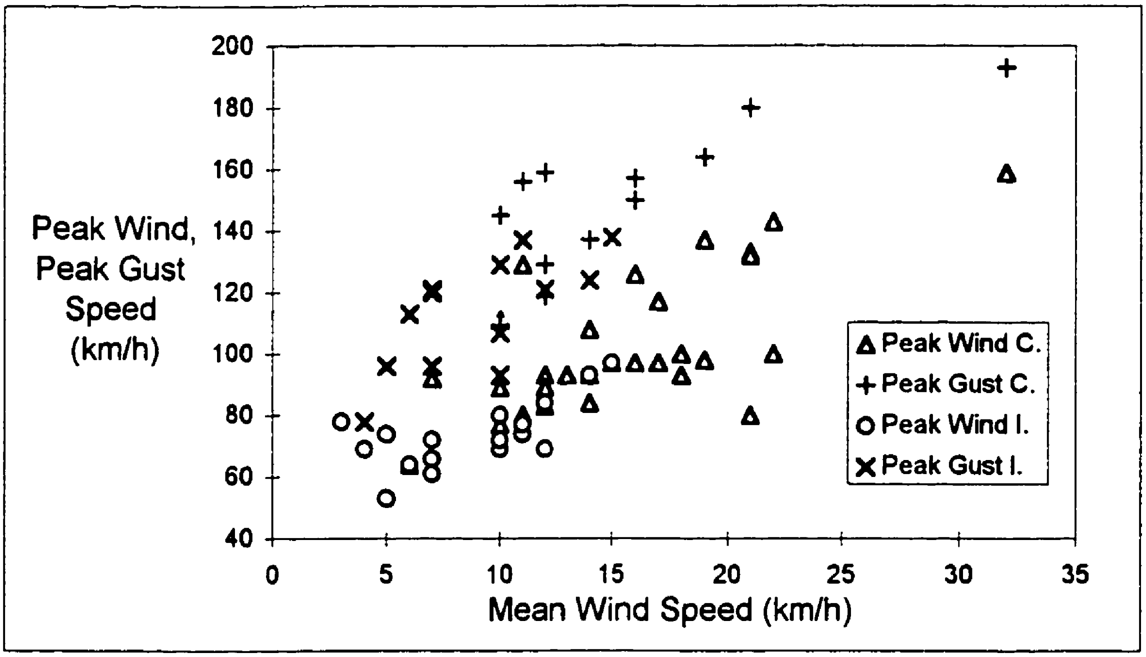


Figure 2.5: Peak hourly mean wind and peak gust of record vs mean wind speed for selected coastal (C) and interior (I) Atmospheric Environment Service (AES) stations. Source of data: Environment Canada (1993). Winds recorded at 10m height over grass. (Mean winds are based on 1-5 minute integration periods; gusts are instantaneous peaks).

Reviewing windthrow in southeast Alaska, Harris (1989) identified four sources of damaging winds: southeast gales, bora winds, thunderstorms and tornadoes. Of these, he considered southeast gales the most important. Tornadoes are rare in British Columbia. Southeast gales are associated with the counter clockwise rotation of low pressure systems originating over the Pacific. These systems stretch out from southeast to northwest as they meet the barrier of the coast mountains giving a long wind run from the southeast. These winds are strongest along the coast but occur in the BC Interior as the lows move eastward. The strongest southeasters are associated with fast moving deep lows from the southwest Pacific. These are typically accompanied by very high rainfall. Deep lows travelling southwest from the Gulf of Alaska occasionally produce high northwest winds in the Queen Charlottes and northern Vancouver Island. Bora or outflow winds occur when cold high pressure interior air masses move south and west and spill out through the long coastal valleys which cross the Coast Range. These winds are pronounced in the Fraser Valley and tributaries, Squamish Valley and Bute Inlet. Fast southward moving Arctic fronts occasionally cause winter damage on the interior plateau (Environment Canada 1992, 1993). In contrast with the widespread damage caused by high and low pressure systems, thunderstorm damage is very localized. Thunderstorm damage is common in the BC interior. The direction of damaging winds reflects the tracking of individual storm cells.

There are no published analyses of extreme storm events for coastal BC. Unpublished results for peak hourly mean winds obtained from the AES (E. Coatta AES Vancouver, personal communication 1992) for BC stations are summarized in Table 2.4. Murphy and Jackson (1997) analyze peak gusts at four north-central interior locations (Table 2.5), and Flesch and Wilson (1993) analyzed peak gusts for fourteen stations in Alberta. The results in Figure 2.5

and Table 2.4 show that the wind regime is more severe at the coastal stations than at the interior stations, with the exception of Dawson Creek. The high wind speeds at Dawson Creek are consistent with those found in the Peace River area of northwest Alberta by Flesch and Wilson.

Table 2.4: Return periods in years for peak hourly mean winds of different speeds[1].

Location	Hourly Mean Wind Speed (km/h)						
	50	60	70	80	90	100	110
	Return Period (years)						
Abbottsford	1.0	1.0	2.9	7.5	20.9		
Cape Scott	1.0	1.2	3.2	13.3	62.5		
Castlegar	1.9	6.2	25.4	109.2			
Comox	1.0	1.0	1.9	6.7	28.7	128.2	
Cranbrook	1.8	12	105.2				
Dawson Crk.	1.1	1.3	1.7	2.7	4.6	8.2	14.9
Kamloops	1.1	1.7	3.8	10.1	28.7	80.3	
Quesnel	3.0	14.4	80.0				
Smithers	2.2	8.5	38.9	183.7			
Vancouver	1.0	2.0	13.0				

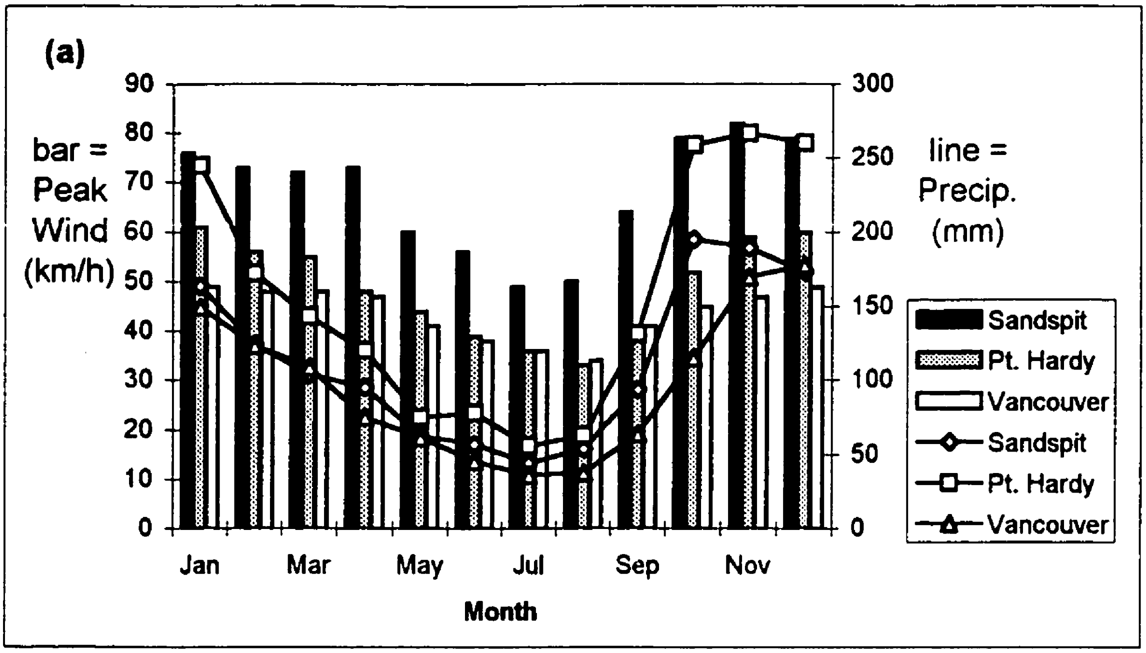
[1]E. Coatta (AES Vancouver, personal communication 1992 - unofficial values)

Table 2.5: Return periods in years for peak gusts of different speeds[1].

Location	Peak Gust Speed (km/h)			
	50	70	90	110
	Return Period (years)			
Prince George	1.0	1.01	1.58	5.47
Quesnel	1.0	1.44	5.14	25.8
Smithers	1.0	1.06	2.06	6.88
William's Lake	1.0	1.07	4.27	39.4

[1]Murphy and Jackson (1997)

In order to compare wind and precipitation regimes for the BC coast and interior, three coastal and three interior weather stations with 24-hour monitoring were selected. The Vancouver, Port Hardy and Sandspit stations represent climate regimes along the length of the coast. William's Lake, Quesnel and Prince George represent climate regimes on the central interior plateau. The climate data was obtained from the Canadian Monthly Climate Data and 1961-1990 Climate Normals (Environment Canada 1994). The Sandspit and William's Lake sites are the closest stations to the study sites in Chapter 3 for which wind information is recorded. Figure 2.6 shows the peak hourly mean winds averaged over a 30 year period for each month of the year for the selected coastal and central interior stations. Mean monthly precipitation averaged over 30 years is overlaid to indicate the coincidence of winds and precipitation.



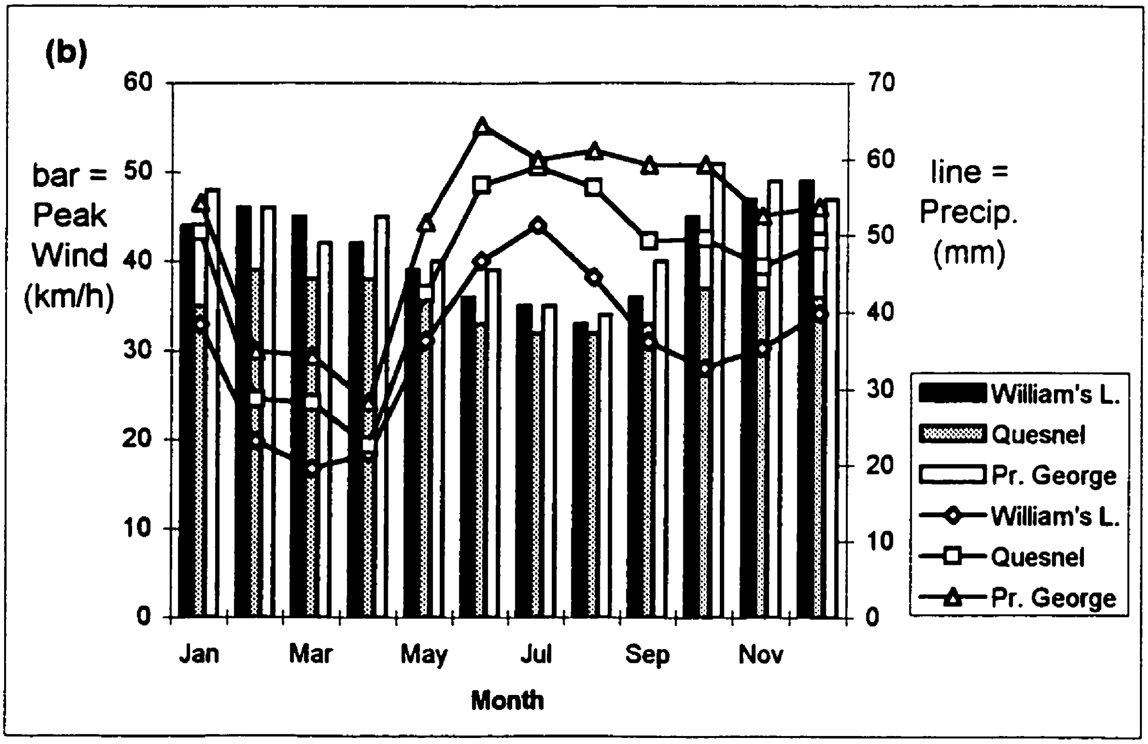


Figure 2.6: Peak hourly mean wind speed (bars) and mean precipitation (lines) by month for selected (a) coastal and (b) interior stations. Source: Environment Canada (1994).

2.2.3.2.4 Timing of Peak Wind Events

Peak winds that occur during winter months are less likely to damage deciduous trees which are bare of foliage. Peak winds that occur while conifer crowns are loaded with snow can intensify damage (Peltola et al. 1997). Rainfall can increase the weight of the crown (Hall 1967), and can saturate soils leading to lower soil and soil/root cohesion. Sustained rocking of trees on wet soils can lead to hydraulic fracture of the root plate from the underlying soil (Rodgers et al. 1995).

For the coastal stations, the highest annual wind speeds coincide with high rainfall during the fall and winter months from October to April. For the interior plateau stations, the difference between winter and summer winds is less pronounced. Precipitation on the interior plateau is greatest during early spring and summer and soils are very wet during and immediately following snow melt in March and April. The number of thunderstorms is summarized in Table 2.6. Thunderstorms are rare at the coastal stations. For the stations on the interior plateau, thunderstorms occur from May to September, peaking in July. The coastal stations have minimal winter snow accumulations. The interior plateau stations have snow accumulations from November to March. Rapid melt of snow in March and early April can lead to temporarily very wet soils during 'spring breakup' (Table 2.7).

Table 2.6: Number of thunderstorms by month[1].

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
William's Lake Airport	0	0	0	0	3	5	6	4	2	0	0	0
Quesnel Airport	0	0	0	0	2	5	5	4	2	0	0	0
Prince George Airport	0	0	0	1	3	5	6	5	2	0	0	0
Vancouver Airport	0	0	0	0	0	0	1	0	0	0	0	0
Port Hardy Airport	0	0	0	0	0	0	0	0	0	0	0	0
Sandspit Airport	0	0	0	0	0	0	0	0	0	0	0	0

[1] Source: Environment Canada (1994)

Table 2.7: Month end snow cover by month (cm)[1].

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
William's Lake Airport	39	32	12	0	0	0	0	0	0	1	13	28
Quesnel Airport	38	27	8	0	0	0	0	0	0	1	11	26
Prince George Airport	31	22	7	0	0	0	0	0	0	1	11	21
Vancouver Airport	1	1	0	0	0	0	0	0	0	0	0	4
Port Hardy Airport	2	0	0	0	0	0	0	0	0	0	1	1
Sandspit Airport	3	2	0	0	0	0	0	0	0	0	1	3

[1] Source: Environment Canada (1994)

Table 2.8: Wind direction by month for mean wind and peak hourly mean wind[1].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					William's Lake Airport							
Mean Wind	SE	SE	SE	SE	C	C	C	C	C	SE	SE	SE
Peak Hourly	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE
					Quesnel Airport							
Mean Wind	C	C	C	C	C	C	C	C	C	C	C	C
Peak Hourly	NW	NW	SE	SE	SE	NW	NW	NW	NW	SE	SE	SE
					Prince George Airport							
Mean Wind	S	S	S	S	S	S	S	S	S	S	S	S
Peak Hourly	S	S	S	S	S	S	S	S	S	S	S	S
					Vancouver Airport							
Mean Wind	E	E	E	E	E	E	E	E	E	E	E	E
Peak Hourly	W	W	W	W	W	W	W	W	W	W	W	W
					Port Hardy Airport							
Mean Wind	SE	SE	SE	SE	C	C	C	C	C	SE	SE	SE
Peak Hourly	E	E	E	E	E	E	NW	NW	E	E	E	E
					Sandspit Airport							
Mean Wind	SE	SE	SE	SE	SE	SE	W	W	SE	SE	SE	SE
Peak Hourly	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE

[1] Source: Environment Canada (1994)

The orientation of mean winds and peak hourly mean winds is summarized in Table 2.8. The predominance of south to southeast flow is clear. With the exception of the Vancouver Airport station, there is a general correspondence of peak wind and mean wind orientation.

2.2.3.2.5 Lowest Critical Wind Speeds

Oliver and Mayhead (1974) documented hourly mean wind speeds of 40 km/h with gusts to 100 km/h above a Scots pine plantation during a gale as windthrow occurred. Beckwith and Woods (cited in Smith et al. 1987) list 14 windstorms with hourly mean wind speeds ranging from 60 to 70 km/h known to have caused windthrow in black spruce stands in north central Ontario. Peak hourly mean winds of 53km/h and 58km/h were sufficient to cause damage of retained trees in recently harvested shelterwoods at Robert's Creek and Boston Bar, BC (B. D'Anjou BCMOF Nanaimo, personal communication 1992). The peak hourly mean wind speed recorded at the Quesnel Airport during the May 5, 1990 event was 54 km/h (E. Coatta, AES Vancouver, personal communication 1994). The return periods listed in Tables 2.4 and 2.5 indicate that most regions of BC experience winds capable of causing damage in the most vulnerable stands every 1-3 years.

2.2.3.3 Influence of Site, Stand and Management Factors

The vulnerability of stands is determined by site, stand and management factors. There are many general reviews of windthrow in the literature (e.g. Mayer 1987; Harris 1989; Schaetzl et al. 1989; Stathers et al. 1994; Ruel 1995) each of which summarizes the contributions of climate, site, stand and management factors to windthrow risk. The incorporation of these risk factors into models for predicting windthrow is discussed in Chapter 4.

2.2.3.3.1 Topography

2.2.3.3.1.1 Topographic Modification of Wind

Local topography modifies the strength, direction and turbulence patterns of local and regional winds. Valleys and ridges funnel wind, causing changes in speed, orientation and turbulence (Hutte 1968; Alexander 1987). In BC, separation of coastal and interior air masses by the coast mountain range and the penetration of large coastal rivers like the Fraser, Squamish and Homathko through the coast range results in high speed cold air outflows in these drainages during the winter. Summer daily temperature differentials that develop on either side of mountain ranges also cause high speed local winds. Examples of this in BC include the summer Qualicums through the Cameron Valley on Vancouver Island, and the summer canyon winds in the Lytton, Lillooet and Spences Bridge areas (Environment Canada 1992; J. McDuff AES Victoria, personal communication 1998).

2.2.3.3.1.2 Measuring Windflow in Complex Terrain

Without local wind data, the influence of topography can be considered in terms of increasing or decreasing exposure relative to measurements taken at the nearest stations. In upland Britain topographic exposure scores are used for evaluating wind exposure. A 'Topex' score is the sum of the angles of elevation to the visible skyline for the eight major compass points with negative angles given the value of zero (Wilson 1984). A refinement of this scoring system, the Topex-to-distance method allows negative angles and places a limit on the distance to which skyline angle is sought (Quine and White 1994). Tatter flags have been used in Britain as an inexpensive way to locally calibrate windiness (Quine and White 1994). Wind tunnel models (e.g. Ruel et al. 1998) and numerical models (e.g. Dandul 1998) of complex terrain can show the sheltering or accelerating effects of topography. Ruel et al.

(1997) compared results of a wind tunnel model, numerical models and Topex scoring for an area in the Laurentian Hills in Eastern Canada and found good correlations between wind tunnel results and the other methods for strong winds. Topographic maps are available for all of BC at 1:20 000 scale or better. This information is available in digital format, which presents the opportunity for automation of exposure determinations (e.g. Wright and Quine 1993).

In the absence of local wind data, observations of damage can provide useful information. The orientation and age class of windthrow give a local indication of peak wind direction and the periodicity of damaging events (Jonsson and Dynesius 1993). Perkins et al. (1992) used the distribution and age of birch seedlings to indicate canopy gap expansion rate and direction in spruce-fir stands in Vermont. Soil pit-mounds remain as windthrow root wads deteriorate. These pit-mounds are characterized by a trough-like pit oriented perpendicular to the direction of windthrow, to the lee of which is a mound containing an inverted humus horizon. Pit-mounds are often the most prominent feature of micro-topography and can provide information on the frequency and direction of windthrow events for many years after the trees have decayed. Ziede (1981) suggests a means of dating pit-mounds and their rate of subsidence using perched trees rooted on the mounds. A number of indicators of wind speed and direction have been developed based on the sensitivity of trees to long term wind exposure. Wade and Hewson (1979) discuss two indicators of wind exposure based on crown deformation and propose a third, the 'compression index' based on bole radial asymmetry. Robertson (1987) demonstrates an application of a crown deformation index in mapping wind flow over complex terrain, and presents a detailed study of bole radial asymmetry in Newfoundland forests (Robertson 1991).

2.2.3.3.2 Soil Characteristics

2.2.3.3.2.1 Root Architecture and Soil Properties

Tree root systems provide both support and anchorage. The large structural roots which resist bending or tensile stresses from tree movement are anchored by sinker roots. The strength of this anchorage is a function of the soil volume exploited by the root system and the strength of the bond between roots and soil media (Coutts 1983). Root strength is a function of root diameter and wood properties. Root tortuosity increases the elasticity of roots (Commanduer and Pyles 1991) and may be important in damping. Root architecture is strongly influenced by soil conditions (Sutton 1991). In soils with high coarse fragment content, root movement can result in abrasion and breakage. This loss of roots may lead to instability, growth losses and mortality (Rizzo and Harrington 1988). The soil volume available for exploitation by the root system is limited by physical barriers to root penetration such as high bulk densities or rock, and unsatisfactory growth conditions such as anaerobic or cold temperatures (Sutton 1991). Armstrong et al. (1976) noted that 'shaving brush' roots in Sitka spruce were characteristic of repeated outgrowth and die-back in response to periodic waterlogging of soils.

2.2.3.3.2.2 Root-Soil Cohesion

The strength of the root-soil bond is determined by soil strength and root strength and the cohesion between roots and soil. The former is a function of texture, soil structure and moisture content. Fraser (1962) found resistance to winching of planted Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was approximately double for trees growing on sands versus trees on clays. Anderson et al. (1989) found higher shear strengths for root plate-soil interfaces in brown earths than for peaty gleys, and attributed this to the sharpness of the rooting boundary where water tables were limiting.

2.2.3.3.2.3 Sources of Soil Information

Broad level mapping of soils and ecosystems is not routine in BC, but this information is available for some locations. Soils maps produced by the Soil Survey of Canada are available for some forested sites. Assessment of soil properties, pedogenesis and classification of soil great groups is a routine component of stand level site diagnosis during silviculture prescription development in BC (Hadley et al. 1990; Green and Klinka 1994).

2.2.3.3.3 Stand Characteristics

2.2.3.3.3.1 Stand Structure and Density

Stand structure refers to the vertical arrangement of trees within the stand. Stand density is a measure of the amount of tree cover on a unit of land area and is generally expressed as number of trees, wood volume or the sum of stem basal area per hectare (Smith 1986). Top height refers to the average height of dominant trees in the main canopy. The exposure of individual trees within a stand to wind depends on the structure and density of the canopy, and the position of the tree crown within the canopy. Competition between trees for growing space and site resources as they increase in size results in gradual overtopping of weaker trees and differentiation of trees into dominant, codominant, intermediate and suppressed crown classes (Smith 1986). A category of trees called super-dominants or emergents whose crowns extend above the main canopy is also recognized. Live crown length is typically highest, and slenderness lowest for dominants. As stand density increases, live crown lengths are reduced and slenderness increases, particularly for sub-dominant trees.

Emergents and dominants projecting up through the canopy are more exposed than codominants or intermediates, but the added exposure of the largest trees does not necessarily result in increased risk of damage. Alexander (1964) found that Engelmann spruce (*Picea engelmanni* Parry) of all sizes were equally susceptible to damage along clearcut boundaries, whereas for lodgepole pine (*Pinus contorta* Dougl.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), smaller trees were more susceptible. In the Oregon coast range, Ruth and Yoder (1953) found that larger trees were more heavily damaged along clearcut edges but that there were no size related trends in partial cuts. In unharvested areas damaged by a major windstorm they found that dominant conifers growing within deciduous stands were undamaged.

Multi-storied stands are aerodynamically rough which increases both the amount and the turbulence of wind energy transferred to the canopy. Increased penetration of wind results in continual exposure of trees at all canopy heights (Vlad 1973). In stands with smooth canopies, energy transfer and penetration is considerably lower. Intercrown contact between swaying trees damps sway (Blackburn et al. 1988). This combination of shelter and damping is sometimes referred to as 'mutual support' (Groome 1988). Coutts (1983) observed that the root plates of young Sitka spruce growing on wet sites were often interconnected and groups of trees were occasionally pulled over as a result of a load applied to one tree. Smith et al. (1987), in winching experiments with black spruce (*Picea mariana* (Mill.) B.S.P.) stands growing on organic soils in Ontario, found that critical turning moments increased with higher stand density and they attributed this to greater root inter-growth in these stands.

2.2.3.3.3.2 Tree Acclimation to Windloads

Numerous experiments have shown that trees strengthen in response to increased windloading (e.g. Larson 1965; Telewski and Jaffe 1986a,b; Valinger 1992), and that trees in stands grown at lower densities are more windfirm (e.g. Reukema 1970; Cremer et al. 1982; Becquey and Riou-Nivert 1987). In uniform stands, stand stability declines as top height increases (Lohmander and Helles 1987; Smith et al. 1987), and this pattern of instability forms the basis for the 'critical heights' predicted in the British windthrow hazard rating system (Miller, 1985). Further evidence for tree acclimation, constraining factors and consequences for windthrow assessment and management are discussed below.

2.2.3.3.3.3 Tree Species and Health

Reports in the literature vary as to the susceptibility of various species. In Europe and North America, spruce (*Picea spp.*) are more frequently subject to windthrow than other species but, as Kennedy and O'Cinneide (1974) suggest, this is likely due to the tendency for spruce to grow on sites with high water tables. Lohmander and Helles (1987) found spruce (*Picea* spp.) to be more stable than true fir (*Abies* spp.) or Douglas-fir on similar sites. Stem and root decay is implicated in increased rates of windsnap and windthrow (Landis and Evans, 1974; Whitney, 1976). Forest cover maps showing stand composition, age of dominants, height of dominants, stocking class and site class are available at 1:20 000 scale for forest land in BC.

2.2.3.3.4 Management Actions

Removing blocks of trees results in a downward shift in the horizontal wind profile and higher wind speeds acting on the crowns of trees on the sides and downwind end of the opening (Peltola 1996). Recently thinned stands have also been found to be vulnerable to wind damage (e.g. Laiho 1987; Lohmander and Helles 1987). Removing individual trees increases wind speeds within the canopy and reduces inter-tree contact and damping (Blackburn et al. 1988; Gardiner et al. 1997). Gardiner et al. found that the wind induced bending moment on residual trees increased linearly with the ratio of inter-tree spacing to tree height for uniform stands. Establishment density and thinning affect the space and site resources available for growth and affect the form and windfirmness of trees. This is discussed further below. Somerville et al. (1979) found that deep ripping improved the strength of anchorage of radiata pine (*Pinus radiata* D.Don.) growing on compacted gravels in New Zealand, however, the total moment at failure was only slightly increased by this practice and stem failure was more common than in non-ripped areas.

2.3 Summary of Windthrow Studies from the Pacific Northwest, BC and Alberta

Review articles on windthrow draw on published studies, but lack the detail of the source material and may mask inconsistencies in study results. In order to identify trends and anomalies in the factors that contribute to windthrow in BC, several field based studies of wind damage on the Pacific coast, BC interior and Alberta were summarized. The study methodologies varied (Table 2.9). Some used systematic plot based measurement, others mapped and classified damaged sites and compared their characteristics with those of undamaged sites. In each of these studies, topographic, soil, stand and management factors were examined separately, enabling identification of risk indicators for each factor.

2.3.1 Meteorological Trends

The coastal studies (Moore 1977; Harris 1989; Ruth 1976) identified winter Pacific low pressure systems with southeasterly flow as causing the most damage. Moore commented that these storms were coincident with periods of high rainfall. Holmes (1985), also working on the coast, concurred with the direction of damaging winds. The interior studies (Benskin

1976; Walker 1982; Adams and Gould 1976) identified frontal winds during October-November and during spring breakup in March-April as the principal source of damage, particularly when associated with heavy rains. Both Walker in Prince George and Adams and Gould in the Peace River indicated that southwest and west winds caused the majority of damage. Coates (1998) observed damage primarily from the south in the Kispiox valley which is in the coastal-interior transition. Walker found that summer thunderstorms also caused damage in the Prince George area.

2.3.2 Topographic Trends

Topographic features which project into or constrict windflow were identified as contributing to higher levels of windthrow by Moore, Ruth and Harris. Holmes did not observe any topographic associations in his Tsitika Valley study. Valleys and inlets which open to or are aligned with south and southeast were more heavily damaged in Moore's study. Harris found that flat valley bottoms were vulnerable in coastal Alaska, and Benskin found a similar result in the Prince George area. Two coastal studies found damage on leeward upper slopes extending downslope where slopes were less than 50-70% (Moore) or 70% (Ruth). In the Peace River, Adams and Gould found more damage on windward lower slopes than on upper or leeward slopes. Both Harris and Moore found damage increased along coastal margins. Moore also reported higher levels of damage at the end of large lakes. In coastal Alaska, Harris found that wind direction was realigned in complex terrain by as much as 90 degrees, but found only 1.6% of damaged areas showed a random fall pattern associated with vorticing winds. Both Moore and Harris reported general increases in windthrow with elevation, but Moore noted that damage was lower in areas with prolonged snow cover, and Harris reported a decrease in damage near the tree line.

Table 2.9: Windthrow studies from the Pacific Northwest, British Columbia and Alberta.

Author	Date	Location	Objectives / Methods
Adams and Gould	1976	Grande Prairie AB	factors contributing to edge windthrow / aerial and ground survey of damaged areas (chain along edge of 63 damaged areas, recorded data at 200m interval; 0.02ha circular plots in windthrow)
Benskin	1975	Prince George, BC	factors contributing to windthrow in Prince George District / interviews
Coates	1997	Hazelton, BC	partial cutting and stand factors contributing to windthrow / strip transects through stand
Harris	1989	SE Alaska,	factors contributing to windthrow patches / photo-reconnaissance of portion of SE Alaska, identified windthrow patches on forest cover maps compared to map information on topography, soils, stand
Holmes	1985	Tsitika River, BC	factors contributing to edge windthrow / edges of 1-8yr old clearcuts divided into 400m long sampling units (su), randomly selected su's, 2*0.05ha circular plots randomly located per selected su, outer plot edge touched boundary. 100plots total
Moore	1977	Vancouver Island, BC	factors causing blowdown in riparian leave strips / observed 59 watersheds; compared results to literature
Ruth	1976	Oregon Coast	factors contributing to damage in 1951 storm on Oregon coast / combination of ground surveys and aerial reconnaissance
Walker	1982	Prince George BC	observations of Nov. 1975 damage in Bowron Valley from ground and aerial reconnaissance

2.3.3 Soil Trends

Shallow soils were identified by most authors as contributing to higher levels of windthrow, particularly where they overlay bedrock or watertables on the coast. In the Prince George area, Walker noted that soil drainage was more important than depth with wet sites being more vulnerable regardless of depth of rooting. Moore, Benskin, and Adams and Gould also reported that poor drainage contributed to vulnerability. In the Kispiox, Coates found no soil moisture effects. Holmes and Moore found greater damage on sites with skunk cabbage and sphagnum moss. In contrast, Holmes, and Harris found less damage on organic soils. Sites with higher productivity were found by Harris to have more damage. Moore, and Adams and Gould, reported higher damage on sloping seepage sites.

2.3.4 Stand Trends

Western hemlock was found to be the most susceptible species by Moore, Ruth and Harris. Amabilis fir (*Abies amabilis* (Dougl.) Forbes) was grouped with hemlock by Moore. Spruce was more susceptible when associated with hemlock (Harris) or on shallow wet soils (Moore), and less susceptible in pure stands (Harris) and on deep alluvial soils (Moore). Ruth found Sitka spruce in Oregon to be equivalent in windfirmness to Douglas-fir. Douglas-fir was found to be relatively windfirm by Moore and Ruth. Western redcedar (*Thuja plicata* Donn) was considered the most windfirm by Harris. Western redcedar and red alder (*Alnus rubra* Bong.) were considered by Moore to be intermediate in windfirmness. Holmes found no species trends. Coates working in the coastal-interior transition ranked amabilis fir and trembling aspen (*Populus tremuloides* Michx.) as least windfirm and lodgepole pine and redcedar as most windfirm, with western hemlock, interior spruce (*Picea glauca x engelmanni*), and paper birch (*Betula papyrifera* Marsh.) as intermediate. Coates found no damaged black cottonwood (*Populus trichocarpa* Torr. & Gray). Walker, and Adams and Gould found interior spruce to be less windfirm than lodgepole pine.

Both Harris and Moore found that very dense stands were most vulnerable especially when tall, and short open grown stands least vulnerable. Holmes reported lower damage with increasing stand density, and increasing damage with stand height. Ruth found young and mixed species stands less vulnerable. Moore reported less damage in stands with uneven canopies. Harris found that damage was less intense but more dispersed in overmature stands. Coates reported more damage in old growth stands. Benskin and Adams and Gould reported more damage in overmature stands. Adams and Gould found more damage in dense stands and taller stands, and less in low density stands. Open grown stands on organic soils were found to be more windfirm by Moore, Harris, and Adams and Gould. Harris and Walker found that trees growing along natural stand edges were more windfirm.

Emergents and very large dominants were considered more windfirm than other crown classes by Moore and Ruth. Coates found no dominance related stability trends but noted that windthrown hemlock and birch were smaller in diameter but taller (higher height-diameter ratio) than standing trees. Holmes found that damaged trees were larger in diameter and height than standing trees. Dominance trends were not noted in the Prince George or Peace River studies.

2.3.5 Management Trends

Boundaries on the lee side of clearcuts were found to have much higher levels of damage than parallel or upwind boundaries by Adams and Gould (95% of edge damage), Ruth (93% of edge damage), Harris (66% of edge damage) and Holmes. Moore found more damage in riparian leave strips at right angle to wind direction. Corners were associated with higher levels of damage (Ruth, Benskin) especially at lee end of block (Harris). Boundary projections were found to be more vulnerable by Benskin, and Harris, but Holmes found straight edges to be more vulnerable. Adams and Gould found that the majority of damage occurred within the first 2 years after harvest. Harris notes that edge damage is most severe in the first few years after cutting. Moore notes that windthrow often occurs during the first storm to hit a new riparian leave strip, and that little damage occurs if nearby cutblock edges are more than five years old with minimal damage. Holmes found that damage did not increase with age of cutblock edge.

2.3.6 Inconsistent Results

The results of the sample of studies illustrate some strong trends, but also some interesting inconsistencies. One such inconsistency is the fact that coastal windthrow occurred throughout the winter months, whereas interior windthrow peaked at each end of the winter season. Climate data for the Prince George and William's Lake Airports indicate that monthly peak winds are similar in magnitude for the period October-March and slightly lower in April. Daily average rainfall is very low and snow accumulations are greatest in December-February. During March and April the snow pack melts and soil moisture levels increase. The October-November and March-April peaks in wind damage reported in the interior might result from an interaction of peak winds and high soil moisture levels.

Other inconsistencies appear to be the result of interactions between stand and site attributes. For example it was observed that organic soils increased vulnerability to windthrow, but low productivity open grown stands on organic soils were more windfirm than other stand types. More damage was observed near the ocean and large lakes, but the stands immediately along the edges experienced less damage. Walker referred to this as 'conditioning'. Stand vulnerability increased with stand height, but large dominant and emergent trees were less vulnerable than other crown classes within a stand. An interaction between the effects of management actions such as creating openings or thinning on the vertical wind speed profile, and the vertical distribution of crown mass for trees from different crown classes may contribute to the variability observed in relative windfirmness of different crown classes.

The effects of these interactions on overall risk of windthrow highlight the importance of having complete descriptions of site and stand attributes, and integrating these attributes with management actions during the evaluation of risk. One approach would be to recognize distinct combinations of topographic, soil and stand variables which are consistently associated with higher or lower levels of wind damage (e.g. highly windfirm low volume redcedar dominated old-growth stands along the west coast margins of Vancouver Island on moderately well drained podzols). However, with the heterogeneity of stands and the varying combinations and interactions of climate, stand, soils, topographic and attributes in BC, this would require that a very large number of combinations be recognized and evaluated. An alternative approach is to separately evaluate each component and recombine them to estimate the overall windthrow risk of a site.

Knowledge of the mechanics and ecology of windthrow and the consequences of management has enabled the development of windthrow risk assessment techniques. The premises, information requirements, and limitations of three standard approaches to windthrow assessment are reviewed in Chapter 4. The requirements of an assessment approach suitable for current use in BC forest management are discussed and a new diagnostic framework for windthrow risk is presented.

2.4 Windthrow as a Problem of Tree Acclimation

2.4.1 Stand Characteristics and Tree Acclimation

There is ample evidence in the windthrow literature of the consequences of acclimative growth for the windfirmness of stands. Moore (1977) observed that:

> 'blowdown is more a result of trees which were long protected from the full force of the wind, suddenly being exposed, than of excessively strong or freak winds'.

Similarly Harris (1989) and Adams and Gould (1976) noted that the majority of edge damage occurred within the first few years after harvesting. Laiho (1987) and Lohmander and Helles (1987) studying wind damage following large storms in Scandinavia, and Cremer et al. (1982) in Australia observed that thinned stands were more vulnerable to wind damage in years immediately following thinning.

Moore observed that 'very large dominant trees and trees in stands with a rough, broken canopy also appear to be relatively windfirm'. Ruth and Yoder (1953) reported similar findings for conifer emergents in hardwood stands and large dominants. Open grown stands on organic soils were found more windfirm by Moore, Harris and Adams and Gould. Harris (1989) and Walker (1982) found that trees growing along edges of natural openings were more windfirm.

There are numerous studies which indicate the relationship between stand density and individual tree windfirmness. In their study of wind damage in radiata pine plantations, Cremer et al. (1982) noted that the incidence of wind damage was lower in plantations raised at lower densities. Reukema (1970) reported that the proportion of damaged stems in a Douglas-fir planting density trial was lowest in the lowest density and increased with planting density. In their calculations of the effect of planting density on windfirmness in British Sitka spruce plantations, Petty and Swain (1985) concluded that the increased resistance to stem breakage or uprooting caused by an increase in the initial spacing outweighed the greater drag forces on trees at wider spacings.

2.4.2 Physiology of Windfirmness

2.4.2.1 Tree Design Constraints

Trees are tall perennial plants which increase their potential for photosynthesis by elevating their foliage above that of other plants. A critical problem associated with this strategy is one of self-support and resistance to wind and snow loads while maintaining optimal arrangement of foliage (Wilson 1970). Trees grow incrementally through the addition of successive cell layers, increasing in size by many orders of magnitude as they grow from seedling to maturity. That trees do not routinely collapse as they increase in size suggests that tree stability is maintained in equilibrium with self-loading and normal loads from wind and snow. However, widespread periodic failure under peak loads point to limits on the degree of stability. Variation in tree stability from stand to stand, and from tree to tree within stands suggests that there are both intrinsic and extrinsic determinants of stability. In dense stands, trees compete for growing space and site resources with their neighbours and must be efficient in both their design and use of resources. Wainwright et al. (1976) present a biological interpretation of the engineering concept of safety factor, in which the value of the safety factor is not arbitrary, but is determined by the process of natural selection. The resulting value represents a balance between the selective advantage of surviving increasingly improbable loads, versus the selective disadvantage of allocating growth resources to structural strength. In order to make the most efficient use of resources available for structural increment, resources would be allocated such that resistance to failure is equivalent in all regions of the stem and structural roots. Wilson and Archer (1979) proposed the 'constant strain hypothesis' to explain this pattern of allocation. This theory of stem form has been investigated by numerous authors including Mattheck (1990) who concluded that the design of the load carrying parts of a tree was in agreement with this theory. Morgan and Cannell (1994) examining stem form concurred with this conclusion but found that the stem profile giving uniform stress varied depending on the wind speed assumed. For high wind speeds, the height-diameter profile giving uniform stress was more tapered than the profile giving uniform stress for lower speeds. Given the stem forms observed for Sitka spruce within uniform canopies, they concluded that stem shape develops in response to average loading conditions experienced by trees as they grow.

2.4.2.2 Form Changes in Response to Mechanical Stress

In addition to maintaining equilibrium as they increase in size, to increase chances of survival trees must also be responsive to short term changes in environmental conditions. There are many examples of morphological plasticity, or the ability of plants to change form in response to changing environmental stresses. The term 'thigmomorphogenesis' was coined to describe the thickening of plant parts and modification of anatomy in response to mechanical perturbation (Neel and Harris 1971). Telewski (1995) reviewed wind induced physiological responses in trees and stated:

> 'The growth process incorporates both physiological and biomechanical acclimation to the site specific, chronic wind conditions within the development of foliage, canopy and vascular support tissues. The developmental acclimation prevents the tree from buckling under the existing wind loading conditions by reducing drag and increasing mechanical strength.'

The guying studies of Jacobs (1954), Burton and Smith (1972) and Fayle (1976), and Larson's (1965) work with potted *Larix* spp. under wind stress demonstrated the relationship between wind induced sway and growth allocation to radial increment. Other examples of allocative responses to wind stress include stem radial asymmetry (e.g. Robertson 1991; Wade and Hewson 1979; Larson 1965) in which conifers grow wider rings on the side of the stem opposite to the prevailing wind direction (lee side), and formation of compression wood (Timell 1986). Nicoll and Ray (1996) found that root systems of Sitka spruce with rooting depth restricted by a water table, had more structural root mass on the lee side.

Sinnott (1952) proposed the concept of equilibrium position to explain the formation of reaction wood in response to stem or branch displacement from initial position. While it is known that trees respond to permanent or short duration bending, there is still debate as to whether the stimulus is mechanical or gravitropic or a combination of both (Timell 1986). Telewski (1989) investigating growth responses to mechanical stimuli identified a new class of reaction wood which he termed 'flexure wood' which forms in shoots which are flexed back and forth, but not permanently displaced. Flexure wood has properties which are intermediate between normal and compression wood. Recent work by Valinger et al (1995) has shown that trees have a 'memory' of loads applied during the dormant period. Bending of dormant Scots pine (*Pinus sylvestris* L.) seedlings resulted in stem thickening during the subsequent growing season. Reaction wood formation is viewed as a geotropic phenomenon associated with internal redistribution of hormonal growth regulators, primarily auxin, in response to stem or branch displacement (Kozlowski and Pallardy 1997). Telewski (1995) suggests that there may be a different mechanism of perception for flexing, associated with stretch-activated ion channels and calcium transport.

2.4.2.3 Allocation Hierarchies

In their hierarchy of normal photosynthate allocation in stand-grown trees, Waring and Schlesinger (1985) considered that photosynthetic tissues represented by buds and new foliage had the highest priority followed by new fine roots and stem storage. Radial growth and protective chemicals had the lowest priority. Under normal conditions, ring cross-sectional area increases linearly with distance down the stem within the live crown, and from the base of the crown becomes constant until it expands again in the region of buttswell (e.g. Farrar 1961). In the corresponding pattern for ring width, the ring is widest towards the base of the live crown and diminishes in width towards the base. In dense stands, as the crown base lifts there is less and less increment in the lower stem and trees become increasingly slender over time.

The guying studies of Jacobs (1954), Larson (1965), Burton and Smith (1972) and Fayle (1976) have shown that allocation to radial increment diminishes when the bending stimulus is removed. Similarly Larson, Fayle, and Valingers' wind loading studies indicate that radial increment in the lower stem increases when wind loads are increased. Larson referred to the normal pattern of ring width distribution as 'passive' and the more basal pattern observed with wind loading as 'stimulatory'. Telewski (1995) tabulated the results of studies of mechanical perturbation of trees. In the majority of cases height increment was lower following treatment and radial increment greater. A period of increased basal radial increment has been observed in residual trees in thinned stands (e.g. Myers 1963; Valinger 1990, 1992). Along with reduced height increment, Valinger (1990) reported a lower proportion of total branch extension in the upper crown in thinned trees. In his guying and sailing studies Valinger found that height increment was unaffected by treatment, but branch extension in the upper crown was lower for trees with sails attached and greater for guyed trees. Urban et al. (1994) studied radial increment in the lower stem and proximal structural roots of white spruce (Picea glauca (Moench) Voss) from a 120 year old stand 'released' by the clearing of road right-of-way 16 years earlier. They found that increment on the upper side of structural roots increased immediately following release whereas increment in the lower stem remained unchanged for 3 to 9 years. They suggested that this lag resulted from preferential allocation to root growth in order to increase tree stability.

2.4.3 Tree Form Indicators of Acclimation

Tree level indicators of windfirmness commonly reported in the literature include stand height, live crown ratio and height-diameter ratio. In their observational studies of windthrow, Harris (1989), Moore (1977), Holmes (1985) and Adams and Gould (1976), and Smith et al. (1987) noted the increasing vulnerability of stands with increasing stand height, and this principle forms the basis for the British Forestry Commission's windthrow assessment method (Miller 1985). Crown length in stands is inversely related to stand density, and is referred to by Oliver and Larson (1990) as a measure of tree vigour. Konopka (1977, cited in Navratil 1994) showed significant differences in the live crown ratios (crown length divided by tree height - LCR) of wind damaged (44-49%) and undamaged (78%) spruce trees and suggested optimal values ranging from 52-73% depending on elevation zone or ecoregion. Tree slenderness, quantified by the ratio of total height to stem diameter at breast height (HDR), is inversely correlated with LCR and is the principal indicator of windfirmness reported in the literature. Cremer et al. (1982) reported that trees with HDR less than 60 were stable while those above 100 were unstable. Becquey and Riou-Nivert (1987) combined stand height and mean HDR to identify zones of instability within stands, with the critical value of HDR declining as stand height increased.

2.4.4 Indicative Value of Tree Form Changes

Stem form at a given point in time is used as an indicator of stand stability, and the principle of acclimative growth is now accepted as a basis for the management of stands to reduce risk of damage (e.g. Quine et al. 1995). However, the pattern of form change has not been used as an intrinsic indicator of post-treatment acclimation with wind loads. Results from the studies discussed above show that when bending stresses are changed, trees actively re-allocate resources in a manner which suggests re-equilibration of form with new loading conditions. Similarly in nutritional studies it has been observed that nutrient limitation induces a change in biomass allocation. The root:shoot ratio changes as long as internal nutrient status changes, but once the tree reaches a nutritional steady-state, the adjustment of root:shoot ratio ceases (Ingestad and Ågren, 1991). Extending the notion from nutritional to mechanical equilibrium, observations of the direction, magnitude and duration of growth allocation patterns should provide insights into the progress of mechanical re-equilibration following thinning.

CHAPTER 3 - ACCLIMATIVE GROWTH IN SITKA SPRUCE AND DOUGLAS-FIR FOLLOWING THINNING

3.1 Introduction

3.1.1 Rationale for Experiment

The acclimative capability of trees suggests a new approach to windthrow risk assessment in which the relative acclimation of trees to above canopy winds is evaluated by examining tree growth responses to increased exposure. The removal of trees from the canopy during pre-commercial thinning, commercial thinning or partial cutting increases the wind loading on the remaining trees. Observations of the direction, magnitude and duration of the patterns of stem growth allocation following thinning should provide insights into the degree and duration of mechanical re-equilibration. Trees which are more destabilized by thinning would be expected to make larger adjustments in form. Distinctive patterns of acclimative growth could be useful tree based diagnostic indicators for evaluating the relative post-thinning windfirmness of different crown classes, and could assist foresters in scheduling appropriate intervals between thinning entries to allow for stand re-acclimation.

3.1.2 Objectives of Experiment

The objectives of the experiment were to: i) determine if the longitudinal and radial stem growth patterns in the years following pre-commercial thinning in naturally regenerated trees are consistent with short term acclimative responses to mechanical or wind loading reported in the literature; ii) determine how stem slenderness changes in the years following thinning for trees of different initial slenderness; iii) document how growth responses vary with initial tree slenderness; and iv) identify variables which could be used as tree-based indicators of re-equilibration with post-thinning conditions.

3.1.3 Experimental Approach

The study was designed to test whether growth responses reported in the literature from short term studies of seedlings and trees in forest plantations occur in trees growing in naturally established stands, and to follow the changes in the pattern of response over many years. The study sites were very high density stands where trees had high initial slenderness. Portions of each study site had been pre-commercially thinned (trees felled but left on site). Sample trees were selected from a range of initial crown classes to enable determination of the influence of initial slenderness on post-thinning growth patterns. Two study sites with different species in continental and coastal locations were chosen, in order to test for the generality of growth responses. Repeatability of the growth pattern in time was tested at the Douglas-fir site by sampling trees from portions of the same initial stand which were thinned at two different dates. A retrospective, reconstructive approach was used to enable documentation of a long period of growth response.

3.1.4 Principal Hypotheses Tested

The following hypotheses were tested: i) radial increment will increase, height increment will temporarily decrease, and basal allocation will increase in the years following thinning; ii) slender trees will converge on the form of the more tapered trees and relative post-thinning responses will be greater for the initially more slender trees; and iii) the more tapered trees will be better able to resist wind loads.

3.2 Methods

3.2.1 Selection of Study Sites

Douglas-fir and Sitka spruce were chosen as the species of interest because they are major timber producing species in BC and other countries. Both species have determinant shoot growth which facilitates stem and crown reconstruction. Candidate Douglas-fir sites were viewed in the Nelson, Kamloops and Cariboo Forest Regions. Sites in the wetter northern Cariboo and Nelson Region had insufficient densities, and many of the high density stands in the Kamloops Region had suffered severe western spruce budworm (*Choristoneura occidentalis* Freeman) defoliation in the late 1980's. Candidate Sitka spruce sites were viewed in the vicinity of Queen Charlotte City and Moresby Camp on the Queen Charlotte Islands. These were readily accessible areas which had been harvested during the 1940's. The stand selected for the study was chosen because the trees were very tall at the time of thinning and because it had a large control area. There were no pure spruce stands with sufficient initial densities, so a mixed Sitka spruce-western hemlock stand with a high proportion of spruce was selected. The locations of the study sites are shown in Figure 2.1. The attributes of the sites selected for study are summarized in Table 3.1.

3.2.2 Stand History Records and Climate Data

Opening records, stand tending reports and maps were obtained from the licensees and Ministry of Forests for each location. Climate data was obtained from the *Canadian Monthly Climate Data and 1961-90 Climate Normals* (Environment Canada 1994) for the nearest weather stations with wind and precipitation data. The William's Lake Airport station is approximately 90km northwest of the Douglas-fir study site but at a similar elevation and in similar geography. The Sandspit Airport station is approximately 25km northeast of the Sitka spruce study site. The study site is in hillier terrain and more sheltered from south and westerly winds than the airport.

3.2.3 Site Classification

For each site and treatment a soil pit was dug at a representative location. Soil horizons were classified and hand textured. Indicator plants were recorded and the site series was keyed out (Green and Klinka 1994; Steen and Coupé 1997). Angle to skyline was recorded for the eight cardinal directions to enable calculation of topographic exposure (Topex) score (Quine and White, 1994).

Table 3.1: Summary of study site characteristics.

	Sitka spruce site	Douglas-fir site
Licensee	Western Forest Products Ltd. TFL 25	Lignum Ltd.
Mapsheet/Polygon	103F010.4-326 (WFP Stand 31-103 F/1 8)	1978: 92P063-27 1983: 92P063-23
Permanent Sample Plot	---	1978 GY Plots: EP 987-03
Spacing Project Number	JS 1980, Opening 40	1978: ST92P116JS 1984: ST84C-04-007
Spacing Dates	800802-800829	1978: 780918-790510 1984: 840401-840701
Location	Mosquito Lake	Tatton Lake Road
Nearest town	Sandspit, BC	100 Mile House, BC
Nearest AES weather station	Sandspit, BC - wind & ppt	100 Mile House - ppt William's Lake - wind & ppt

Table 3.1 (cont.): Summary of study site characteristics.

	Sitka spruce site	Douglas-fir site
Stand origin	natural regeneration following logging in 1946	natural regeneration following wildfire ca. 1942
Species comp. pre-treat	Hw 54% Ss 46%	Fd 94% Pl 4% Willow 2%
Species comp. post-treat	Ss 70% Hw 30%	Fd 96% Pl 4%
BEC Subzone/Site Series	CWHwh1 / 01 zonal site, submontane wet hypermaritime	IDFdk / 01 zonal site, dry cool subzone
Latitude	53 04'	51 42'
Longitude	132 07'	121 24'
Elevation	100 m	980 m
Precipitation	1360 mm	430 mm
% Precipitation as snow	5 %	50 %
Mean annual wind speed	19km/h	10km/h
Mean wind direction	SE, W July and August	SE all months
Peak hourly wind direction	SE	SE (minor NW and S)
Topography	Rolling hills, lake to west, site at mid-slope in small E-W valley; 10 %slope	Rolling plateau, site on gentle north facing upper slope; 4% slope
Topographic exposure	moderately sheltered Topex=115	exposed Topex=8
Soil Order	Podzolic	Brunisolic
Soil texture	shallow, silty loam	silty loam veneer over fine sand
Restricting layer and depth	basal till with seasonally perched watertable, rooting to 100 cm	none, rooting to 120 cm

3.2.4 Study Site Location and History

3.2.4.1 Sitka Spruce Site

Juvenile Spacing Opening 40 on Western Forest Products TFL 25 is in a small valley cutting east-west through a low ridge at the east end of Mosquito Lake. The site is in the Submontane Wet Hypermaritime variant of the Coastal Western Hemlock zone (CWHwh1), with a maritime climate characterized by mild, wet winters with little snowfall and cool moist summers (Green and Klinka 1994). The stand was clearcut in 1946 and naturally regenerated to Sitka spruce and western hemlock. At the time of pre-commercial thinning in August of 1980, the stand density was 6470 stems per hectare in the control stand with a mean tree height of 11.6 meters and top height of 18.6 meters (Table 3.2). Post thinning density averaged 770 trees per hectare. Removal was from below, with spruce retained preferentially. Several large portions of the stand were left unthinned. These portions had characteristics similar to the thinned portions and provided suitable controls. The majority of trees were sampled during November 1993. Three additional treated trees and two additional control trees were sampled during August 1994. The Sitka spruce treatments were designated CON for control and THIN (or J80) for the 1980 thinning (Figure 3.1). Because the thinning occurred towards the end of the growing season after the completion of height increment, the pre-treatment year for the 1980 thinned plot was considered to be 1980, and pre-treatment tree dimensions were those at the end of the 1980 growing season.

3.4.2.2 Douglas-fir Site

Opening 92P063-27 is adjacent to the Tatton Lake Road in the 100 Mile House Forest District on the north side-upper slope of a low ridge in an area of gently rolling topography on the Cariboo Plateau. The site is in the Dry Cool Fraser variant of the Interior Douglas-fir zone

(IDFdk3) with a continental climate characterized by warm dry summers and cool winters (Steen and Coupé 1997). The even-aged Douglas-fir stand regenerated naturally following a wildfire that occurred circa 1942 based on the ages of the oldest sample trees. The forest cover label indicated that residual mature trees were harvested between 1952 and 1965. A BCMOF growth and yield installation was established during the pre-commercial thinning of September 1978-May 1979 with plots in the 1978 thinning and in a central control strip. The April-June 1984 thinning was to the west of the control strip. Sampling was carried out during July 1994. At the time of the 1978 thinning stand density in the control stand was 23570 stems per hectare with a mean tree height of 3.9 meters and top height of 7.6 meters (Table 3.2). Post thinning density for the 1978 thinning was 1300 stems per hectare and for the 1984 thinning was 1650 stems per hectare. Removal was from below. The Douglas-fir treatments were designated as CON for control, J78 for the 1978 thinning and J84 for the 1984 thinning (Figure 3.2). For J78, the thinning was complete prior to the commencement of growth in 1979 so the pre-treatment year was 1978 and the pre-treatment tree dimensions were those at the end of the 1978 growing season. For J84, the thinning occurred during the early part of the growing season of 1984. The pre-treatment year was considered to be 1983, and pre-treatment dimensions were those at the end of the 1983 growing season.

Table 3.2: Summary of stand attributes immediately after treatment.

Species	Treatment	Code	Year	Stems/ha	Top height	Mean HDR
Sitka spruce	Control	CON	1980	6470	18.6 m	117
	Thinned 1980	THIN	1980	770	18.1 m	95
Douglas-fir	Control	CON	1978	23570	7.6 m	122
	Thinned 1978	J78	1978	1300	8.2 m	96
	Thinned 1984	J84	1983	1650	9.3 m	104

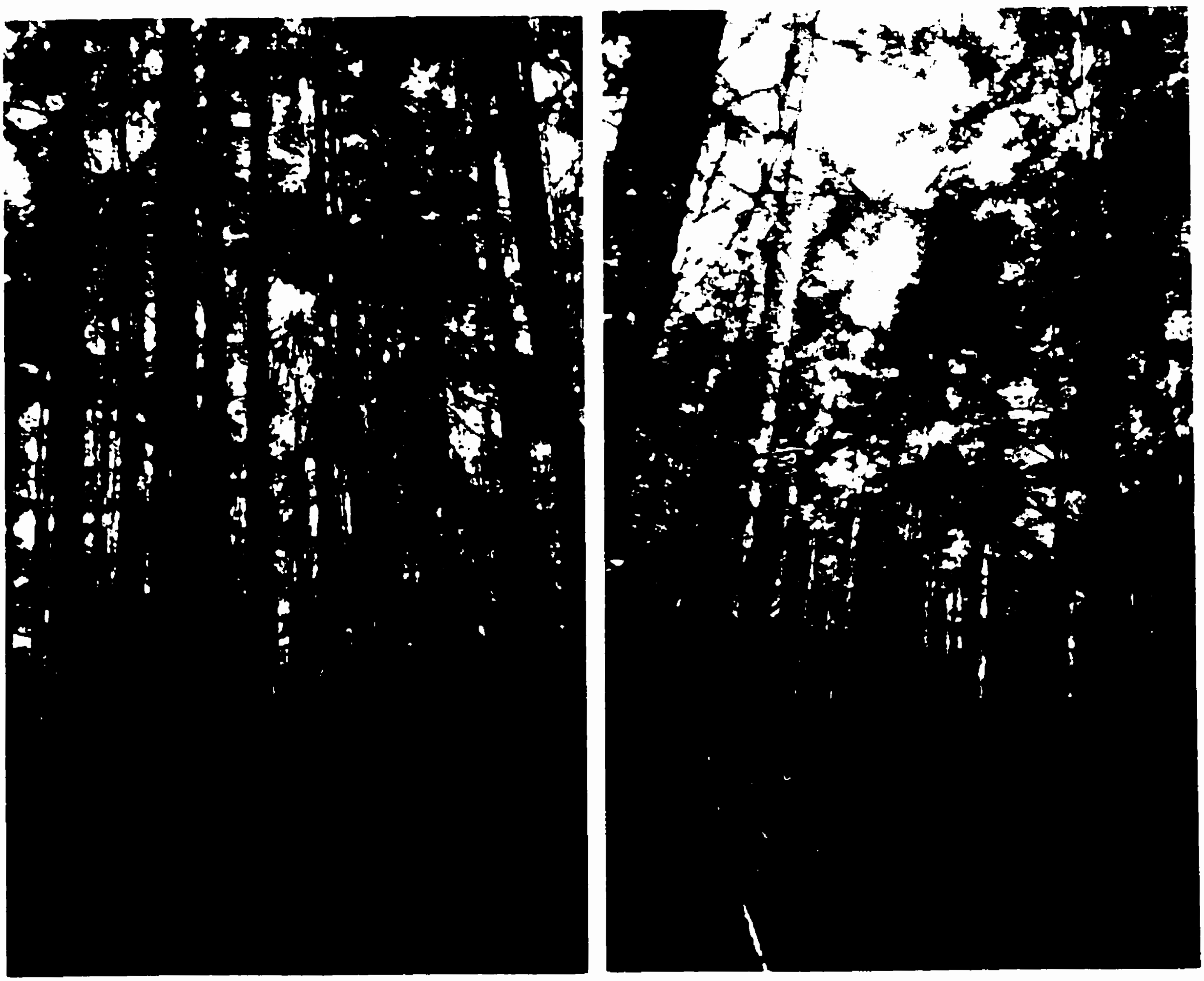


Figure 3.1: Photographs of the (a) control (CON) and (b) thinned 1980 portions (THIN) of the Sitka spruce study site in 1993.

Figure 3.2: Photographs of the (a) Control (CON) and (b) thinned 1978 (J78) portions of the Douglas-fir study site in 1994.

Figure 3.2 (cont.): Photograph of the (c) thinned 1984 (J84) portion of the Douglas-fir study site in 1994.

3.2.5 Selection of Sample Trees

In order to test the growth responses of trees with different initial form, five trees were selected from each of the current dominant, codominant and intermediate crown classes for each treatment. Suppressed trees were excluded from the sample with the result that the smallest diameter classes were not represented. Some of the selected dominants at the Sitka spruce site were too large to fell safely within the stand, so fewer dominants were sampled at this site than other crown classes (Table 3.3).

Table 3.3: Number of sample trees from each crown class.

Crown Class	Spruce Thinned 80	Spruce Control	Douglas-fir Thinned 78	Douglas-fir Thinned 84	Douglas-fir Control
Dominants	3 trees	2 trees	5 trees	5 trees	5 trees
Codominants	5 trees	5 trees	5 trees	5 trees	5 trees
Intermediates	5 trees	5 trees	5 trees	5 trees	5 trees

Striplines were run through unthinned and thinned portions of each stand and marked at 15 meter intervals. Each interval mark was randomly assigned to one of the three crown classes. The nearest tree of the assigned class to the interval mark which also met the sample tree and plot criteria listed in Table 3.4 was labelled as a sample tree. Unhealthy, damaged or leaning trees were not selected, nor were trees with missing, dead or dying nearest neighbours. 'Nearest neighbours' were trees immediately adjacent to the sample tree. Their crowns were not separated from that of the sample tree by other tree crowns. If no candidate sample trees were found within 7.5 meters of the interval mark which met the criteria, the interval mark was skipped and an additional interval was added to the end of the stripline.

Table 3.4: Sample tree and plot selection criteria.

Sample tree criteria	Sample plot criteria
No breakage	No missing, dead or dying nearest neighbours
No pathogens or decay indicators	
Rooted on stable substrate	
Not leaning more than 4 degrees from vertical	

3.2.6 Field Measurements

3.2.6.1 Plot Measurements

Plot measurements were taken to enable documentation of stand composition, stocking and tree size distribution within the vicinity of each sample tree. A fixed area circular plot 3.99 meters in radius was centered on each sample tree. The species, crown class, status (live, standing dead or cut) and diameter breast height (dbh) of all standing live, standing dead or cut dead trees whose point of germination fell inside the plot were recorded. If the dbh of cut trees could not be determined, stump diameter was recorded. For the Douglas-fir site there were a large number of very small diameter stems. Any stems less than 3cm dbh were simply counted. The direction and slope of the ground was recorded at each plot.

The nearest neighbours were identified and recorded whether they were inside or outside of the 3.99m plot. Each nearest neighbour was numbered and stem mapped (distance and bearing from sample tree), and species, dbh, crown class, diameter stump height (30cm), and height were recorded. For living nearest neighbours, an increment core was taken at breast height on the side nearest the sample tree. For thinned plots, cut trees which would have been nearest neighbours prior to thinning were also identified. For the cut trees, the height and crown measurements taken were those at the time of thinning. There was no difficulty in finding cut neighbours at either site. For about 10% of cases decay was well advanced so full height and dbh at time of thinning had to be estimated from the decayed material present. The additional height and increment core data recorded for nearest neighbour trees was taken to assist with stand reconstruction.

3.2.6.2 Sample Tree Measurements and Collection of Stem and Branch Samples

Sample tree measurements and stem and branch samples were collected to document current stem and crown form and enable reconstruction of past stem growth of each tree. The radius of the crown from stem was recorded in each of the eight cardinal directions and the amount and direction of lean was noted for each sample tree prior to felling. The north side of the tree was marked. Following the collection of tree and plot data, the sample trees were felled. Total height and height to each whorl were recorded and the height of the lowest live whorl was noted. All branches on each whorl were removed, counted and weighed. Internodal branches were added to the whorl below for weighing. A main whorl branch of median length was labelled and retained for every fourth whorl for the spruce and every third whorl for the Douglas-fir. Stem sections were removed at 10 cm, 30 cm, 80 cm and 130 cm from root collar (Disks 1-4), and at six additional positions along the bole (Disks 5-10). The spacing between Disks 5 to 10 was determined by dividing tree height less 1.3 meters by 6. Disk 5 was removed one half spacing up from Disk 4. Disk 10 was removed approximately one-half spacing back from the tree top. The exact height of each disk in the tree was recorded. The north side of each disk was marked prior to removal. Each disk was labelled with treatment, tree number, disk number and north arrow on the upper surface.

3.2.7 Winching

Twelve trees from each treatment at the Douglas-fir site were winched using the technique of Smith et. al (1987) with modifications suggested by Bill Chapman (BCMOF Cariboo Region, personal communication 1994). The winch was a hand winch with 2000lb maximum capacity. A 10000lb BLH Electronics U3G1 load cell connected to a volt meter was used to measure applied force. The load cell was placed at the point of attachment. Small trees were pulled with a straight pull. For larger trees, the cable was anchored at one end and run over a pulley attached to the load cell, with the winch at the other end. On average, the point of attachment on the stem was at 20% of tree height. Because of the weight of the load cell and cables, the point of attachment was placed lower on the stem for very small trees. An angle gauge was placed at the base of the stem measuring deflection between 10cm to 45cm up the stem. A plumb-bob hanging from the point of attachment enabled measurement of horizontal displacement. The soils were relatively dry at the time of winching in late July.

The height of attachment, cable length, angle and direction were recorded at the commencement of winching (Figure 3.3). Deflection angle, horizontal displacement and voltage were recorded as the trees were winched in increments of 1 degree deflection. Load was considered critical when additional deflection did not result in increased voltage readings. Once critical load was reached, the base of the stem and roots were inspected and the method of failure was recorded as uprooting, root failure, or stem failure, in accordance with the descriptions of Somerville (1979). In uprooting, the root plate lifted some distance from the tree on the opposite side from the winch. In root failure, large tap or prop roots failed right at the base of the stem and there was no lifting of the perimeter of the root plate.

The original intention was to use a green wood density value from the literature and therefore stem mass was not recorded at the time of sampling. Recognizing that a local measure of stem density was preferable, three trees from the 1978 thinning and two control trees were felled, cut into 2 meter sections, measured and weighed. The gross density of each stem section was determined by dividing fresh mass into total sectional volume including bark. The trees represented the size range of trees winched. While gross stem density varied from tree to tree (684 kg/m3 - 875 kg/m3), it was not related to tree size. It did however increase with height in the tree. A linear regression relating stem gross density including bark to percent height in tree was fit (R^2=0.62). The density-height relationship for control and thinned trees was similar and therefore the same equation was used to estimate the sectional gross densities for all winched trees.

3.2.8 Disk Scanning

Disks were stored frozen prior to scanning and were prepared for scanning by cutting a shallow v-notch along each of the north, south, east and west radii with a sharp blade. The disks were scanned using an Addovax scanner with a precision of 0.01 mm and capture software. The disk was viewed through a stereo-microscope with cross-hairs. The disk was moved across the scanner bed with a screw thread, and a trigger was depressed each time an annual earlywood-latewood boundary passed the cross hairs.

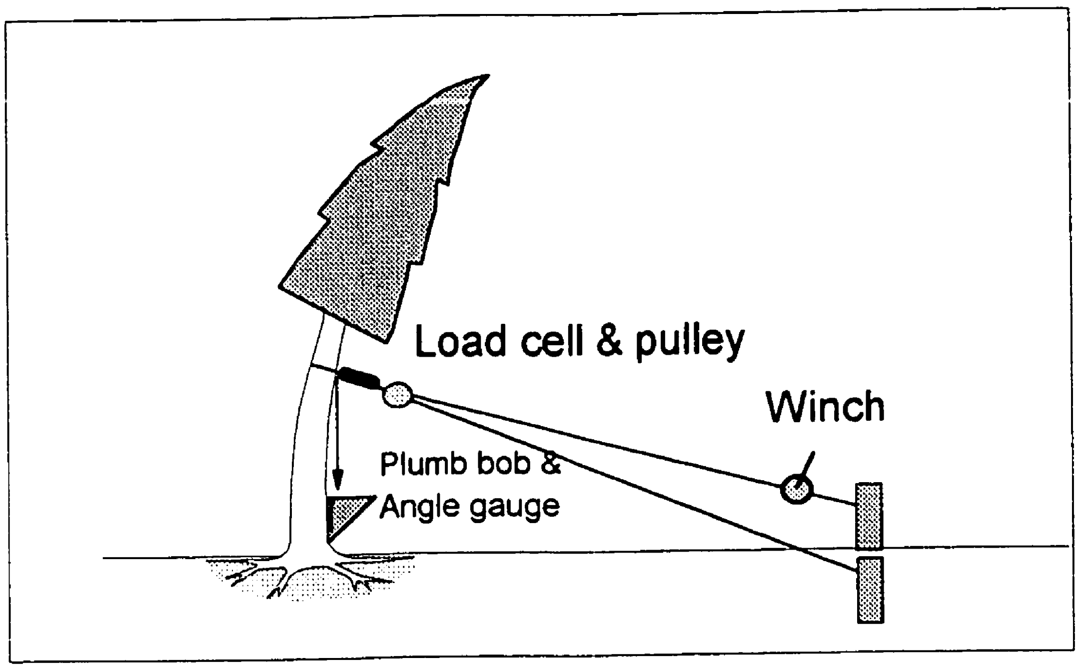


Figure 3.3: Diagram of winching arrangement.

3.2.9 Determination of Response Variables

3.2.9.1 Annual Response and Form Variables

The response variables are summarized in Table 3.5. Annual height increment (HTINC) is the difference between total stem heights from one year to the next. This was determined from the field measurements of annual internode heights, working from the top of the tree down. The age of internodes was checked during the stem analysis phase. Some corrections were made where estimated age of main stem internode, branch internode and stem ring years did not agree. In most cases this was due to missed main stem internodes resulting from very short or damaged main stem extension. Annual radial increment inside bark was calculated from the mean annual radius of the north, south, east and west radial axes. Sectional ring volumes were calculated from the average of the measured annual ring cross sectional area at top and bottom of each section, multiplied by section length. The section of ring above the top disk was assumed to be conical. Sectional ring volumes were summed to produce annual ring volume. Specific volume increment (RVSA, the current year stem volume divided by previous year stem surface area) was used as the measure of stem radial increment. This measure was preferred to ring width at a reference height (e.g. at 1.3m) because it indicated how thick the ring would be if the stem wood produced in a given year were distributed uniformly over the bole. This was useful for comparing with the allocation of wood along the bole (RV50) which was calculated by dividing the annual ring volume in the lower half of the stem to annual ring volume in the upper half of the stem. Higher values of RV50 indicate more basal allocation of stem wood. For brevity, RVSA is referred to as 'radial increment, or ring thickness' and RV50 as 'allocation, or basal allocation'.

Relative responses in the post-treatment years (RHTINC, RRVSA, RRV50) were calculated by dividing annual values by the mean of the variable for the three years immediately prior to treatment. For determination of mean relative responses in each treatment (Section 3), the pre-treatment mean value was determined using the following weights: w_{tp}=0.50, w_{tp-1}=0.33, w_{tp-2}=0.17 for tp=year of treatment (e.g. Valinger, 1990). These weights were confirmed by regressing w_t vs w_{t-1} and w_t vs w_{t-2} for each variable, and they represent reasonable values. For the analysis of relative growth responses to initial tree slenderness in Section 4, the pre-treatment mean was left unweighted (w_{tp}=w_{tp-1}=w_{tp-2} =1) to avoid biasing the slope estimates.

Annual stem form was described by the height-diameter ratio (HDR - also referred to as stem slenderness), calculated by dividing annual tree height by annual diameter breast height inside bark. Sectional stem volumes were calculated from the average of the measured annual stem cross sectional areas at the top and bottom of each section, multiplied by section length. The section of stem above the top disk was assumed to be conical. Sectional volumes were summed to produce annual tree volume (TRVOL).

Table 3.5: Summary of annual response, relative response and form variables.

Variable Abbreviation	Variable Name	Method of Determination
	Response	
HTINC	height increment	$height_t - height_{t-1}$
RVSA	mean ring thickness over whole stem	annual ring volume/previous years bole surface area; is mean ring width
RV50	longitudinal allocation of ring volume	ring volume in lower 50% of stem / ring volume in upper 50% of stem
	Relative Response[1]	
RHTINC	height increment relative to mean 3-year pre-treatment height increment	$htinc_t / [(htinc_{tp} * w_{tp} + htinc_{tp-1} * w_{tp-1} + htinc_{tp-2} * w_{tp-2}) / 3]$
RRVSA	mean radial increment relative to mean 3-year pre-treatment mean radial increment	$rvsa_t / [(rvsa_{tp} * w_{tp} + rvsa_{tp-1} * w_{tp-1} + rvsa_{tp-2} * w_{tp-2}) / 3]$
RRV50	allocation relative to mean 3-year pre-treatment allocation	$rv50_t / [(rv50_{tp} * w_{tp} + rv50_{tp-1} * w_{tp-1} + rv50_{tp-2} * w_{tp-2}) / 3]$
	Form and Size	
HDR	height-diameter ratio	annual height / annual inside bark diameter
TRVOL	stem volume inside bark	sum of sectional stem volumes for each year

[1]for tp=year of treatment, tp-1=1 year pre-treatment, tp-2=2 years pre-treatment; w=weight

3.2.9.2 Mechanical Variables

The equations used for calculating potential and applied loads are summarized in Table 3.6. Wind drag on the crown of each tree was estimated using equations relating drag to crown mass and wind speed obtained from Mayhead et al. (1975). These equations are valuable because they account for the effects of crown streamlining at higher wind speeds. In Mayhead et al.'s experiments with Sitka spruce and lodgepole pine, the maximum wind tunnel speed was 28 m/s. Because it was necessary to extrapolate out to 36m/s for some trees, the more linear equation for lodgepole pine was used. According to Mayhead et al., the fixed-wind speed drag coefficients for Douglas-fir and lodgepole pine were similar. The drag values calculated for the Douglas-fir in this study are simply estimates, but they enable comparison of loading on trees of various crown sizes under different wind regimes. The estimated wind speed acting at the crown center of gravity which produced a drag force equal to the horizontal pulling force at time of failure was considered to be the critical wind speed (Ucrit).

A safety factor (SF) was calculated as the ratio of critical turning moment to wind induced turning moment for an above canopy wind speed (Uh) of 30m/s. Overturning resistance was calculated for all trees using an equation relating critical turning moment to diameter determined from the winching results. The drag for each whorl for all trees was determined using Mayhead et al.'s equation for pine. The wind speed at each height (Uz) was determined using the exponential formula for within-canopy profile with three different attenuation coefficients representing open, moderately open, and dense canopies (α=0.5, 1.5 and 3) (e.g. Landsberg and James 1971; Oliver and Mayhead 1974). Sectional turning moments were calculated as the product of height to whorl and sectional drag. These sectional turning moments were summed to determine total wind induced moment. The gravitational component of critical turning moment was determined for winched trees by multiplying sectional crown and stem mass, by the horizontal displacement of the section. The gravitational component was found to account for 12% of the total moment at failure on average and was excluded from the safety factor calculations.

Table 3.6: Equations used for calculating critical wind speed and safety factor.

Equation

1. Within-canopy wind speed profile

   $$Uz=Uh[1+\alpha(1-(z/h))]^{-2} \qquad \text{for } \alpha \text{ from 1.5 to 3.0}$$

   for h=top of canopy
   z=height of interest
   α=attenuation coefficient

2. Above-canopy wind speed profile[1]

   $$Uz = Uh\ [\ln((z-d)/zm)/\ln((h-d)/zm)]$$

   for d=zero plane displacement (0.66h)
   zm=momentum roughness length (0.1h)

3. Crown drag for variable wind speed (for lodgepole pine)[2]

   $$Fd=u^2\ m^{2/3}\ (0.0256e^{-0.004124u^2} + 0.01643)$$

4. Wind applied moment at base of stem

   $$Mw=\Sigma\ [Fdz*z]$$

5. Gravitational moment at base of stem

   $$Mg=\Sigma\ [(\text{mass stem}+\text{mass branches})*x_z)]$$

   for x_z=horizontal displacement of section z

6. Total applied moment at base of stem

   $$Ma=Mw+Mg$$

7. Critical turning moment Douglas-fir[3]

   $$Mc=350.87 + 13.04*DBH^{2.76} \qquad R^2=0.96$$

8. Safety factor

   $$SF=Mc/Ma$$

[1] From Jarvis et al. (1976). [2] From Mayhead et al. (1975). [3] From winching tests.

3.2.10 Determination of Stand Characteristics

The objective of the stand reconstruction was to characterize the stand at the time of thinning and check for similarity of pre-thinning conditions in the treatments. Data obtained from stem analysis were used in conjunction with plot and nearest neighbour measurements to reconstruct stand attributes at the time of thinning. Stand densities were determined from the number of trees within the 3.99m radius plots. Because the plots were centered on the sample trees, and sample points with missing neighbours were not used, there was the potential to over-estimate overall stand density with this approach. However, the densities obtained were similar to the densities recorded in the stand tending reports for both sites. Trees recorded as standing dead at the time of sampling were assumed to have died since the time of thinning, with a constant annual mortality rate.

Past breast height diameters of each tree in the sample plots were calculated using regressions relating diameter in a given year to diameter at the time of sampling. The regressions were determined using DBH measurements and increment cores taken from the nearest neighbour trees in each plot.

For the mean diameter trees and top height trees, the time of thinning heights were derived from height vs diameter curves constructed from field measurements of the heights and diameters of cut nearest neighbours. The height for tree of mean diameter at the time of sampling was derived from a height vs diameter curve constructed from measurements of live nearest neighbours. The top height trees were the largest trees in each plot. Top height at the time of sampling was determined directly from height measurements.

3.2.10.1 Sitka Spruce Stand

The pre-thinning, post-thinning and time-of-sampling properties of the control and 1980 thinning for the Sitka spruce stand are summarized in Tables 3.7 and 3.8. The pre-thinning stand characteristics were reconstructed as described above. F-tests were performed only on measured variables, and not on derived variables. Stand density, mean diameter, mean diameter top height trees, and stand basal area were equivalent for the control and thinned stands prior to thinning in 1980. Height, diameter and slenderness of the largest trees in the control and thinned plots were equivalent in 1993.

In 1980, stand densities were very high and mean trees were slender with HDR's of 129 and 123. Selection during thinning was from below, substantially increasing the size of the mean tree in the post-thinning stand. Spacing also favoured Sitka spruce, bringing the proportion of spruce in the thinned stand up to 70% from 46% prior to thinning. Spacing reduced the basal area to 31% of pre-treatment levels, and at the time of sampling the basal area in the thinned treatment was 53% of that in the control. The top height trees in both the thinning and control treatments increased in height by 20% since 1980.

Table 3.7: Summary of Sitka spruce stand characteristics in 1980.

	Control Untreated	Thinned 80 Pre-Treat	Diff. $p<0.05$	Thinned 80 Post-Treat
sph	6466	6815	No	769
dbh mean (cm)	8.2	8.5	No	16.4
ht mean tree* (cm)	1060	1050	n/a	1630
hdr mean tree*	129	123	n/a	99
ba (m^2/ha)	49.8	58.2	No	17.8
dbhtop (cm)	23.7	25.4	No	23.4
ht top tree* (cm)	1810	1800	n/a	1800
hdr top tree*	76	71	n/a	77

Based on 12 control and 13 thinned plots, 3.99m in radius; '*' indicates heights estimated from height vs diameter curves.

Table 3.8: Summary of Sitka spruce stand characteristics in 1993.

	Control	Thinned 80	Diff. $p<0.05$
composition (%)	Hw54 Ss46	Ss70 Hw30	Yes
sph live	4600	769	Yes
sph standing dead	1666	0	Yes
dbh mean (cm)	11.3	23.0	Yes
ht mean tree* (cm)	1340	1910	n/a
h:d mean tree*	119	83	n/a
dbhtop (cm)	29.7	30.9	No
ht top tree (cm)	2180	2170	No
h:d top tree	75	71	No
ba (m^2/ha)	67.4	36.0	Yes

Based on 12 control and 13 treated plots, 3.99m in radius; composition codes: Hw=western hemlock, Ss=Sitka spruce; '*' heights estimated from height vs diameter curves.

3.2.10.2 Douglas-fir Stand

The pre-thinning, post-thinning and time-of-sampling properties of the control, 1978 and 1984 thinned Douglas-fir stands are summarized in Tables 3.9, 3.10 and 3.11. In these tables, stems per hectare and basal area are given separately for 'all trees' and for 'trees greater than 3cm DBH'. Variables identified with the same letter for different treatments were not significantly different.

Pre-thinning densities were very high, with densities exceeding 17200 sph for trees of all sizes. For stems greater than 3cm prior to thinning in 1978, the stand density was lower in the control (6200sph) than in the J78 stand (9200sph), with the J84 stand intermediate in density (7800sph) and equivalent to both the control and J78 stand. The basal area was equivalent for the J78 and J84 stands, both of which had higher basal areas than the control. The mean tree diameter and top tree diameter were equivalent for all three treatments. For stems greater than 3cm prior to thinning in 1984, the stand densities of the control and J84 stands were equivalent, but the basal area was higher in the J84 stand. The mean tree diameter was larger in the J84 stand but the top tree diameter was equivalent.

Thinning was from below, increasing the size of the mean tree in both the 1978 and 1984 thins. Selection during thinning reduced mean tree HDR from 110 to 95 in 1978, and from 109 to 99 in 1984. Thinning substantially reduced stand basal area, from 23.4 to 5.3 m^2/ha in 1978 and from 27.7 to 7.4 m^2/ha in 1984. At the time of sampling in 1994, the stand densities and basal areas of the J78 and J84 stands were still only half that of the control, but were equivalent to each other at 17.5 and 15.4 m^2/ha respectively. The mean tree and top height tree diameters were largest in the J78 stand and smallest in the control, but top heights were the same for all three stands. In the years following thinning, the J78 top height trees increased in height by 44%, and the J84 top height trees by 14%.

All three stands had a high proportion of Douglas-fir, with lodgepole pine contributing 2-17% of the stems and interior spruce and willow (*Salix* spp.) the remainder. The proportion of pine was highest in the J78 stand and lowest in the J84 stand. The percentage of dead stems larger than 3 cm present at the time of sampling ranged from 9 to 17%, with the highest proportion in the J78 stand and the lowest in the J84 stand. Willow accounted for more than 90% of the dead stems in the thinned stands.

Table 3.9: Summary of Douglas-fir stand characteristics in 1978.

	Control Untreated	J78 Pre-Treat	J84 Pre-Treat	J78 Post-Treat
sph all trees	23573	22107	17227	1306
ba (m^2/ha) all trees	19.3	25.5	23.1	5.4
sph trees > 3cm	6266 a	9226 b	7800 ab	1013
ba (m^2/ha) > 3cm	16.3 a	23.4 b	21.7 b	5.3
dbh mean (cm) >3cm	5.0 a	5.0 a	5.2 a	7.7
ht mean tree* (cm) > 3cm	550	550	560	730
hdr mean tree*	110	110	108	95
dbhtop (cm)	8.2 a	9.7 a	9.5 a	9.4
ht top tree* (cm)	760	830	850	820
hdr top tree*	93	86	90	87

Based on 15 plots per treatment, 3.99m in radius; '*' heights estimated from height vs diameter curves; pre-treatment values with same letter are not significantly different alpha=0.05.

Table 3.10: Summary of Douglas-fir stand characteristics in 1983.

	Control Untreated	J84 Pre-Treat	J78 Post-Treat	J84 Post-Treat
sph all trees	23168	17227	1239	1653
ba (m^2/ha) all trees	25.6	29.0	8.5	7.7
sph trees > 3cm	8543 a	8840 a	986	1573
ba (m^2/ha) > 3cm	21.7 a	27.7 b	8.4	7.4
dbh mean (cm) > 3cm	5.1 a	5.6 a	9.4	7.4
ht mean tree* (cm) > 3cm	570	610	830	730
hdr mean tree*	112	109	88	99
dbhtop (cm)	9.5 a	10.5 a	11.7	10.2
ht top tree* (cm)	890	950	920	930
hdr top tree*	94	91	79	91

Based on 15 plots per treatment, 3.99m in radius; '*' heights estimated from height vs diameter curves; pre-treatment values with same letter are not significantly different alpha=0.05.

Table 3.11: Summary of Douglas-fir stand characteristics in 1994.

	Control	J78	J84
sph live all trees	22273	1093	1506
ba (m^2/ha)	38.4	17.6	15.4
composition trees > 3cm (%)	F93P7	F81P17 S1W1	F98P2
sph live trees > 3cm	10973 a	1080 b	1506 b
ba (m^2/ha) trees > 3cm	35.4 a	17.5 b	15.4 b
sph standing dead > 3cm	1300	213	147
composition standing dead (%)	F53 P15W29S3	W91F9	W94F6
dbh mean (cm) >3cm	5.4 a	13.5 b	10.4 c
ht mean tree* (cm)	680	1000	830
h:d mean tree*	126	74	80
dbhtop (cm)	11.9 a	17.3 b	14.7 c
ht top tree (cm)	1070 a	1180 a	1060 a
hdr top tree	92 a	69 b	73 b

Composition codes: F=Douglas-fir, P=lodgepole pine, S=interior spruce, W=willow
*heights estimated from height vs diameter curves; values with same letter are not significantly different for alpha=0.05; trees less than 3cm dbh tallied not measured

The growth trajectories of the Douglas-fir and Sitka spruce stands are shown on the stand density management diagrams (Farnden 1996) in Appendix B - Figures B2.1 and B2.2. The stands were positioned on the diagram using stems-per hectare, top heights and quadratic mean diameters (calculated from sph and basal area) from Tables 3.7 to 3.11. The Sitka spruce and Douglas-fir control stands are within the zone of imminent competition mortality. The thinned stands have yet to cross this zone but the spruce stand is closer than the fir stands.

3.2.11 Sample Tree Characteristics

The mean and range in height, stem diameter inside bark at 1.3m and height-diameter ratio inside bark (HDR) for the sample trees in the year of treatment and at the time of sampling are summarized in Table 3.12 and 3.13. Height and diameters for years prior to the sampling year were determined from radial increments in disk 4 (1.3m) and height increment measurements.

For the Sitka spruce, the mean tree diameter, height and tree volume at the time of thinning in 1980 were not significantly different for the thinned and control samples, but mean HDR was 15% lower for the control sample. The overall difference in HDR between treatments reflects the fact that there are three dominant trees in the thinned sample and only two in the control. Fewer dominants were sampled because they couldn't be safely felled. Comparison of the equations relating HDR to DIB indicated that sample trees from both control and thinned treatments of a given diameter have equivalent HDR's in 1980. In 1993, the mean heights were not significantly different for thinned and control samples, but tree volume and diameter were larger for the thinned sample and HDR was smaller.

No significant differences were found for the means of these variables for any of the treatments in 1978 at the Douglas-fir site. The J84 means for these variables were not significantly different from the controls in 1983. In 1994 diameter was larger and HDR was lower for both thinning treatments compared to the control, but there was no difference between the two thinning treatments. The average height of the sample trees in 1994 was the same for all three treatments.

Table 3.12: Sample tree attributes at the time of treatment[1].

Species	Treatment	Year	# Trees sampled	Height mean, range (m)	DIB mean, range (cm)	HDRIB mean, range
Sitka spruce	Control	1980	12	13.8 9.1-18.7	12.4 5.8-19.5	118 81-156
	Spaced 1980	1980	13	15.0 10.5-18.6	15.6 7.5-21.9	100 82-139
Douglas-fir	Control	1978	15	5.8 3.4-9.6	4.9 2.7-10.9	124 88-166
	"	1983	"	6.5 4.1-10.7	5.3 3.2-12.0	121 89-183
	Spaced 1978	1978	15	6.2 3.8-10.2	5.6 2.6-10.9	117 93-149
	Spaced 1984	1983	15	7.4 5.3-10.3	6.3 3.9-10.6	123 97-156

[1] Douglas-fir control trees in 1978 and 1983 are the same trees. Values determined by back-dating height and stem increment.

Table 3.13: Sample tree attributes at the time of sampling[1].

Species	Treatment	# Trees sampled	Height mean, range (m)	DIB mean, range (cm)	HDRIB mean, range	LCR mean, range
Sitka spruce	Control	12	18.2 14.0-24.7	15.9 8.1-27.4	123 82-174	44 32-58
	Spaced 1980	13	19.8 15.0-24.8	23.1 12.7-32.2	88 72-119	61 50-80
Douglas-fir	Control	15	8.8 5.5-12.5	7.0 4.0-14.0	134 90-203	45 33-72
	Spaced 1978	15	10.2 6.1-17.0	11.2 5.6-19.7	94 78-112	67 49-80
	Spaced 1984	15	9.3 6.6-12.4	9.5 5.5-14.6	101 85-129	58 45-70

[1]Sampling in 1993 for Sitka spruce, 1994 for Douglas-fir

3.3 Results

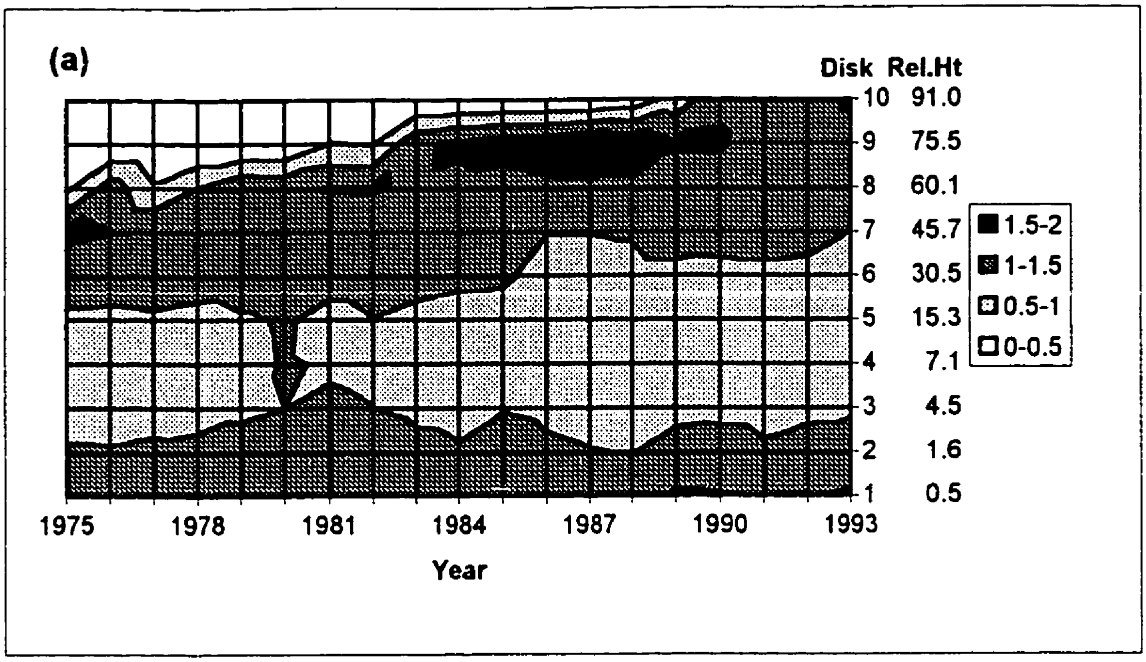
3.3.1 Longitudinal and Radial Growth Patterns in the Stem

3.3.1.1 Longitudinal Allocation of Radial Increment

In order to investigate the pattern of radial increment along the bole, the mean ring increment at each disk height was divided by RVSA to determine the 'relative ring increment' in each year. The distribution of relative ring increment along the bole over time is shown in Figures 3.4 and 3.5. Disks 1 to 4 were sampled at the same fixed heights on all trees. The relative heights for the other disks were similar on all trees and are shown as a percentage of total tree height at the time of sampling.

These figures are intended to illustrate the pattern of allocation averaged for all trees in each treatment. For simplicity of calculation, two assumptions were made in constructing the figures: i) while the relationship between RVSA and 'average ring width along the bole' varies slightly depending on ring shape, RVSA was used as a surrogate for 'average ring width along the bole'; ii) the number of rings in upper disks varies from tree to tree depending on height growth rates. In years where fewer than 75% of sample trees contributed to the estimate of relative ring increment in the uppermost disk, the average value was not calculated.

In the pre-treatment years and for control trees throughout the period of measurement for both species, the rings are widest in the upper crown and narrowest in the branch free bole above the region of buttswell. In the years immediately following thinning, for both spruce and fir, the relative ring width in the crown declines, width at the stem base increases, and the zone of minimum width moves up the bole. The changing allocation of radial growth along the stem is captured by the variable RV50 for which the trend over time is shown in Section 2.



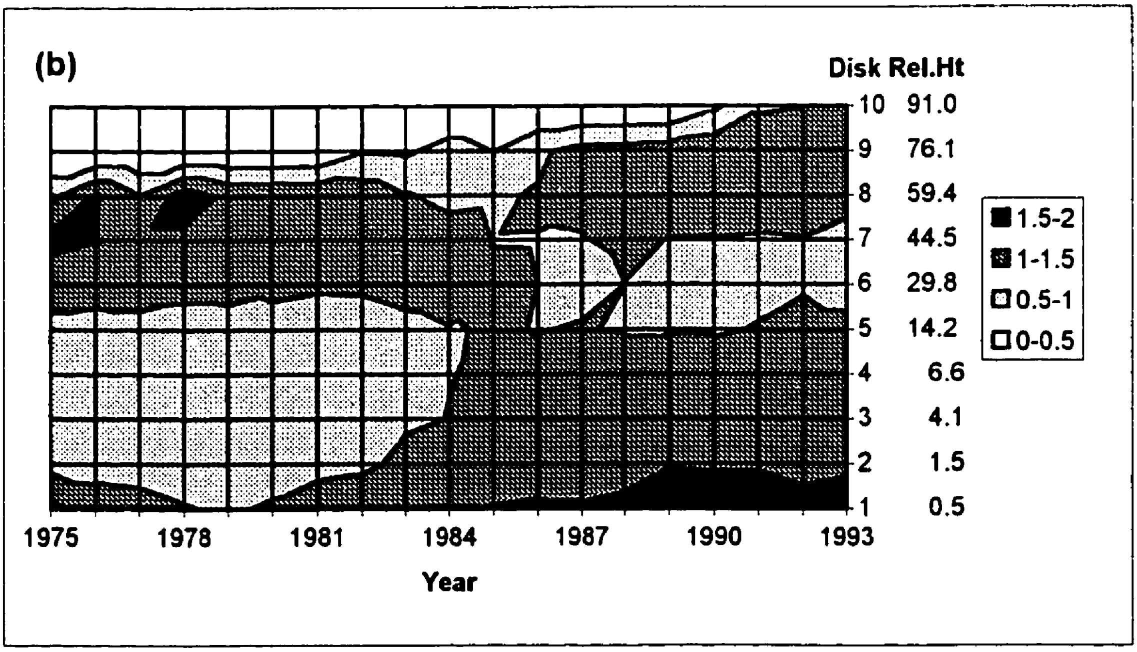


Figure 3.4: Relative ring increment at different bole heights in each year for Sitka spruce (a) control and (b) thinned 1980 treatments. Relative ring increment is the ratio of mean ring increment at a given height to mean radial increment over the whole stem (RVSA). Heights of disks as a percent of tree height in 1993 (Rel.Ht) are shown next to disk number. Darker shading indicates greater relative increment. Result shown is mean for all trees in sample.

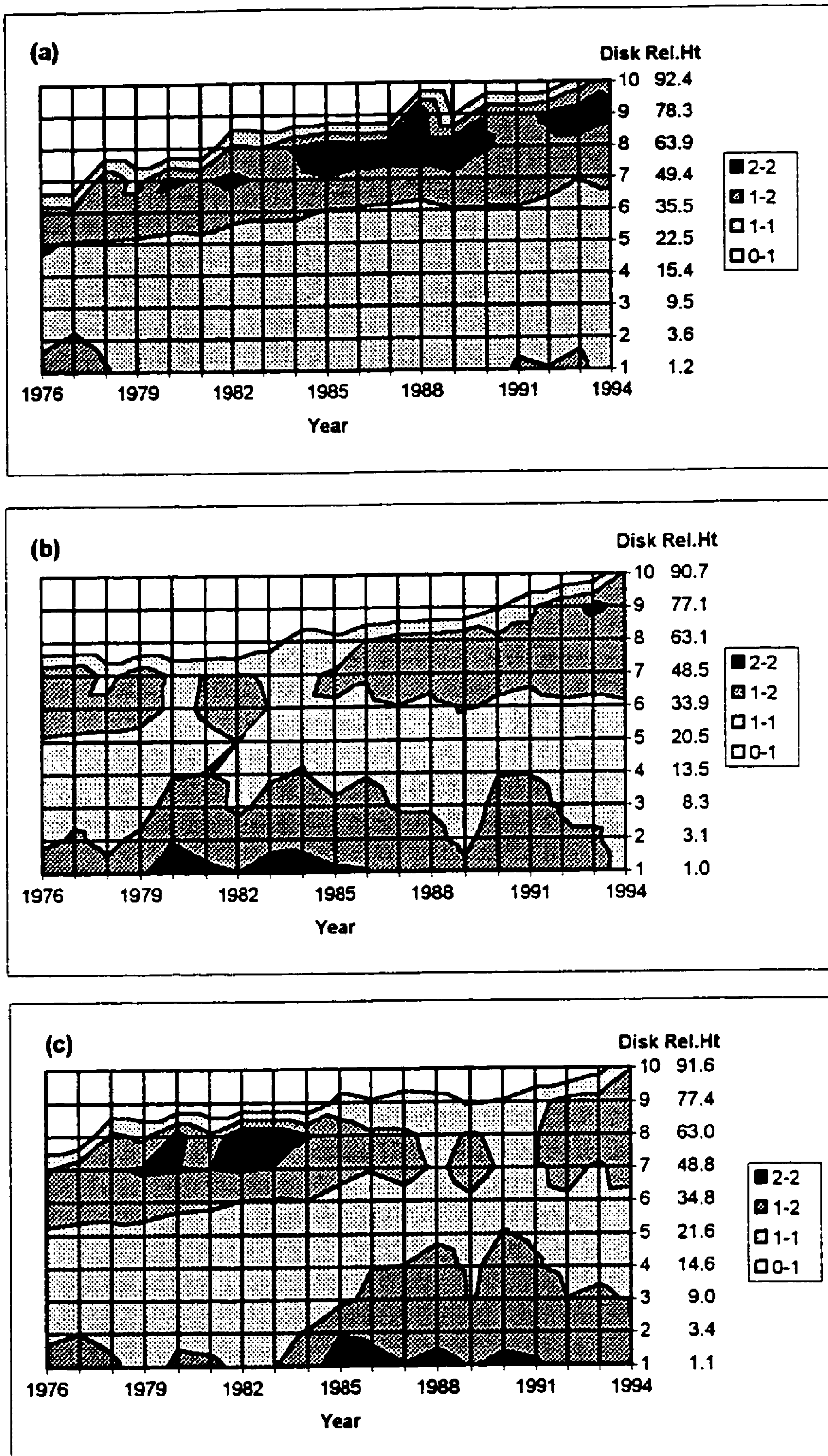


Figure 3.5: Relative ring increment at different bole heights in each year for Douglas-fir (a) control, (b) thinned 1978 and (c) thinned 1984 treatments. Relative ring increment is the ratio of mean ring increment at a given height to mean radial increment over the whole stem (RVSA). Heights of disks as a percent of tree height in 1994 (Rel.Ht) are shown next to disk number. Darker shading indicates greater relative increment. Result shown is mean for all trees in sample.

3.3.1.2 Stem Radius by Direction

The measurement of stem radius in each of the four cardinal directions on each disk enabled the directional allocation of wood to be analyzed. For directional analyses, the relative radius is the ratio of radius inside bark for a given direction to mean disk radius inside bark, for each disk. Figures 3.6 and 3.7 show the relative stem radius at the time of sampling at each disk height for each cardinal direction. The control spruce trees were 15% wider on the north side than on the south side at the base. The thinned spruce were widest on the east side at the base and on the south and east sides in the crown. For the control fir trees, the stems were about 5% wider on the north and east sides than on the south and west sides along the whole bole. For the thinned fir trees, the stems were about 15% wider on the north side than on the south side at the base. This tendency diminishes with height and the J84 trees were slightly wider on the south side than on the north in the upper crown.

The patterns of mean hourly wind speed by direction and frequency of hourly wind speed by direction for the AES weather station nearest each site are shown in Figures 3.8 and 3.9. These values are averaged from 40 years of monthly data for the Sandspit Station and 32 years of monthly data for the William's Lake station. Winds from the southeast predominate at both stations during fall, winter and spring months. During the summer, winds from the north and northwest are similar in frequency and speed to southeast winds at William's Lake. At Sandspit during the summer, winds from the west are similar in frequency and wind speed to southeast winds.

For the Douglas-fir thinned treatments and the spruce control, there is an apparent correspondence between the direction of maximum stem radius at the base of the tree and the dominant direction towards which winds blow during fall, winter and spring. The direction of maximum radius at the base of the thinned spruce trees lines up better with the direction towards which summer winds blow.

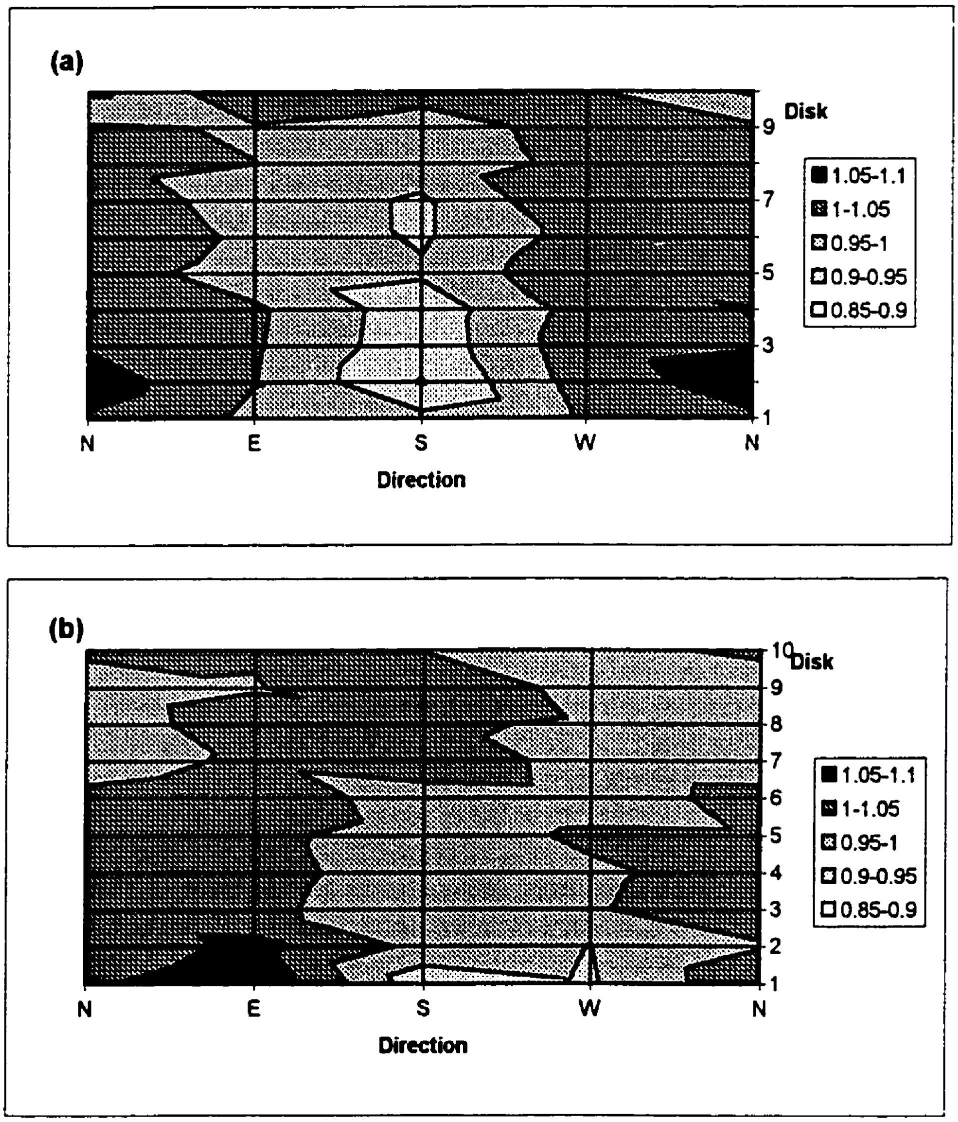


Figure 3.6: Relative stem radius by direction at different bole heights in 1993 for Sitka spruce (a) control, and (b) thinned 1980 treatments. Relative stem radius is the ratio of stem radius in a given direction at a given height to the mean stem radius at that height. Darker shading indicates greater relative radius. Result shown is mean for all trees in sample.

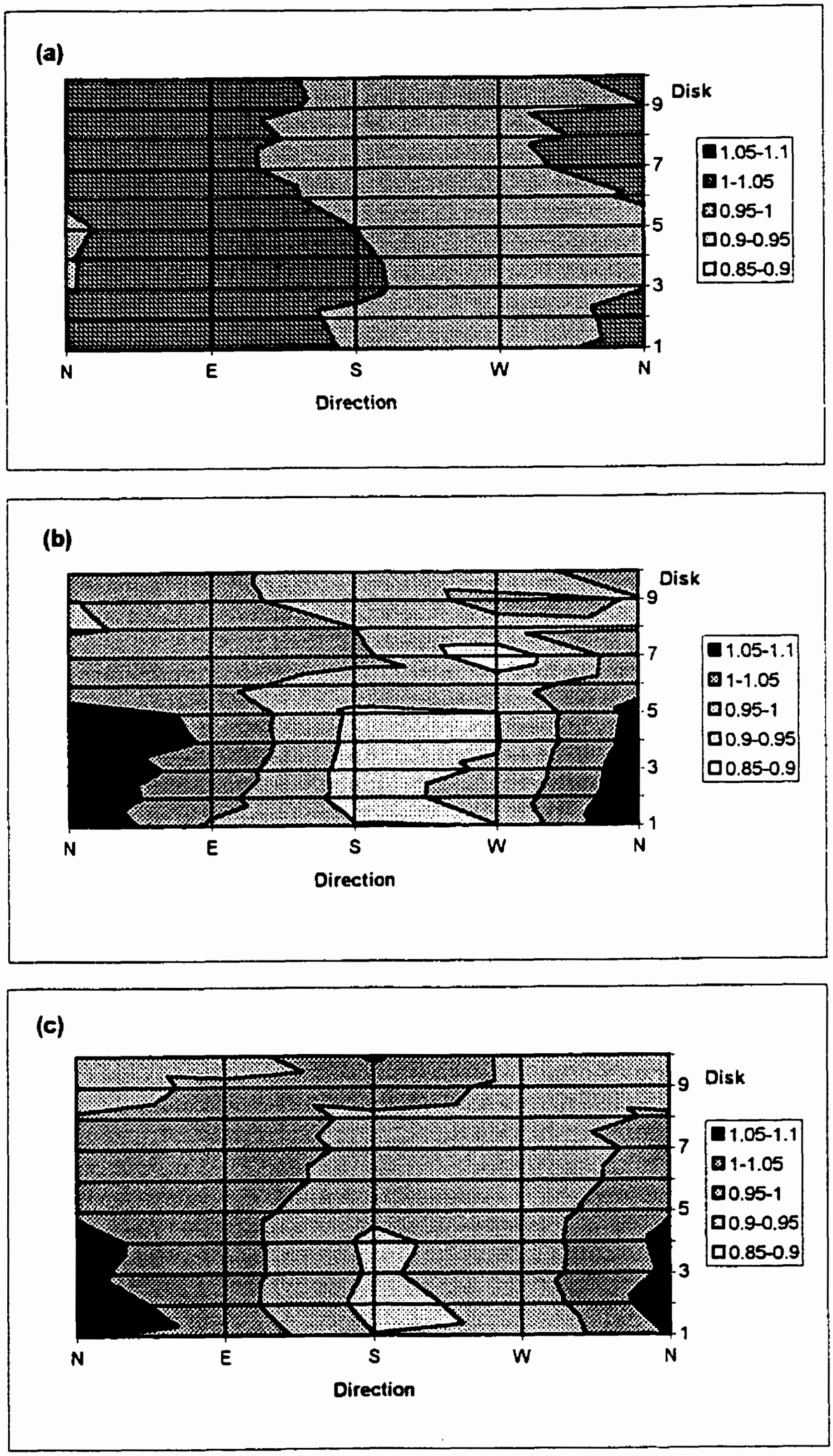


Figure 3.7: Relative stem radius by direction at different bole heights in 1994 for Douglas-fir (a) control, (b) thinned 1978 and (c) thinned 1984 treatments. Relative stem radius is the ratio of stem radius in a given direction at a given height to the mean stem radius at that height. Darker shading indicates greater relative radius. Result shown is mean for all trees in sample.

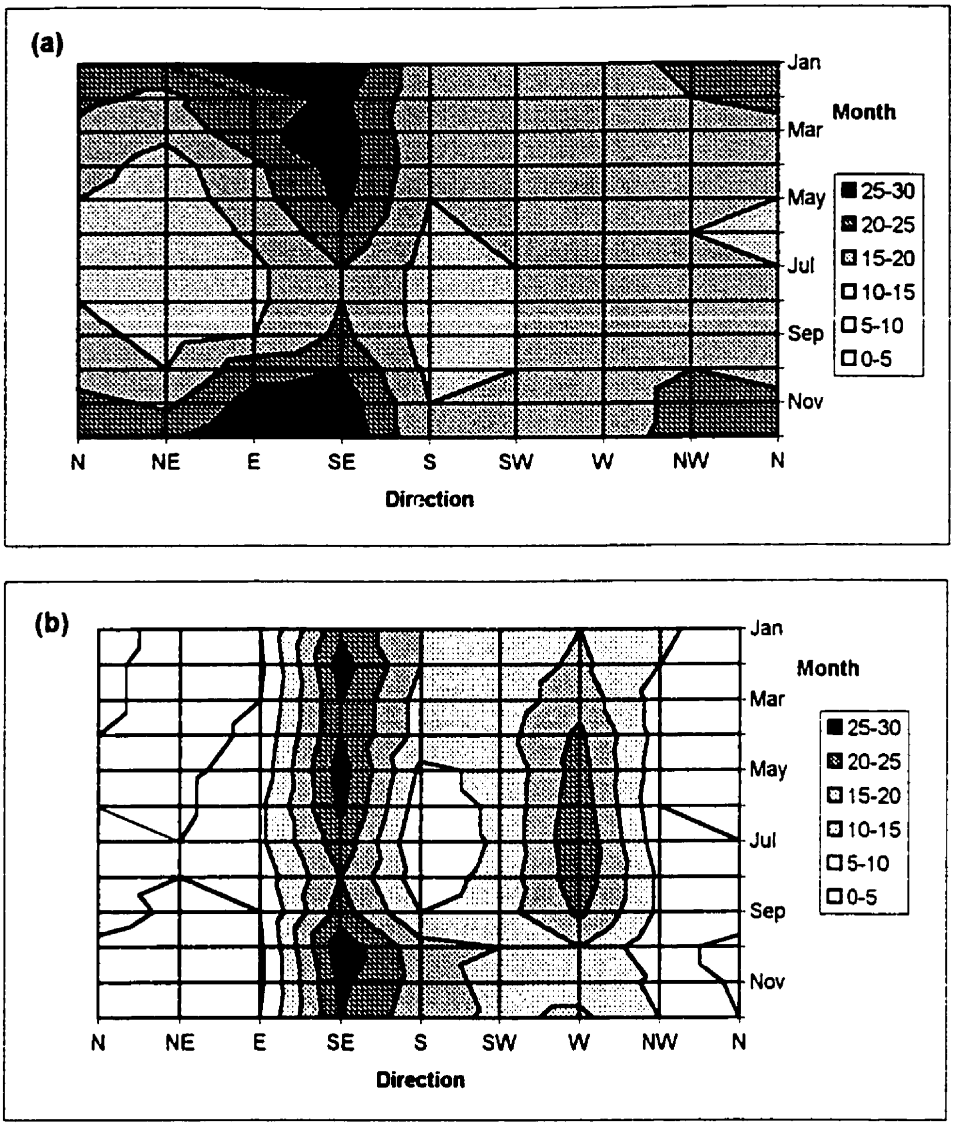


Figure 3.8: (a) Mean hourly wind speed by direction, and (b) frequency of hourly wind by direction at the Sandspit Airport. Darker shading indicates higher wind speed (km/h) for (a), and higher frequency (%) for (b).

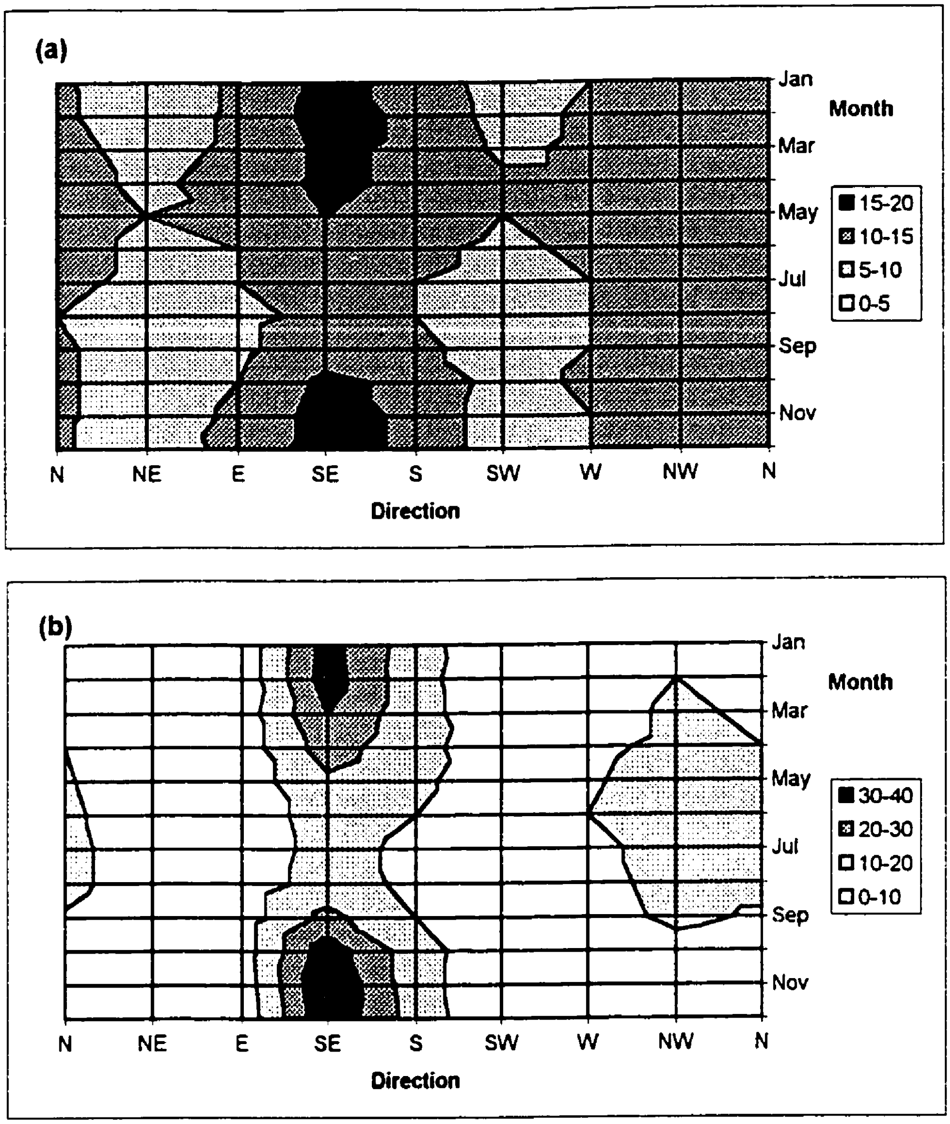


Figure 3.9: (a) Mean hourly wind speed by direction, and (b) frequency of hourly wind by direction at the William's Lake Airport. Darker shading indicates higher wind speed (km/h) for (a), and higher frequency (%) for (b).

3.3.1.3 Directional Allocation of Radial Increment

In order to investigate the pattern of radial allocation further, the relative ring increment along the stem for each radius was plotted over time. Relative ring increment is the ratio of ring increment in a given direction to mean ring increment for that year on a given disk. Both thinned fir treatments showed increased radial growth on the north side of the lower stem in the years immediately following thinning. This was very pronounced for the J84 trees. The growth pattern on the south side of these trees showed the opposite pattern, reduced radial growth of the lower stem in the years immediately following thinning. In later years following thinning, radial growth in the upper crown was greater on the south side than on the north for both thinning treatments (Figures 3.10 and 3.11). Directional differences in yearly radial growth pattern were less apparent for the control and thinned spruce and these figures are not shown.

While the direction and timing of radial allocation responses following thinning was suggestive of adaptive growth, the orientation of peak radius did not line up perfectly with predominant southeast wind direction for either Douglas-fir or spruce. Summer westerlies may have contributed to the development of wood on the east side of the lower bole on the spruce site. At William's Lake, summer winds were from the north and northwest so that explanation works less well for the Douglas-fir. Both sites were some distance from the weather stations in rolling terrain, so local modification of wind direction may have contributed to the variation.

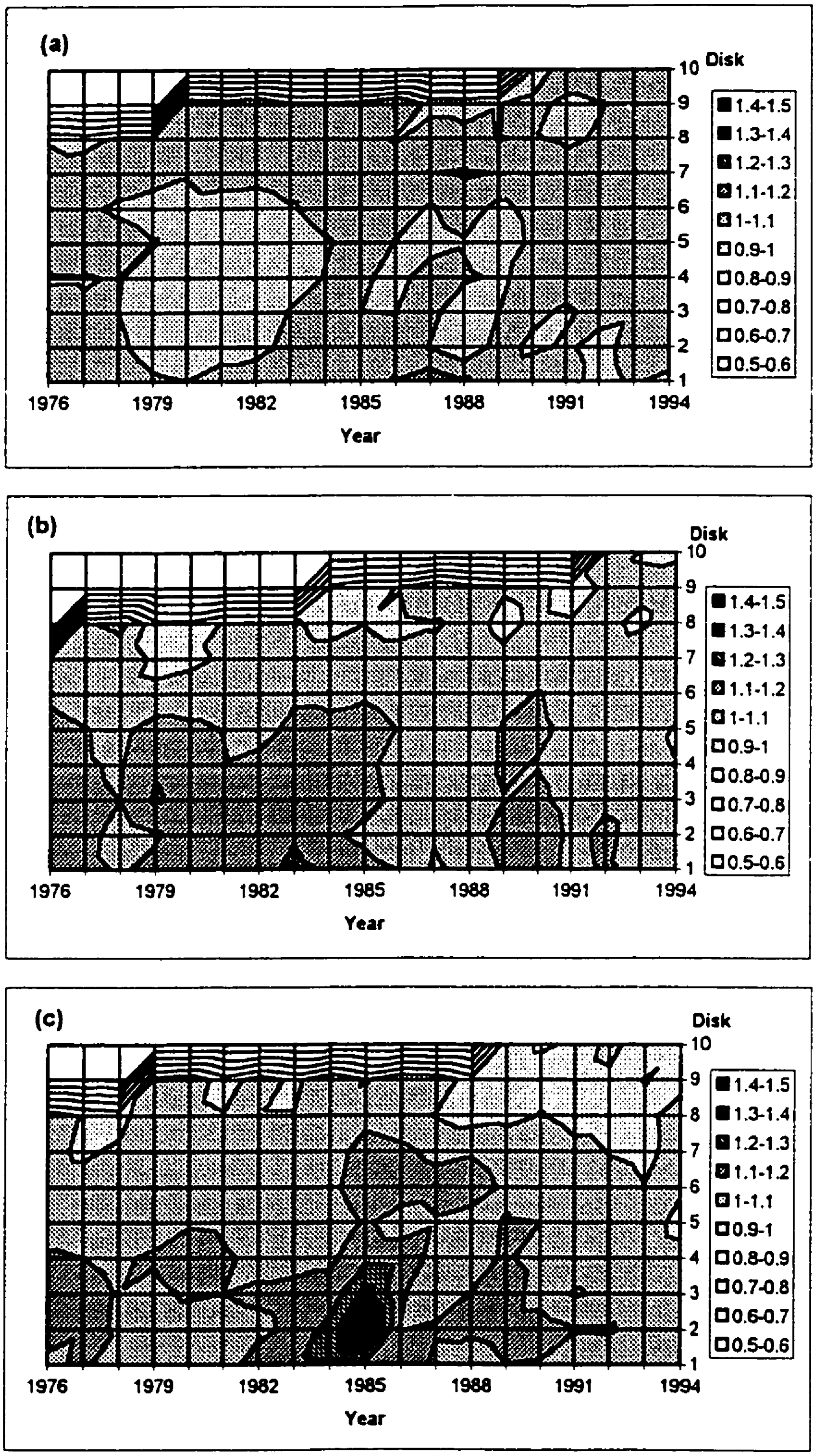


Figure 3.10: Relative ring increment on north side of tree at different bole heights in each year for Douglas-fir (a) control, (b) thinned 1978, and (c) thinned 1984 treatments. Relative ring increment on north side is the ratio of ring increment on the north side at a given height to mean ring increment for all directions at that height. Darker shading indicates greater relative increment. Result shown is mean for all trees in sample.

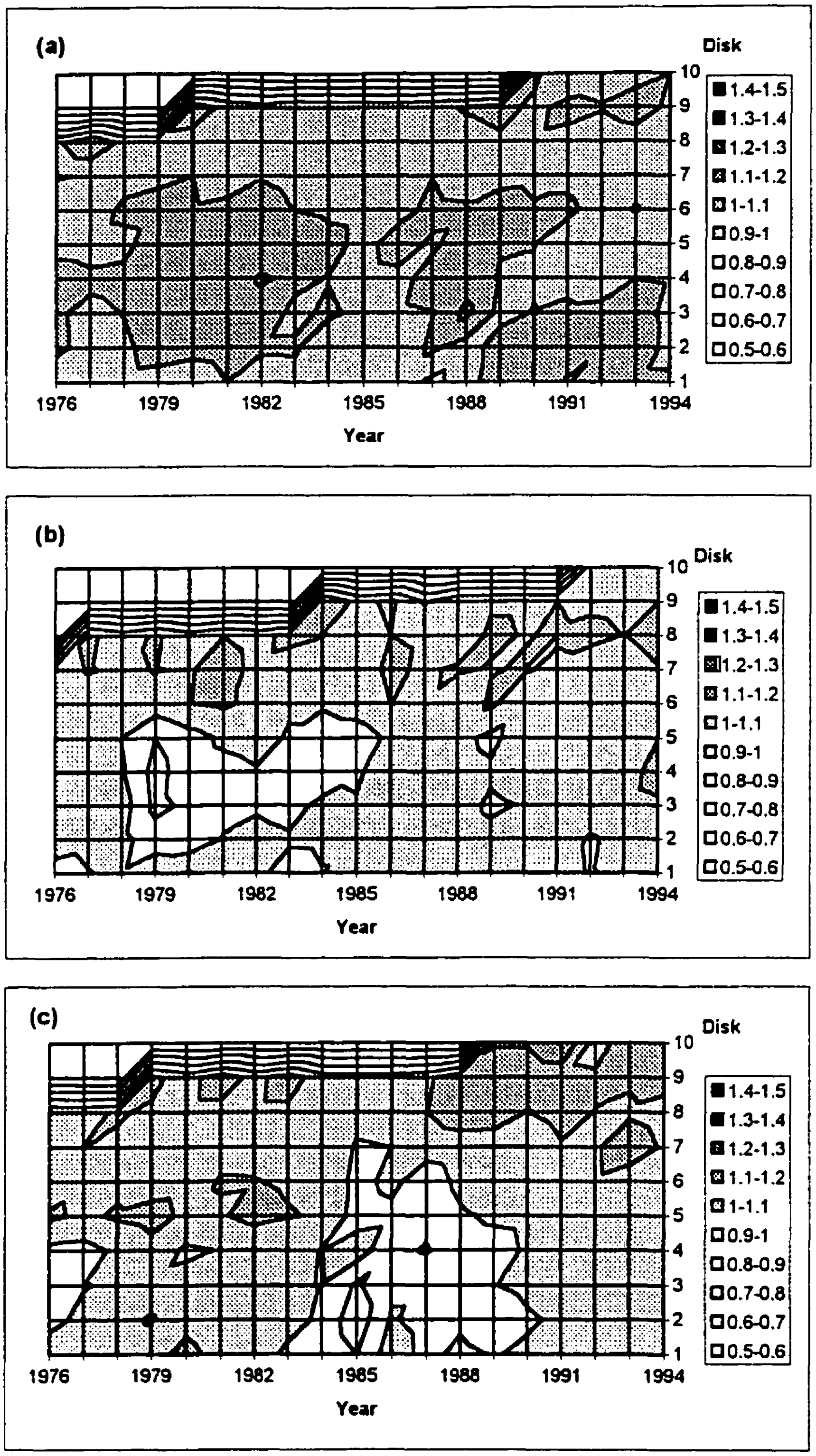


Figure 3.11: Relative ring increment on south side of tree at different bole heights in each year for Douglas-fir (a) control, (b) thinned 1978, and (c) thinned 1984 treatments. Relative ring increment on south side is the ratio of ring increment on the south side at a given height to mean ring increment for all directions at that height. Darker shading indicates greater relative increment. Result shown is mean for all trees in sample.

3.3.2 Trends in Response Variables by Treatment

3.3.2.1 Height Increment, Radial Increment and Allocation

In order to investigate the growth patterns following thinning, response variables were analyzed using repeated measures analysis of variance. The Tukey-Kramer test was used to test for significant differences between control and thinned means in each year (SAS 1989). The trends in growth response variables over time with standard error bars are shown in Figures 3.12 to 3.14. The years in which treatment and control means were significantly different are noted on the figures.

Following thinning, height increment (HTINC) decreases for a short time and then rebounds and becomes equal to or greater than the control. This cross over occurs 5 years after thinning for spruce, and 4 years for the fir. Relative to the control trees, HTINC continues to increase until year 10 for spruce and year 6 for the J78 fir. The J84 fir HTINC is similar to the control until the year of sampling, 11 years after treatment. The variation in HTINC is reduced in the years immediately following thinning and then increases, becoming similar to that of the control in later years (Figure 3.12).

For spruce, RVSA begins increasing the year following thinning, peaking 3 years after thinning. For the fir, radial increment (RVSA) begins increasing 2-3 years after thinning, peaking 5 and 7 years after thinning for the J78 and J84 treatments respectively (Figure 3.13). Basal allocation (RV50) increases 3 years after thinning for spruce and 2 years after thinning for fir. It begins to subside 5 years after thinning for spruce, 6 years for the J78-fir and 5 years for the J84-fir (Figure 3.14). RV50 is more stable from year to year than RVSA, dropping only slightly during the period 1987-1989 at the fir site. Thinning increased the between tree variability in RV50 only for the J84-fir treatment.

The drop in RVSA for the CON and J78 treatments from 1987 to 1989 was consistent with diameter increment patterns observed at other sites in the central interior in the late 1980's (J. Dobry unpublished data, 1999). Dobry attributed this to a period of low annual precipitation from 1986-1988. The 5-year running average precipitation at Quesnel, William's Lake and 100 Mile House (Figure 3.15) shows that the drought occurred across the region. The annual precipitation for the 100 Mile House station (Figure 3.15) was lowest in 1987, but minimum RVSA lagged by a year. The increase in RVSA in all three fir treatments in the early 1990's was also consistent with Dobry's findings and may reflect the increasing precipitation in those years. The pattern in HTINC in the J78 and CON treatments during this period was similar to that of RVSA.

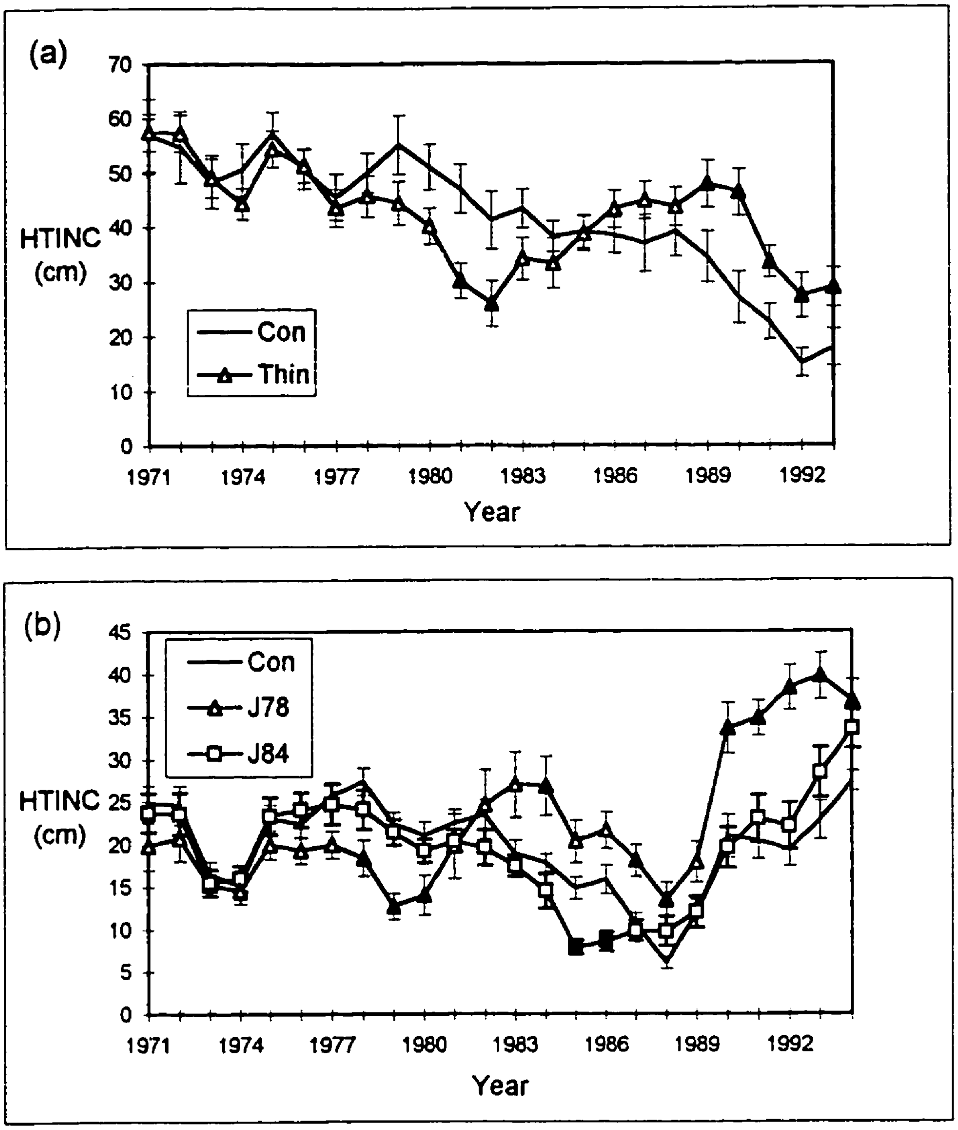


Figure 3.12: Mean height increment (HTINC) by year for (a) Sitka spruce and (b) Douglas-fir. Error bars show standard error. Symbols at data points in years with a significant difference in slope between treatment and control are solid .

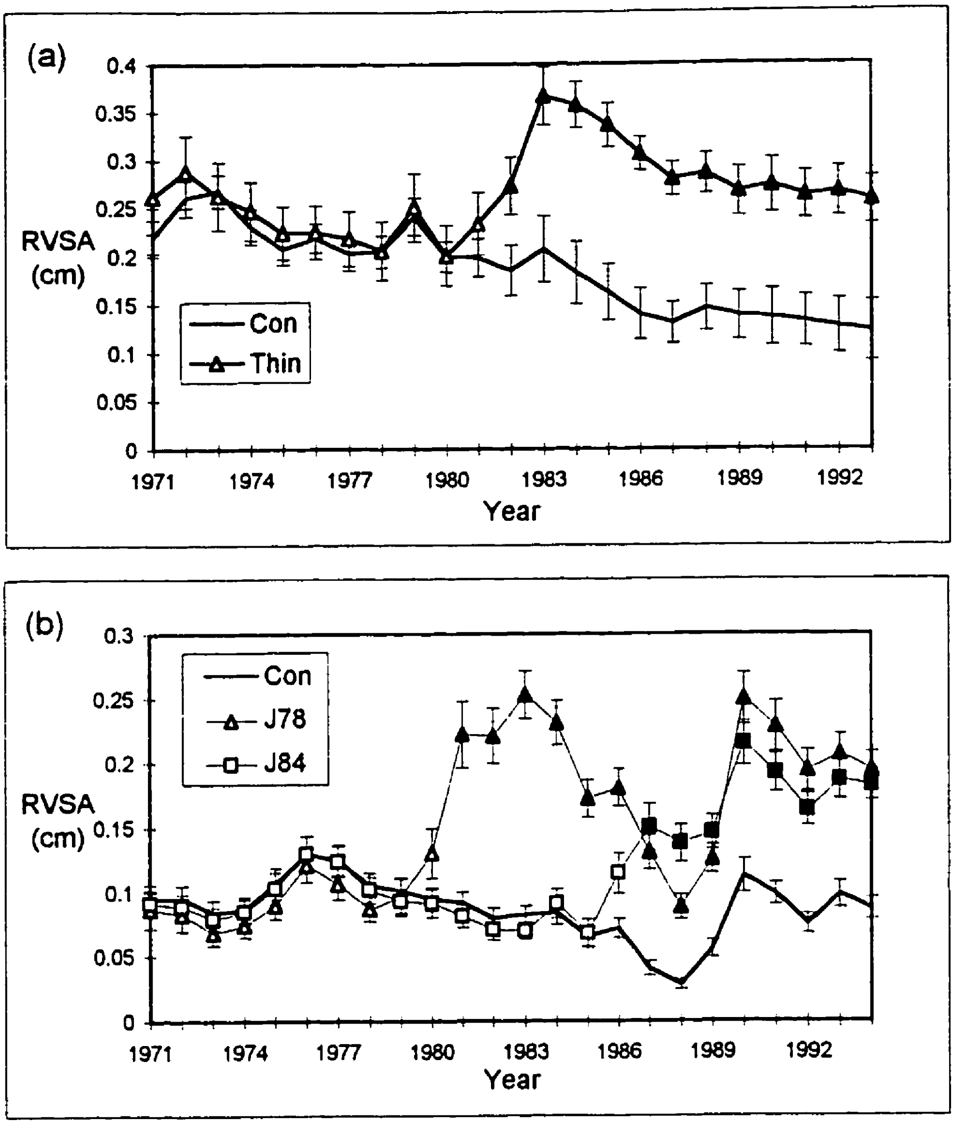
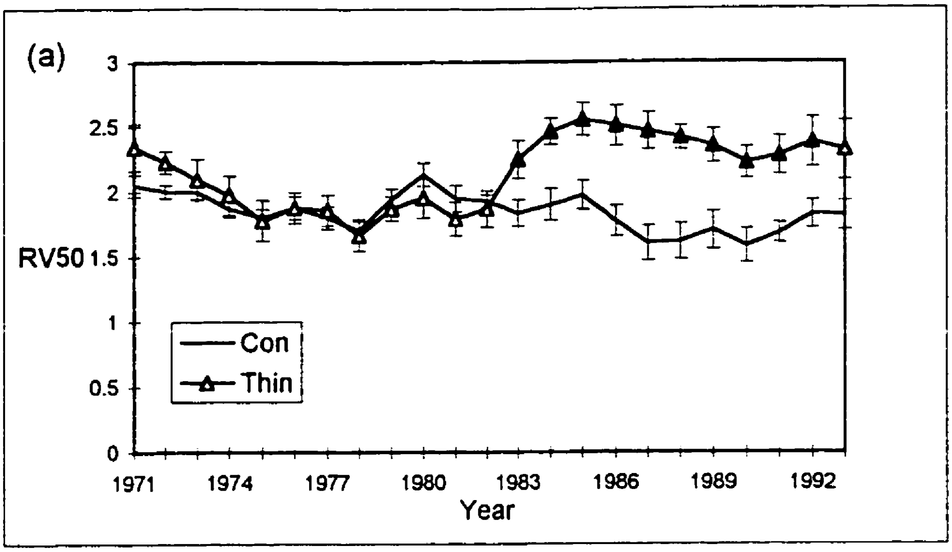


Figure 3.13: Mean radial increment over whole stem (RVSA) by year for (a) Sitka spruce and (b) Douglas-fir. Error bars show standard error. Symbols at data points in years with a significant difference in slope between treatment and control are solid.



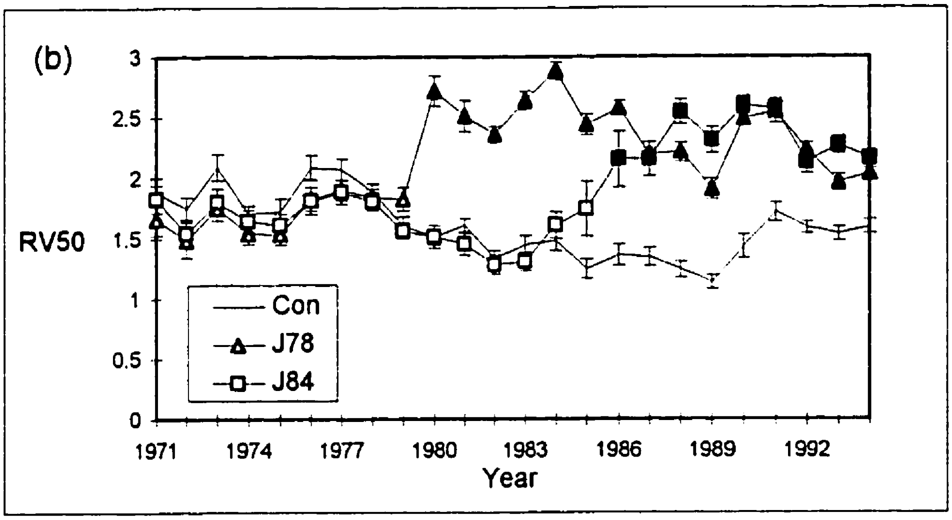


Figure 3.14: Mean basal allocation (RV50) by year for (a) Sitka spruce and (b) Douglas-fir. Error bars show standard error. Symbols at data points in years with a significant difference in slope between treatment and control are solid.

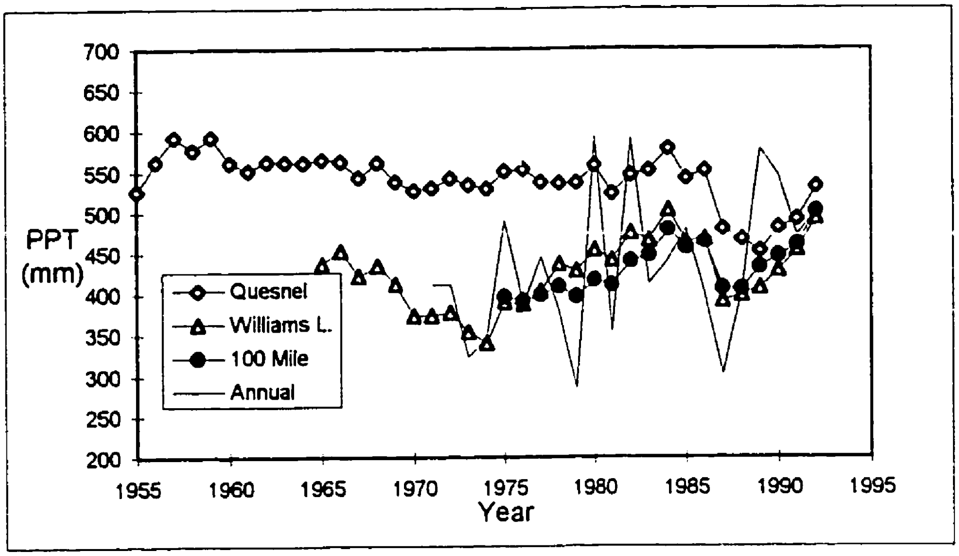


Figure 3.15: Annual precipitation for 100 Mile House, and five-year running average precipitation for 100 Mile House, William's Lake and Quesnel.

3.3.2.2 Stem Volume and Slenderness

In the thirteen years since thinning, the thinned spruce trees tripled in volume (TRVOL) while the control trees doubled in volume (Figure 3.16). Thinning doubled the growth rate while the rate of volume increase remained relatively constant over time for the controls. The J78 thinned fir grew six times larger in the 16 years since treatment, during which time the control trees tripled in size. The J84 thinned trees grew 4 times larger in the 11 years since treatment during which time the control trees doubled in size. While there was more variation in growth rate from year to year in the fir than in the spruce, the rate of growth remained relatively constant over the long term for the control trees at both sites.

For the control spruce, the height-diameter ratio (HDR) continued to increase each year with a slight decline in the last three years before sampling (Figure 3.17). For the thinned spruce, HDR began declining immediately after treatment with a period of steep decline in years 2-5 after treatment. The rate of reduction in HDR then declined, becoming nearly constant between years 7-10, followed by a slight further decline in the two years immediately prior to sampling, which mirrored the reduction in the control trees. The HDR was declining prior to 1977 in the fir control and was relatively constant in the J78 and J84 treatments. The control and J84 HDR's began increasing in 1978. Following thinning, the HDR for the J78 treatment began declining immediately, with a period of steep decline occurring between years 2-6 after treatment. The reduction in HDR then slowed, becoming nearly constant between years 8-16 after treatment. The HDR leveled following thinning in the J84 treatment and steeply declined between years 3-8 after treatment. The reduction in HDR then slowed, becoming nearly constant in years 10 and 11 after treatment, the last years before sampling.

During the post-adjustment period for the thinned treatments, when HDR was relatively constant, TRVOL continued to rapidly increase in size. For both the J78 and J84 Douglas-fir treatments, the rate of increase in TRVOL was highest in the four years immediately preceding sampling in 1994.

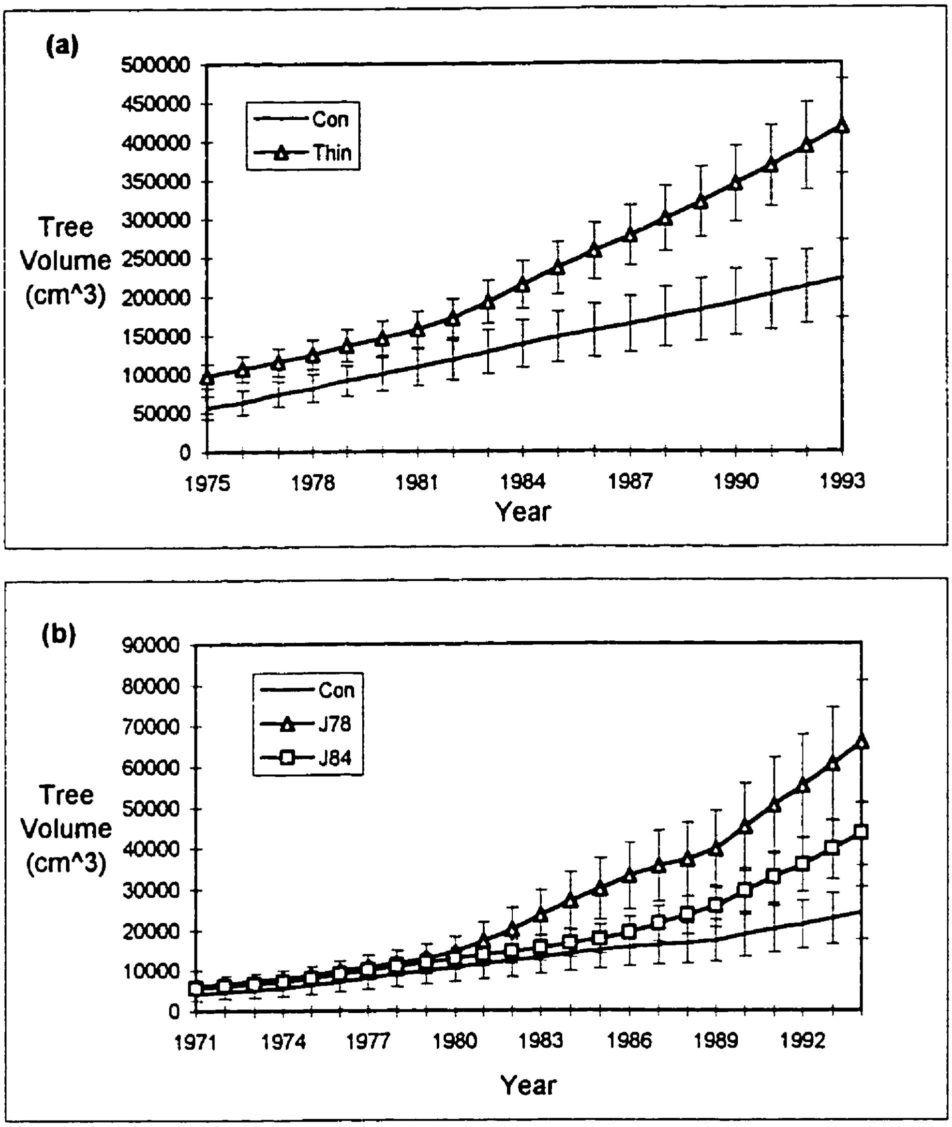


Figure 3.16: Mean tree volume (TRVOL) by year for (a) Sitka spruce, and (b) Douglas-fir. Error bars show standard error.

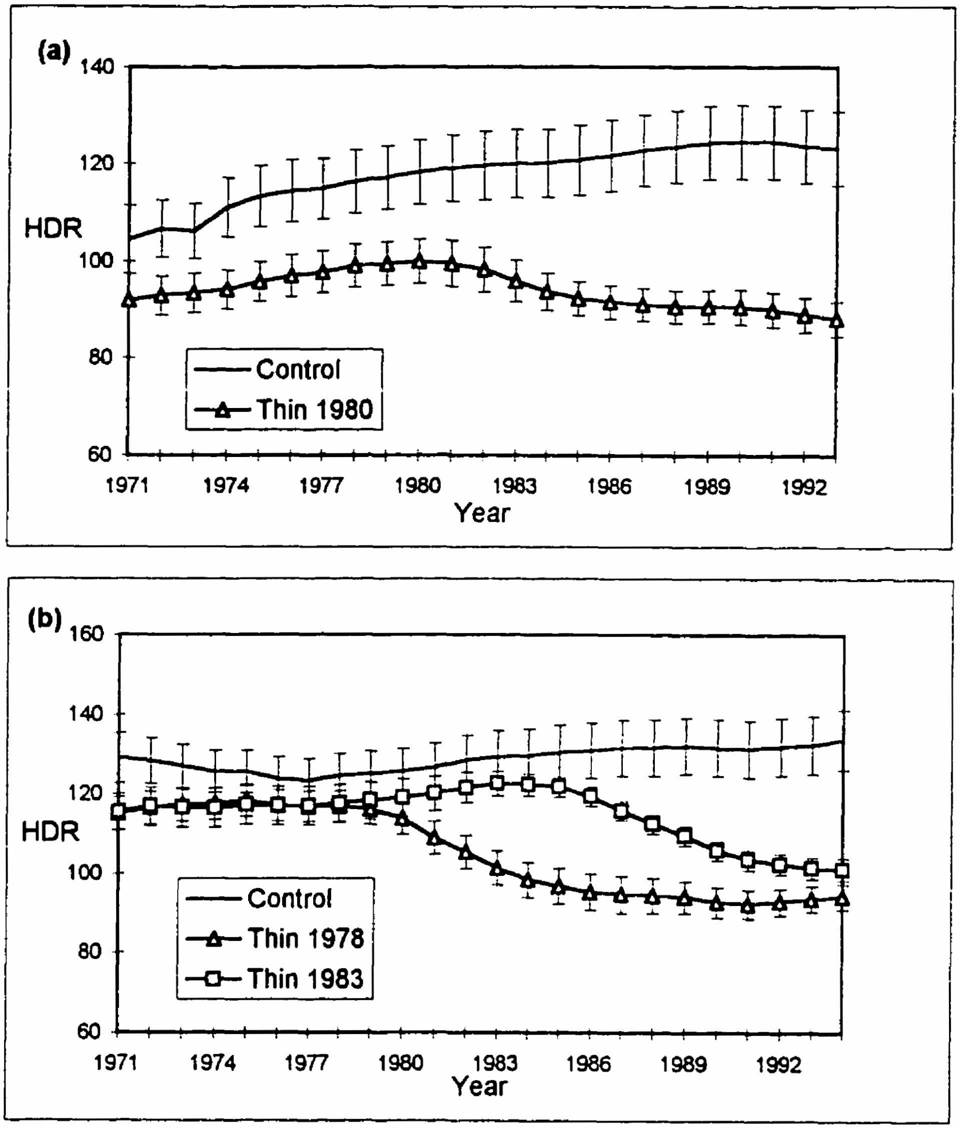


Figure 3.17: Mean height-diameter ratio (HDR) by year for (a) Sitka spruce and (b) Douglas-fir. Error bars show standard error.

3.3.3 Role of Relative Growth Responses in Slenderness Adjustment

The adjustment in HDR resulted from the combined effects of reduced height increment, increased stem increment, and increased basal allocation of stem increment. The contribution of each of these growth responses varies with time from thinning. In Figures 3.18 and 3.19, the HDR curve is superimposed over the curves of relative height increment (RHTINC), relative radial increment (RRVSA) and relative basal allocation (RRV50). The relative post-treatment responses were calculated by dividing the yearly value by the weighted mean for the three years prior to treatment (w_t=0.50, w_{t-1}=0.33, w_{t-2}=0.17). For the thinned spruce and fir treatments, the post-thinning HDR curves had a reverse-S shape and could be divided into four time periods: i) from time of treatment to initial downward inflection, ii) period of rapid HDR reduction, iii) inflection where HDR adjustment slows, iv) period of relatively constant HDR.

For the thinned spruce, the initial downward inflection in HDR resulted from a reduction in height increment and increase in radial increment, with no change in allocation. The period of rapid HDR reduction resulted from a large increase in radial increment and basal allocation, and low but gradually increasing height increment. During the period of reduced HDR adjustment, radial increment subsided, height increments recovered to pre-thinning levels, and basal allocation remained high. In the period of constant HDR, radial increment and basal allocation remain higher than pre-thinning levels but continued to slowly subside, while height increment recovered and gradually increased. There was a further period of HDR reduction in the last three years prior to sampling which resulted from greatly reduced height increment.

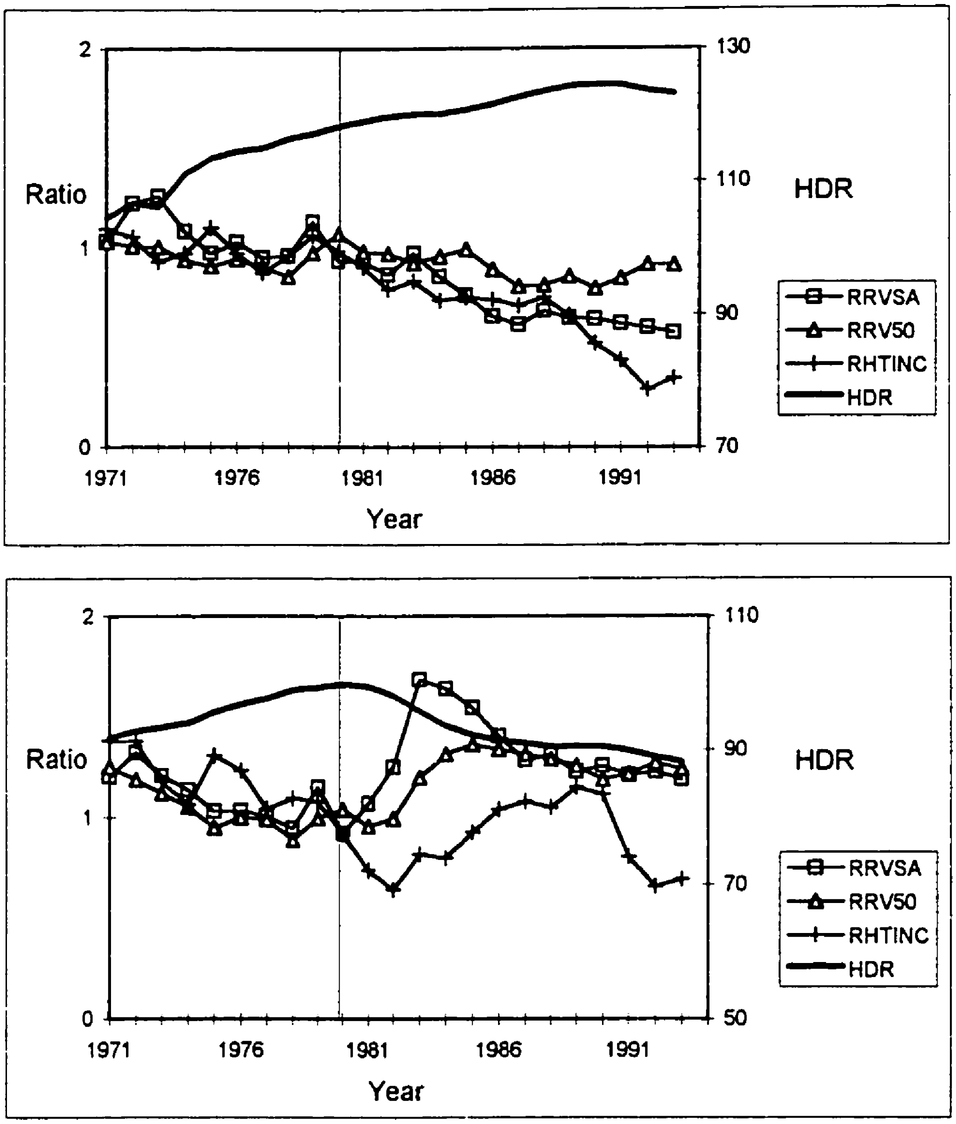


Figure 3.18: Relative growth responses (RHTINC, RRVSA and RRV50) superimposed over mean height-diameter ratio (HDR) by year since thinning for Sitka spruce (a) control, (b) thinned 1980 treatments. Relative growth responses are the ratio of yearly response to weighted 3-year pre-treatment mean response. The vertical line indicates the pre-treatment reference year.

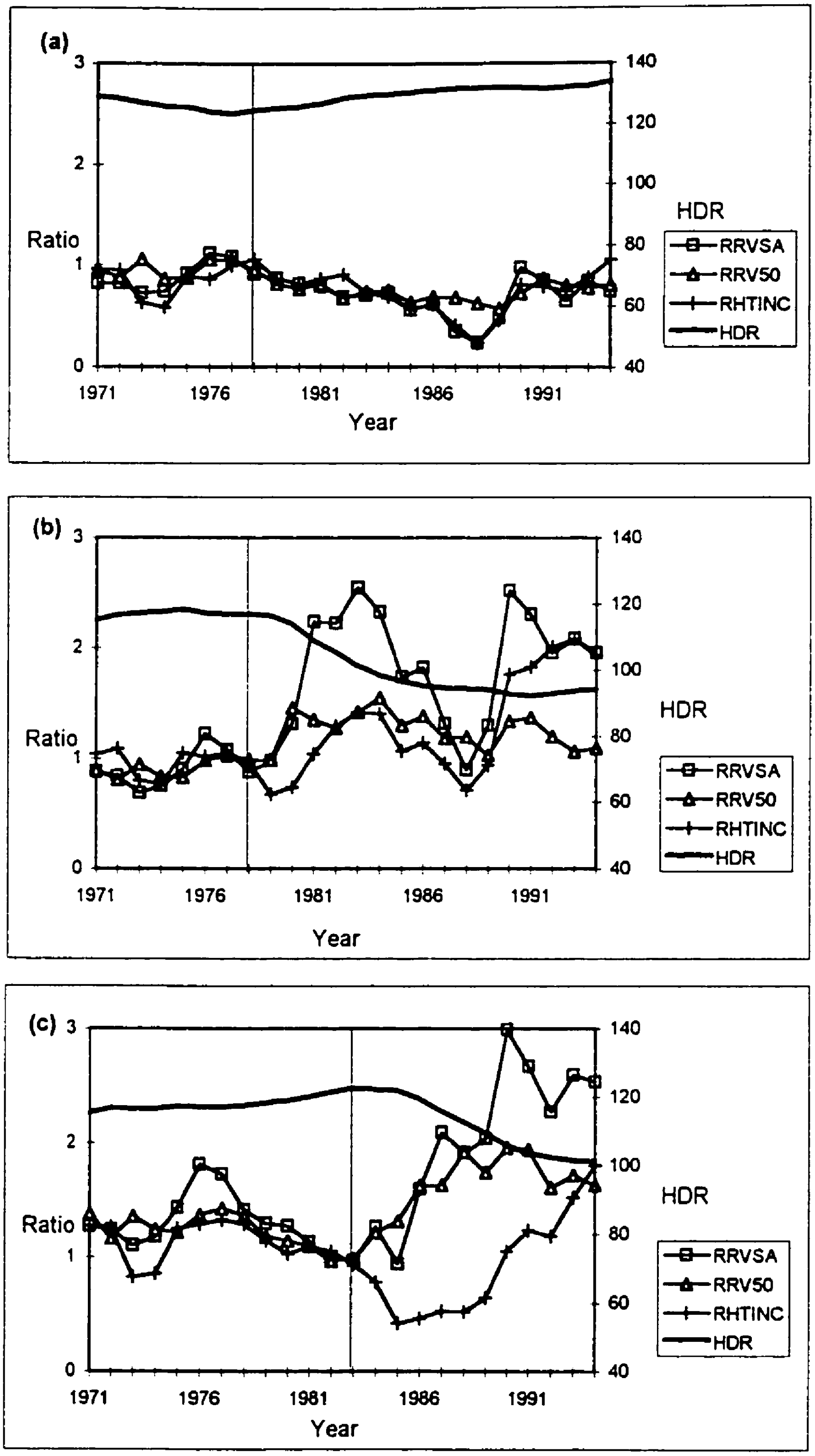


Figure 3.19: Relative growth responses (RHTINC, RRVSA and RRV50) superimposed over mean height-diameter ratio (HDR) by year since thinning for Douglas-fir (a) control, (b) thinned 1978 and (c) thinned 1984 treatments. Relative growth responses are the ratio of yearly response to weighted 3-year pre-treatment mean response. The vertical line indicates the pre-treatment reference year. Note, the 1984 thinning preceded that years growth period.

For the 1978 thinned fir, the initial downward inflection in HDR resulted from a reduction in height increment and increases in both radial increment and basal allocation. During the period of rapid HDR adjustment, height increment recovered and exceeded pre-thinning levels, and radial increment and basal allocation peaked. During the period where HDR adjustment slowed, height increment, radial increment and basal allocation dropped, with allocation dropping the least. The beginning of the period of relatively constant HDR coincided with the drought of 1986-88 during which radial and height increment dropped to pre-thinning levels, while allocation was less affected. All three growth response measures rebounded briefly following the drought. Despite the volatility in annual increment during this period, the HDR ratio remained very stable.

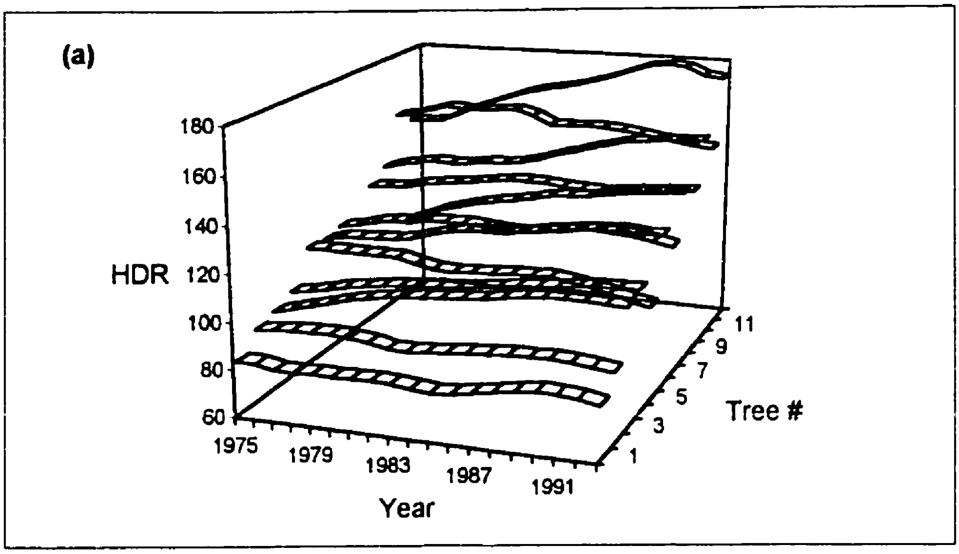
While the shape of the HDR curve was very similar for the 1984 thinned fir, the contribution of the increment and allocation variables was different than for the 1978 thinned fir. During the period of initial downward inflection, height increment dropped and basal allocation increased, while radial increment oscillated. During the period of rapid HDR adjustment, height increment remained below the pre-treatment level and radial increment and basal allocation increased. Unlike the 1978 thinned fir, radial increment was not reduced during the 1986-1988 drought, probably due to reduced inter-tree competition for moisture during the immediate post-thinning period. However, the peak radial increment and recovery of height increment occurred later than for the spruce or 1978 thinned fir, which may be due to the drought. During the period where HDR adjustment slowed, radial increment and basal allocation remained high, but slowly declined, while height increment continued to increase, surpassing pre-thinning levels. It appeared that the period of constant HDR was just commencing at the time of sampling.

For the spruce and both fir thins, the greatest percent change from pre-thinning levels was in radial increment. In all three thinned treatments, the slowing of HDR adjustment occurred as radial increment and basal allocation peaked and began to decline. While there was a general similarity in the shape of the radial increment and basal allocation curves within each treatment, the timing of the peak values differed and basal allocation was less volatile than radial increment. This was especially noticeable during the drought for the 1978 thinned fir.

3.3.4 Relation of Relative Growth Responses to Initial Slenderness

3.3.4.1 Slenderness Adjustment in Individual Trees

The curves of annual HDR for each tree in each treatment were plotted in order of ascending height-diameter ratio at the time of thinning (initial height-diameter ratio, IHDR) in Figures 3.20 and 3.21. There were clearly differences in the trajectories of individual trees in both the control and thinned samples, particularly for the spruce, however the overall pattern of slenderness adjustment in time and with increasing IHDR was clear. The reverse-S curve with downward adjustment following thinning and subsequent levelling of HDR occurred in all but two of the sampled spruce and all but one of the sampled fir. The greatest adjustment and greatest rate of adjustment occurred in the more slender trees in all three thins.



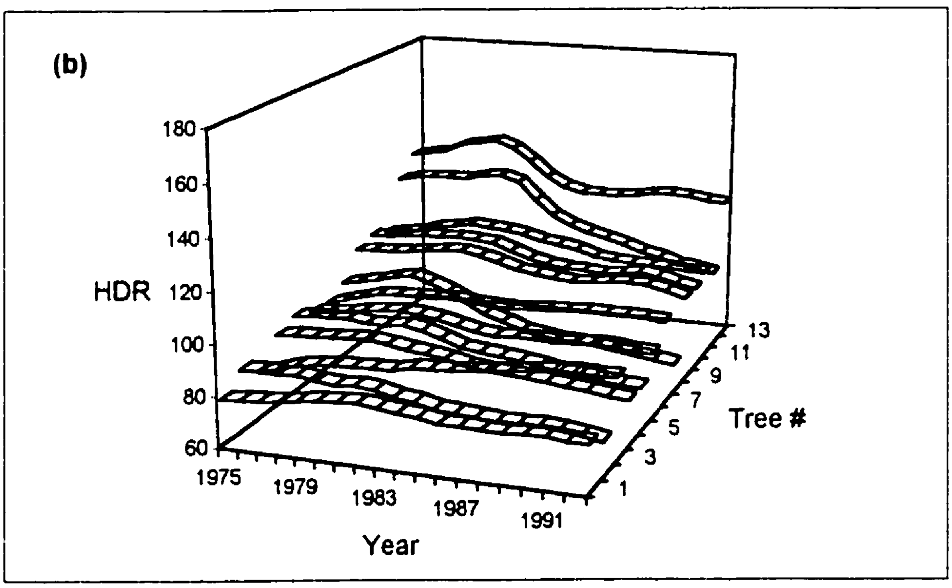


Figure 3.20: Annual height-diameter ratio (HDR) curves for all sample trees ranked by initial height-diameter ratio (IHDR) for Sitka spruce (a) control and (b) thinned 1980 treatments. The tree with the lowest slenderness in the year of thinning (IHDR) is at the front.

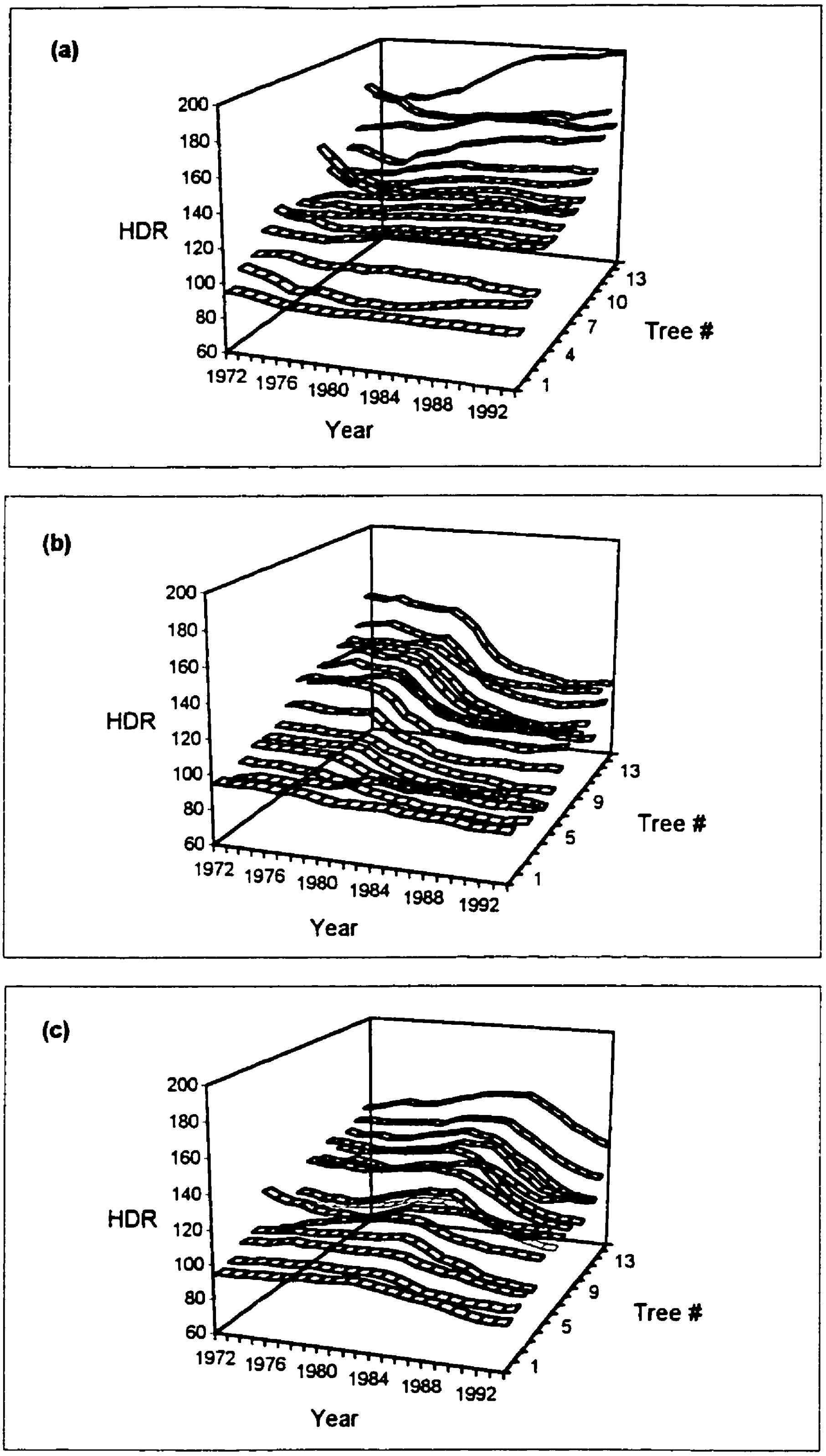


Figure 3.21: Annual height-diameter ratio (HDR) curves for all sample trees ranked by initial height-diameter ratio (IHDR) for Douglas-fir (a) control, (b) thinned 1978 and (c) thinned 1984 treatments. The tree with the lowest slenderness in the year of thinning (IHDR) is at the front.

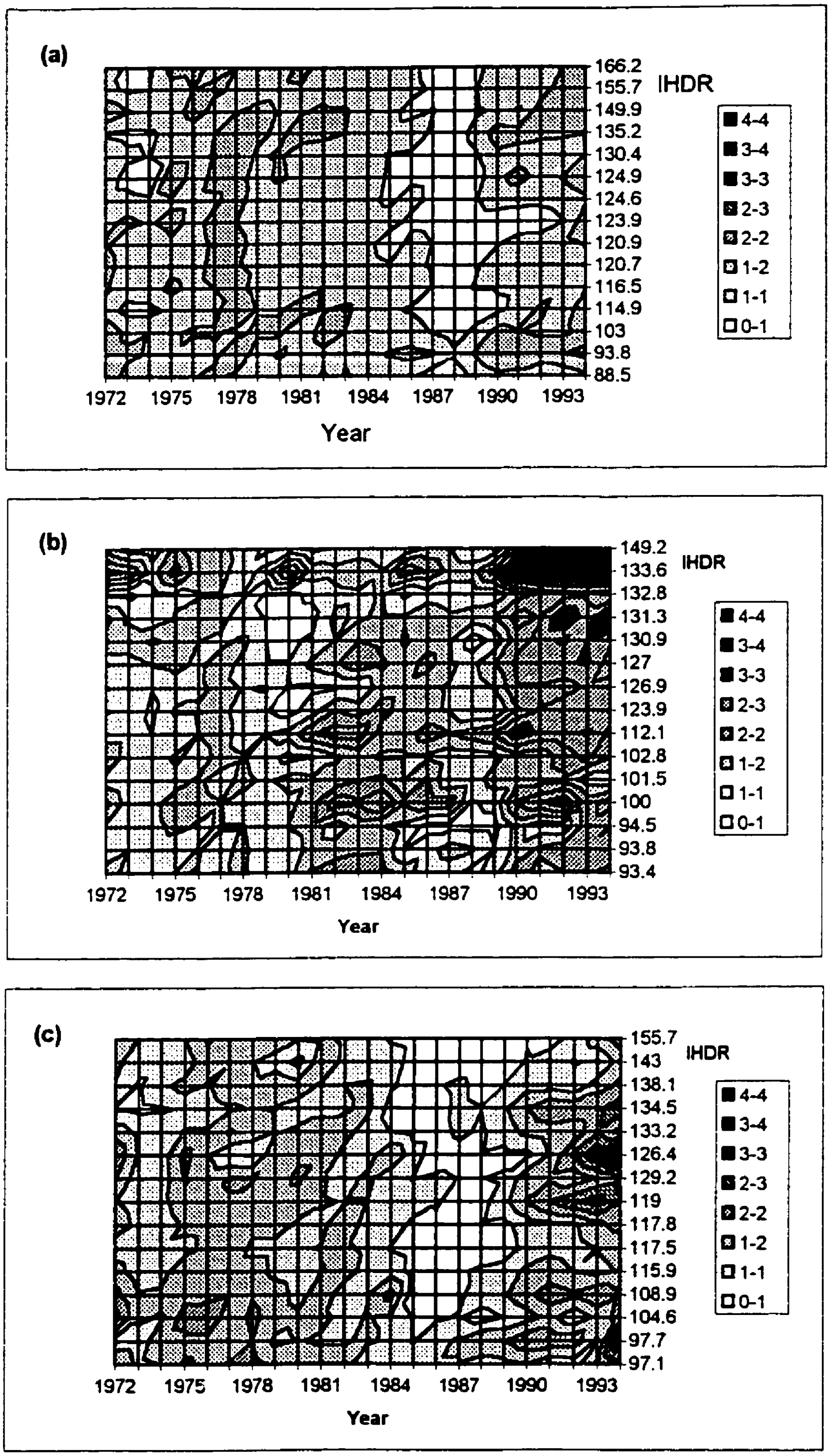


Figure 3.22: Pattern of relative height increment (RHTINC) over time for trees of different initial slenderness for Douglas-fir (a) control, (b) thinned 1978 and (c) thinned 1984 treatments. Darker shading indicates greater height increment relative to pre-treatment levels.

3.3.4.2 Correlation of Relative Responses with Slenderness and Size

The relative post-thinning responses in Figures 3.18 and 3.19 show that the adjustment in HDR resulted from changes in relative height increment, radial increment and basal allocation. Given the greater form adjustment in the more slender trees, it was expected that they would have had greater relative changes in these growth responses than the more tapered trees. Surface plots of relative responses versus initial slenderness by year, such as that shown for RHTINC for the Douglas-fir treatments in Figure 3.22 indicated that there were some differences in relative responses. These trends were then investigated on yearly basis using regression analysis.

Initial tree size and initial tree slenderness should also be related in dense stands. The correlation coefficients for IHDR with IDIB (initial diameter inside bark) were -0.91, -0.78 and -0.85 for the J80 spruce, J78 fir and J84 fir respectively, indicating that slenderness and tree size were highly correlated. While recognizing this correlation, it was expected that post-thinning responses would be better related to initial slenderness than to initial size. To test this hypothesis, the correlation of each relative response variable with IHDR and IDIB for all post-thinning years was tested (Table 3.14).

Overall, the correlations between relative response variables and IHDR and IDIB were weak and there was no consistent pattern in the result between treatments. For the spruce J80 treatment, RRVSA and RRV50 were better correlated with IDIB, while RHTINC was better correlated with IHDR. For the J78 fir, RRV50 was better correlated with IDIB, while the difference in correlation with IHDR or IDIB was minimal for the other response variables. For the J84 fir, all three response variables were better correlated with IHDR (Table 3.14).

Table 3.14: Correlation coefficients for relative response variables with IHDR and with IDIB during post-treatment years, for thinned treatments.

Site		(n)	RRVSA	RRV50	RHTINC
Spruce - J80	vs IHDR	169	0.16	0.27	-0.38
	vs IDIB	169	-0.21	-0.29	0.32
Fir - J78	vs IHDR	240	0.27	-0.00	0.11
	vs IDIB	240	-0.28	-0.33	-0.12
Fir- J84	vs IHDR	165	0.23	0.31	-0.21
	vs IDIB	165	-0.19	-0.23	0.09

To evaluate the strength of relationship of relative response variables with IHDR and IDIB on a year by year basis, a second approach was used. The percentage of post-treatment years in which the coefficient of determination was greater for the regression of response variable with IHDR than with IDIB was summarized (Table 3.15). The result varied from treatment to treatment, but for all variables and treatments combined, the regressions were stronger in more years for IHDR than for IDIB.

Table 3.15: Percentage of post-treatment years in which the coefficient of determination is greater for regressions of response variable with IHDR than with IDIB.

Treatment	RRVSA	RRV50	RHTINC
		% of Years	
Spruce - J80	39	54	54
Fir - J78	31	13	69
Fir - J84	73	73	81

3.3.4.3 Regressions of Relative Growth Responses and Initial Slenderness

Simple linear regressions between relative response variables (RHTINC, RRVSA and RRV50) and slenderness at the time of treatment (IHDR) were fit by year for each treatment. Partial-F tests were used to test for differences between the slopes for control and thinned treatments. The regression slopes are plotted against time since thinning for the spruce and fir thinned treatments in Figures 3.23, 3.24 and 3.25. Years in which there was a significant difference in regression slope between the treatment and control are noted on the figures.

The temporary post-treatment reduction in mean height increment for all three thinning treatments was shown in Figure 3.18. In Figure 3.23, the negative regression slopes for RHTINC after thinning indicate that the more slender trees experienced the greatest reductions in relative height increment. The spruce and J78 treatments both reached minimum slopes 3 years after treatment and the J84 treatment 6 years after treatment. Treatment-control regression slopes were different for year 3 for both the spruce and J78 fir, and for the J78 fir in years 5 and 6. There were no regression slope differences between treatment and control for the J84 treatment in any year.

For RRVSA in the spruce, regression slopes became slightly positive after thinning indicating that relative radial growth was greater in the more slender trees in the years immediately following thinning. There was a large amount of between tree variability in response however, and only in the first year was there a significant difference between the treatment and control regression slopes. The fir show a different pattern with negative regression slopes in the years immediately following thinning which became positive 3-4 years after treatment. This indicates that the more slender trees were slower to increase radial increment, but then caught-up and surpassed the more tapered trees as they responded to the increased growing space. There was a large amount of between tree variability and the treatment-control regression slopes were significantly different only in years 5-6 for the J78 treatment and 6, 8-10 for the J84 treatment (Figure 3.24).

For RRV50 in spruce, the regression slopes became slightly positive in the years following thinning indicating that basal allocation increased relatively more in the slender trees. The regression slopes were significantly different between treatment and control only in year 5 after treatment. Both fir treatments had negative slopes initially and then positive slopes. They showed similar direction in the sign of regression slope and timing of sign change, but very different magnitudes. The regressions for the J78 treatment were very weak with no significant regression slopes or differences in slope between treatment and control in any of the post-thinning years. The negative slopes for the J84 treatment in the years immediately following thinning indicate that the more tapered trees had greater relative increases in basal allocation. The pattern reversed 4 years after treatment when the slender trees caught-up and surpassed the tapered trees in relative basal allocation. For the J84 treatment the regression slopes were significantly different between treatment and control in years 2 (lower) and years 5-8,10 (higher) (Figure 3.25).

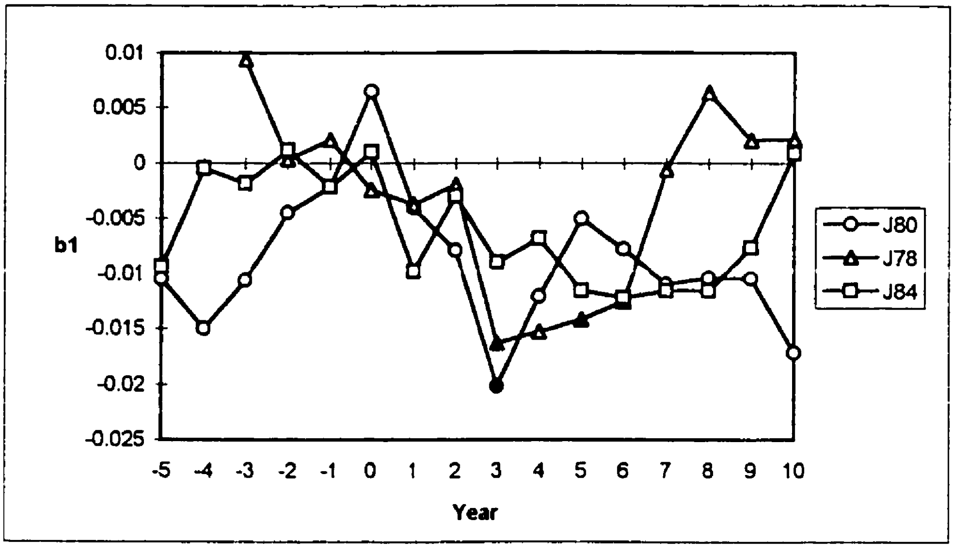


Figure 3.23: Slope of regression (b1) of relative height increment (RHTINC) versus initial height-diameter ratio (IHDR), by year since thinning for Sitka spruce (J80) and Douglas-fir (J78, J84) thinned treatments. Symbols at data points in years with a significant difference in slope between treatment and control are solid.

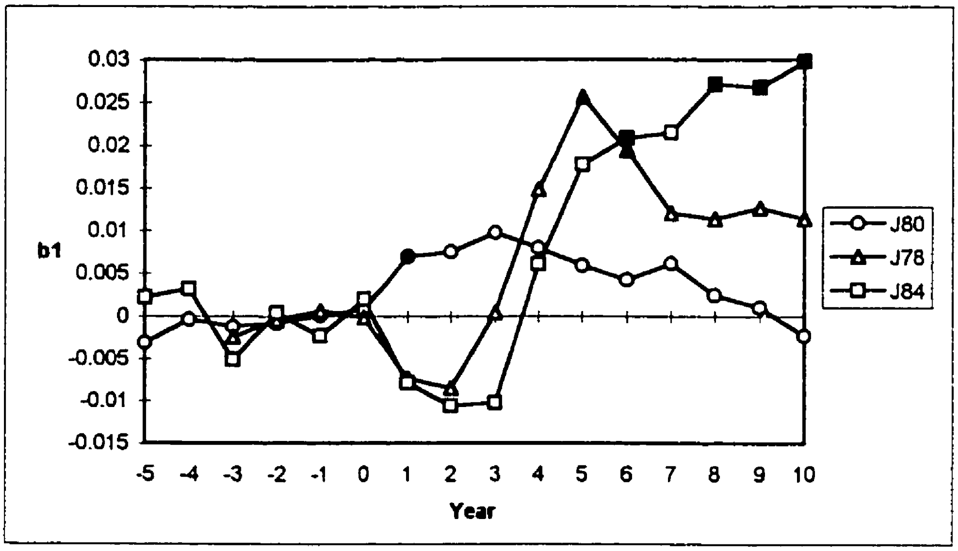


Figure 3.24: Slope of regression (b1) of relative radial increment (RRVSA) versus initial height-diameter ratio (IHDR), by year since thinning for Sitka spruce (J80) and Douglas-fir (J84, J78) thinned treatments. Symbols at data points in years with a significant difference in slope between treatment and control are solid.

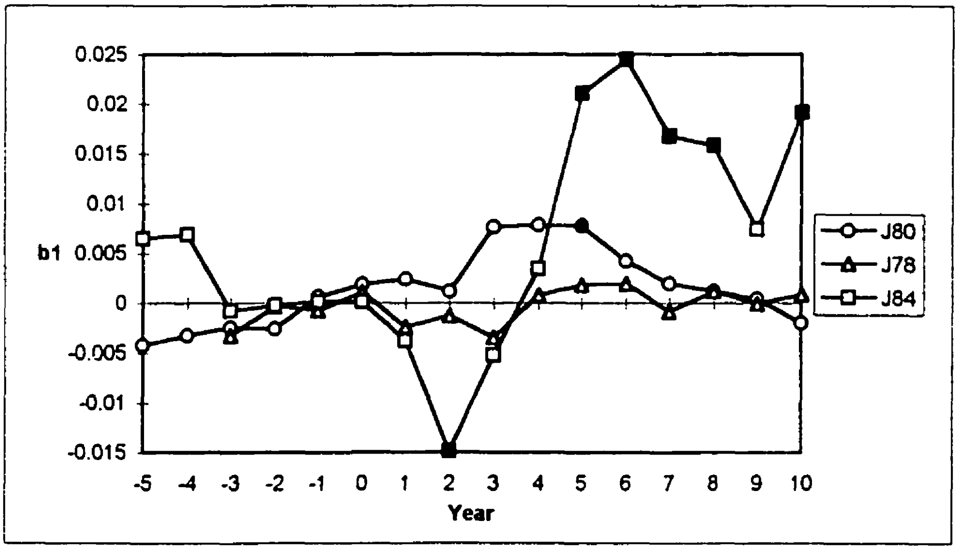


Figure 3.25: Slope of regression (b1) of relative basal allocation (RRV50) versus initial height-diameter ratio (IHDR), by year since thinning for Sitka spruce (J80) and Douglas-fir (J78, J84) thinned treatments. Symbols at data points in years with a significant difference in slope between treatment and control are solid.

3.3.5 Relation of Slenderness with Resistance to Wind Loads

3.3.5.1 Critical Wind Speed for Isolated Trees

The results of the winching study at the Douglas-fir site are summarized in Table 3.16. Critical turning moment (Mc) was strongly related to tree size and the relationship was the same for control, J78 and J84 Douglas-fir treatments (Figure 3.26), and unrelated to the mode of failure. Of the three modes of failure, stem failure was most common (47%), followed by root failure (33%) and uprooting (19%). The uprooted trees were significantly larger (DBH) than the trees which failed by root or stem failure.

Table 3.16: Regression equations for critical turning moment versus tree size.

Critical Turning Moment (N m)	R^2	b0	b1	p
DBH*HT	0.95	-183.19	0.083	0.0001
DBH^3	0.95	840.15	6.794	0.0001
$DBH^{2.76}$	0.96	350.87	13.040	0.0001

Wind drag and resulting turning moments depend on crown mass distribution and within-canopy wind speed profile. Representative crown mass profiles for slender, moderately slender and tapered trees from the control and J78 treatments are shown in Figure 3.27, and crown features for each Douglas-fir treatment are summarized in Table 3.17. The average crown mass in the J78 and J84 treatments was 4 and 3 times that of the control respectively. The tree heights were not significantly different between treatments but the base of live crown heights were, with lowest live crown base in the J78 treatment and highest in the control. The center of crown gravity was located highest in the control trees and lowest in the J78 trees.

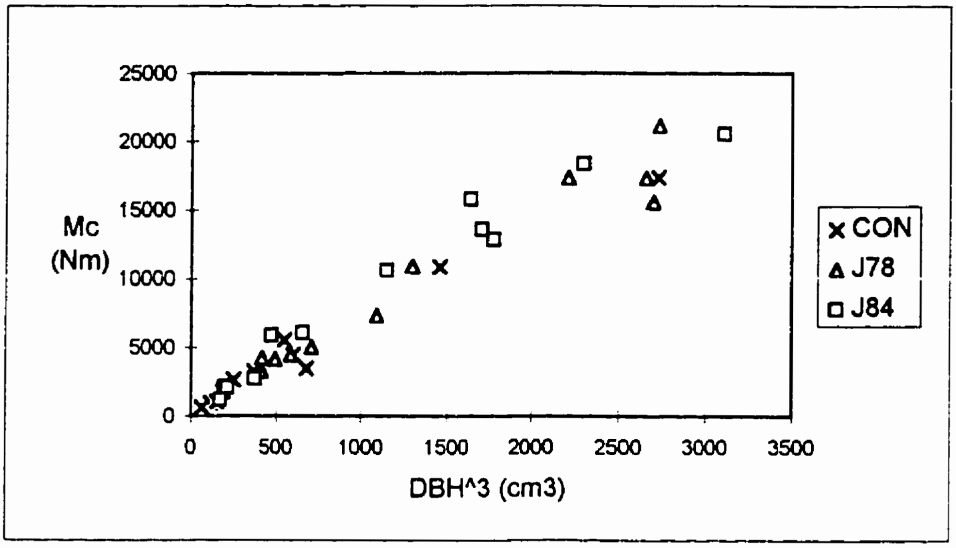


Figure 3.26: Maximum turning moment (Mc) versus stem diameter breast height cubed (DBH^3) for winched Douglas-fir trees.

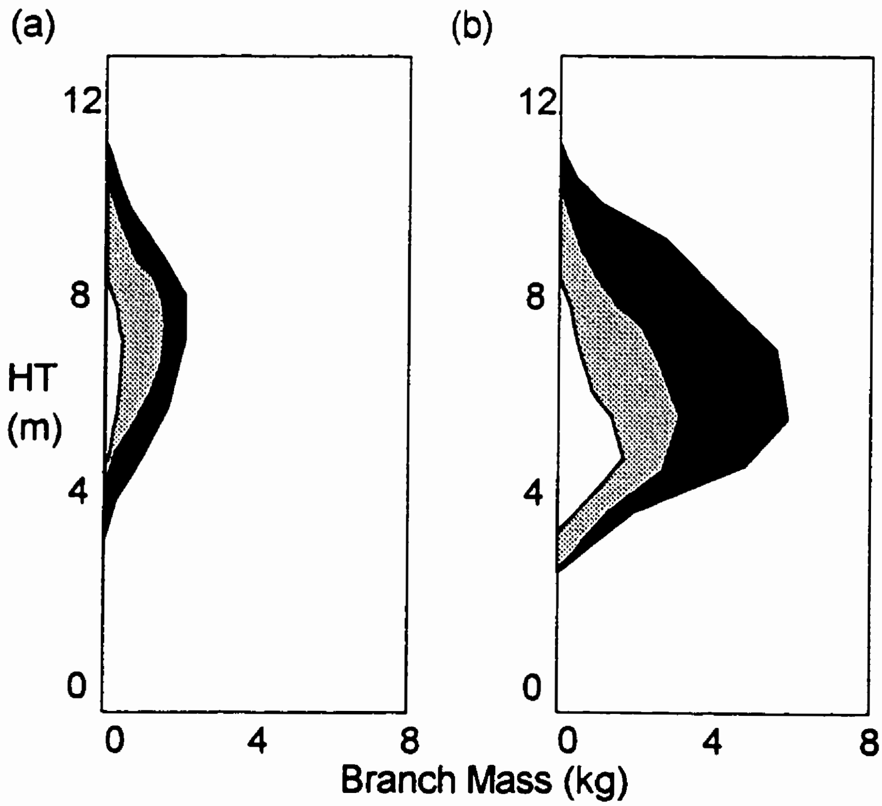


Figure 3.27. Representative crown mass profiles for slender, moderately slender and tapered Douglas-fir from (a) control and (b) thinned 1978 treatments.

Table 3.17: Summary of crown attributes of Douglas-fir sample trees at time of sampling.

	CON	J78	J84
Crown Mass (kg)	8.9 ^{a}	40.6 ^{c}	24.8 ^{b}
Total Height (HT) (m)	8.8 ^{a}	10.2 ^{a}	9.3 ^{a}
Base Live Crown (BLC) (m)	4.5 ^{c}	3.2 ^{a}	3.8 ^{b}
Crown Center of Gravity (CCG) (m)	6.5 ^{b}	5.6 ^{a}	6.3 ^{ab}
CCG as % of HT (%)	75 ^{c}	55 ^{a}	68 ^{b}
CCG within Crown (% up from base)	48 ^{b}	34 ^{a}	45 ^{b}
BLC as % of HT (%)	52 ^{c}	33 ^{a}	42 ^{b}

Values with the same letter are not significantly different for alpha=0.05

Crown mass declined with increasing slenderness particularly for the J78 thinned treatments (Table 3.18). Tree height declined with slenderness for the J78 and J84 treatments but not for the control. The base of live crown as a percent of tree height increased with slenderness for all treatments. Crown center of gravity as a percent of tree height increased with slenderness for the control and J84 treatment but not for the J78 treatment.

Table 3.18: Regression equations for crown attributes versus tree slenderness.

Characteristic	Treatment	p	b1	R^2
Crown Mass (kg)	CON	0.003	-192	0.50
	J78	0.0008	-2082	0.59
	J84	0.0002	-1170	0.78
Tree Height (m)	CON	0.13	-2.6	0.16
	J78	0.004	-16.7	0.48
	J84	0.0001	-13.2	0.70
Base Live Crown as % of Height	CON	0.04	0.17	0.27
	J78	0.018	0.50	0.36
	J84	0.035	0.31	0.25
Crown Center of Gravity as % of Height	CON	0.08	0.09	0.21
	J78	0.23	0.20	0.11
	J84	0.003	0.34	0.50

The calculated critical wind speed (Ucrit) provided an indication of the relative windfirmness of trees exposed to a vertical wind profile with constant wind speed at all heights in the crown. This profile would be similar to the log wind profile that an isolated tree would experience. For all treatments combined, critical wind speed decreased with slenderness (Figure 3.28) and increased with diameter. The results of linear regressions of Ucrit versus HDR and versus DBH for each treatment are summarized in Table 3.19. Both HDR and DBH provided significant regressions for the CON and J84 treatments, and for both of these treatments, critical wind speed was better related to HDR than DBH. There were no significant size or slenderness related trends for the J78 treatment.

3.3.5.2 Safety Factor for Trees in Stands

The effect of different within-canopy wind profiles on safety factors is summarized in Table 3.20. Safety factors (SF=ratio of critical turning moment to applied moment) were calculated assuming a top of canopy wind speed of 30m/s, and three different within-canopy wind profiles calculated using different attenuation coefficients (α). For the very open stand condition (α=0.5), SF was negatively related to HDR for all treatments. This result was consistent with the result for the Ucrit calculations. In the dense stand condition (α=3.0) there was no relationship between SF and HDR for the control treatment, but for the two thinned treatments, safety factor increased with slenderness (Figure 3.29). This occurred because the more slender trees in the thinned treatments benefited more than those in the control from the low wind speeds in the lower canopy where their crown mass was concentrated. The regression slopes in the moderately open stand condition (α=1.5) were transitional between those for the very open and dense condition.

Table 3.19: Regression equations for critical wind speed (Ucrit, ms^{-1}) versus height-diameter ratio (HDR) and stem diameter (DIB, cm).

Treatment	Ucrit vs	R^2	b1	p
CON	HDR	0.72	-0.187	0.001
	DIB	0.65	2.022	0.002
J78	HDR	0.10	-0.122	0.319
	DIB	0.17	0.602	0.189
J84	HDR	0.75	-0.330	0.000
	DIB	0.51	1.184	0.009

Table 3.20: Regression equations for safety factor versus height-diameter ratio for different stand densities (uh=30ms^{-1}; h=12m).

Stand Density; Attenuation Coefficient	Treatment	R^2	b1	p
very open	CON	0.40	-0.008	0.01
(α=0.5)	J78	0.10	-0.008	0.25
	J84	0.16	-0.005	0.14
moderately open	CON	0.06	-0.010	0.38
(α=1.5)	J78	0.17	0.043	0.13
	J84	0.29	0.029	0.04
dense	CON	0.00	-0.012	0.84
(α=3.0)	J78	0.33	0.330	0.02
	J84	0.53	0.270	0.00

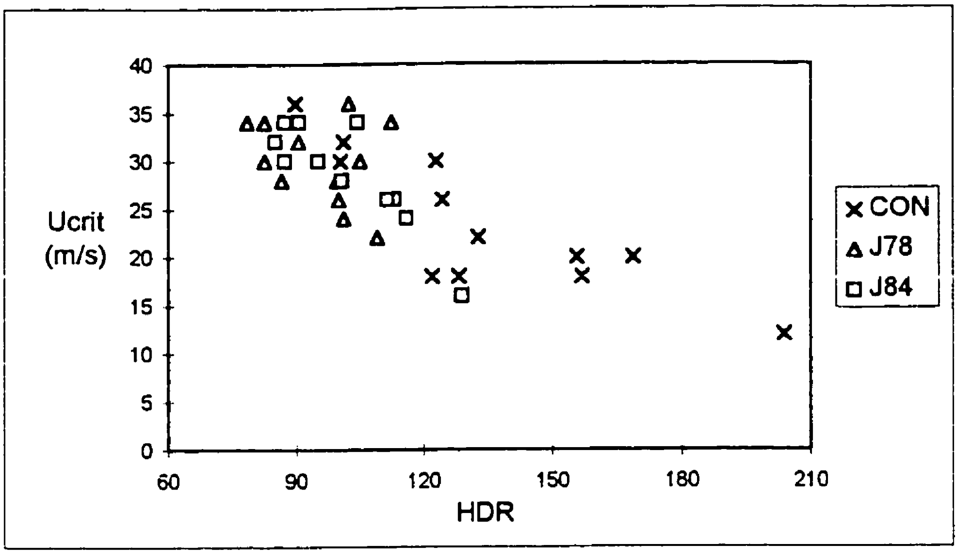


Figure 3.28: Critical wind speed (Ucrit) versus height-diameter ratio (HDR) for winched Douglas-fir sample trees.

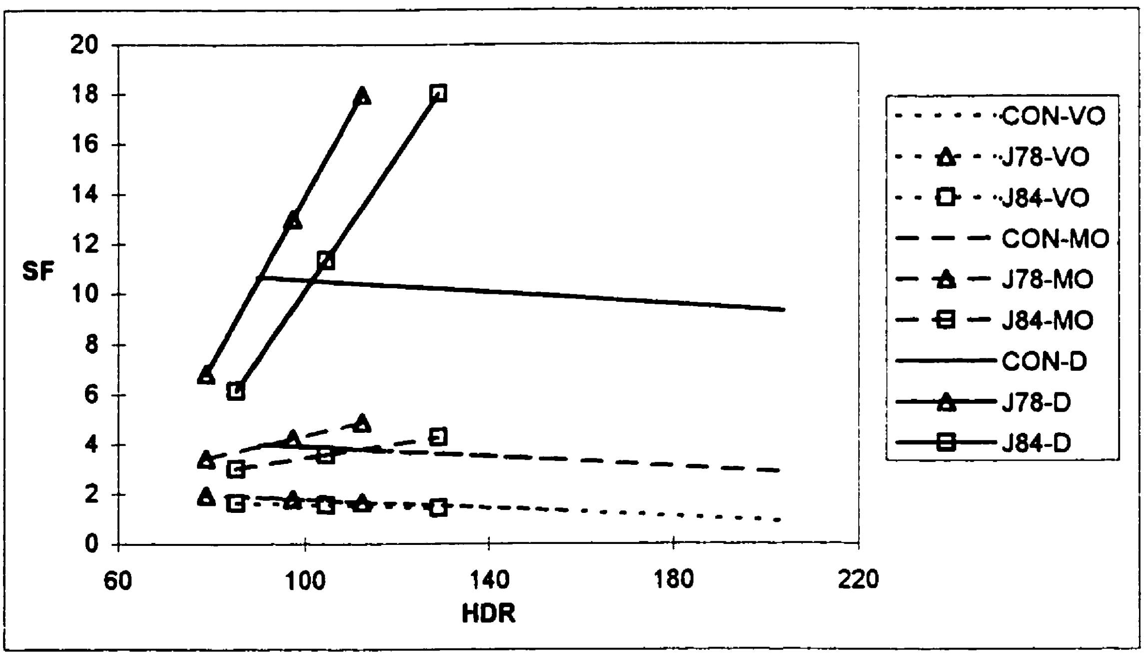


Figure 3.29: Safety factor (SF) for Douglas-fir trees versus height-diameter ratio (HDR) with wind speed profiles for a very open canopy (VO; α=0.5), a moderately open canopy (MO; α=1.5), and a dense canopy (D; α=3.0).

3.4 Discussion

3.4.1 Outcomes of Hypothesis Tests

As predicted, radial increment and basal allocation increased, and height increment temporarily decreased immediately following thinning. Growth reduction following thinning is often referred to as 'thinning shock' and attributed to high respiration associated with a poor ratio of photosynthetic to aphotosynthetic tissue, or to physiological shock due to sunscald (Kozlowski and Pallardy 1997). However in both the spruce and fir, radial increment increased during the period of lower height increment, indicating that the reduction in height increment was not the result of reduction in overall stem growth. For the thinned spruce, increased basal allocation lagged increased radial increment by two years. In both Douglas-fir thinning treatments, increased basal allocation preceded increased radial increment by one year. This is consistent with the 'stimulatory' pattern of allocation observed by Larson (1965). The increase in radial increment started earliest at the stem base (Figures 3.4 and 3.5). This may reflect the pattern of initial allocation to structural roots observed by Urban et al. (1994).

The plots of mean HDR over time for the spruce and fir thinned treatments had a reverse-S shape, characterized by a period of rapid adjustment shortly after thinning which lasted for several years, followed by a gradual slowing in adjustment, and finally by a period during which slenderness adjustment ceased. While slenderness remained constant in this final period, the trees continued to rapidly increase in size. The reduction in slenderness resulted from the interaction of height increment, radial increment and longitudinal allocation. While there were similarities in the direction of response of these variables during each period of slenderness adjustment for the different sites, there were also differences in the magnitude and timing of peak responses from site to site, and from tree to tree. This fact combined with the steady adjustment of slenderness in spite of year to year volatility in radial and height growth, suggests that slenderness adjustment occurs through optimization of the allocation of available growth resources rather than as a passive consequence of the availability of resources. In the immediate post-thinning years, resources were allocated such that slenderness was quickly reduced. In subsequent years, resources were allocated such that slenderness remained constant.

The adjustment of slenderness following thinning followed the reverse-S shape pattern for most individual trees, with the fir conforming to this pattern more clearly than the spruce (Figures 3.20, and 3.21). These figures confirm the hypothesis that trees which are initially more slender make a greater form adjustment. However, the more slender trees did not continue converging on the slenderness of the more tapered trees until they were equal, rather, each tree leveled off at a unique value. The initially more slender trees generally remained more slender than the initially tapered trees. Re-initiation of inter-tree competition resulting in radial growth reduction in trees from lower crown classes would be expected to result in increased slenderness. This was not observed in the treatment mean HDR values, but can be observed in the curves for some individual trees.

It was expected that the greater magnitude and rate of adjustment in the initially more slender trees would result from greater relative post-thinning responses in height increment, stem increment or basal allocation. While there was considerable tree-tree variation within treatments, some differences were observed between thinned and control treatments in the slopes of regressions of relative responses versus initial slenderness. There were also some differences in these results for spruce and fir. The more slender spruce showed greater relative increases in radial increment immediately after treatment, further refuting the notion of physiological shock as being responsible for height reduction in that stand. In the fir the regression slope was initially negative, indicating that relative increment did decline for the more slender trees, however, the slope was not significantly different from that of the control in those years. Relative basal allocation increased slightly for the more slender spruce, peaking 5 years after thinning. For the fir, basal allocation in the more slender trees did not outpace that of the tapered trees until year 5. Relative height increment was lower for the more slender trees after thinning, reaching a minimum at year 3 for the spruce and J78 fir and year 6 for the J84 fir. These minima coincided with the time at which mean relative height increment for the treatment had caught up with pre-treatment levels indicating that the more slender trees took longer to recover in height increment than the more tapered trees.

The strong relationship between critical turning moment and tree size (dbh^3) was consistent with that found in other studies (e.g. Fraser 1962; Blackburn et al. 1988). The similarity of this relationship regardless of mode of failure demonstrates the equivalency of the stem, root and root-soil components of resistance which would be expected given the constant stress theory of wood allocation (Wilson and Archer 1979; Mattheck 1990). Somerville (1979) working with radiata pine also found little difference in the critical moments for different modes of failure on compacted gravels. He found that the slight increase in root anchorage when the gravels were ripped lead to more stem failure. The low proportion of uprooting on the Douglas-fir site indicated that under static loading during the dry, summer conditions present during sampling, root-soil anchorage was not generally limiting. However, given the larger size of the uprooted trees, it may become more limiting as the stand grows taller. On a seasonal basis, anchorage may also be more limiting during snow melt in early spring when soils are saturated.

The analysis of critical wind speeds under conditions of full exposure indicates that more slender trees were vulnerable to lower wind speeds, and that critical wind speed was better related to tree slenderness than tree size. Comparing the range in critical wind speeds shown in Figure 3.28 (44 -130km/h) with the return periods of peak gusts at William's Lake shown in Table 2.5 (70km/h gust return period=1.07 years) shows that a number of the more slender trees would be vulnerable to endemic winds if fully exposed. However, the calculations of safety factor with attenuated within-canopy wind speeds, showed that the relationship between safety factor and slenderness depended on the within-canopy wind profile. The more slender trees in all treatments were shorter than the tapered trees and would benefit more from more attenuated wind profiles. For the most attenuated profile in the dense stand scenario, the more slender trees from the control had equivalent safety factors to the tapered trees. For the same wind profile, the more slender trees from the thinned treatments had higher safety factors than the tapered trees.

The actual conditions experienced in the control would be more like those of the dense stand scenario, whereas the immediate post-thinning conditions would be more like the open stand scenario. In the time since thinning, the canopies in the J78 and J84 stands have filled in which would move these stands towards an intermediate condition where the shorter more slender trees would benefit from a more attenuated wind profile. This modelling of safety factors shows that although the initially more slender trees leveled off at higher final HDR's than the more tapered trees, they may have similar safety factors given the actual within-canopy wind profile which they experience.

3.4.2 Generality of Responses

The coastal Sitka spruce site and the interior Douglas-fir site were chosen in order to test for generality of growth responses in different species and on sites with different climate regimes. The coastal site had relatively warm winters and cool summers compared to the interior site, a much longer growing season, minimal winter snow pack and much high annual and growing season precipitation. Site productivity and annual growth rates were much higher and year to year fluctuations in growth lower at the spruce site. While trees in both stands had similar slenderness and live crown ratios, the spruce trees were much larger than the fir at the time of thinning.

In spite of these site and stand differences, the pattern and rate of slenderness adjustment following thinning and the way in which it varied with initial slenderness was similar for the spruce and fir sites. The relative growth responses were also similar with rapid increases in radial increment shortly after thinning and temporary reductions in height increment at both sites. The relative increase in basal allocation was similar at the two sites, but lagged at the spruce site. For the spruce, the more slender trees increased relative radial increment and basal allocation more quickly than the more tapered trees, whereas for the fir the more slender trees lagged and then caught-up and surpassed the more tapered trees. The relationship of relative height increment with initial slenderness was similar for both sites with more slender trees lagging tapered trees in recovering toward pre-thinning levels of height increment.

Year to year variation was evident in the response curves, particularly the large reduction in radial and height increment during 1987-89 for the control and J78 treatments at the Douglas-fir site. This pattern was consistent with Dobry's (personal communication, 1999) observations at other sites throughout the south central interior and reflected low precipitation during the years 1986-1988. The recently thinned J84 treatment was less affected, likely due to lower between-tree competition for moisture in the years immediately following thinning.

An outbreak of poplar-willow borer (*Cryptorhynchus lapathi* L.) in the late 1980's may have been an additional minor source of annual growth variation at the Douglas-fir site. This introduced insect passed through the central interior between 1987 and 1992 in a wave moving from south to north (L. Rankin, BCMOF Cariboo Forest Region, personal communication 1999). Many of the willow in the control and thinned plots were killed during the early years of this outbreak. Willow accounted for 2% of the total stems greater than 3cm dbh in all treatments 1978. In the thinned treatments, willow were cut at the time of thinning and then resprouted. Of the tallied standing dead trees greater than 3cm dbh in the plots, willow accounted for 29% of the dead trees in the control, 91% in the 1978 thinning and 94% in the 1984 thinning. The standing dead willow were smaller on average (3.7 cm dbh) than the fir and represented less than 2% of the basal area in each treatment in 1987.

3.4.3 Repeatability of Pattern in Time

The independence of the slenderness adjustment pattern from a specific series of annual climates is demonstrated by the similarity of patterns for three different thinning years on the two sites. The choice of two thinning dates at the fir site was intended to specifically test for repeatability of the pattern in time. While the drought of the 1987-1989 period at the interior site affected height and radial increment, basal allocation was relatively unaffected, and the pattern of slenderness adjustment was unaffected. The smoothness of overall adjustment regardless of the year to year fluctuations in resources available for growth suggests that slenderness was adjusted through balanced allocation of resources.

3.4.4 Unexpected Results

While the mean growth response patterns, and individual tree patterns in slenderness adjustment were very similar for each treatment, underlying relationships between annual growth responses and initial slenderness were less clear than expected. There was a large amount of tree to tree variation in the timing and magnitude of specific growth responses which was not related to tree slenderness or size. The strength of regressions between tree slenderness and relative response variables varied considerably from year to year. For example in the spruce, relative basal allocation was positively related to initial slenderness five years after thinning (R^2=0.63), but unrelated just two years later (R^2=0.03). Annual coincidence in the manner of resource allocation among trees with magnitude related to initial slenderness seems to be the exception rather than the rule. Individual trees were likely responding to changing mechanical stresses and annual fluctuations in available growth resources through optimization of growth allocation.

3.4.5 Evidence of Acclimative Growth

Results in the years immediately following thinning were consistent with the findings of other researchers investigating the short term effects of increased wind stimulus. The graphs of relative ring increment by stem position by year for the spruce and fir treatments clearly show a period of increased lower stem increment at the expense of upper stem increment during the years immediately following thinning (Figures 3.4 and 3.5), which is consistent with the findings of Larson (1965) and Valinger (1990). The increased radial asymmetry in the lower stems of the thinned fir is consistent with the radial asymmetry observed by Wade and Hewson (1979), and Robertson (1991) in trees growing with directional wind loads. The pronounced shift in ring increment from south side to north side at the base of the stem during the years immediately following thinning is further evidence of an acclimative response.

The reverse-S pattern of HDR adjustment, rapid at first then levelling off, in spite of continued tree size increase, is strongly suggestive of an equilibration of tree form. The slenderness of slender trees did converge on that of more tapered dominants, however, following the period of major correction, each tree leveled off at a unique HDR, rather than matching that of the dominants. The safety factor modelling showed that with moderately attenuated within-canopy wind profiles the safety factors of the slender trees from the thinned treatments were equivalent to or higher than those of the more tapered trees. Applying the findings of Morgan and Cannell (1994) regarding stem form development and stress distribution, unique stem forms at equilibrium would be expected given tree-to-tree differences in the distribution of crown mass and experienced wind profile. Genetic variation may also contribute to tree to tree differences in final form. Telewski and Jaffe (1986b) found differences in response to mechanical perturbation amongst loblolly pine (*Pinus taeda* L.) from different families. Under similar loading conditions, some individuals may build-in higher safety factors.

3.4.6 Utility of Patterns for Assessing Windfirmness

In keeping with the stress-response principle, the period of reduced height increment and increased basal allocation at the beginning of the slenderness adjustment period would indicate a period during which the tree is under greater mechanical stress. It would be during this period that the trees are most vulnerable to wind damage. It was originally expected that height increment and allocation responses alone would be good indicators of the duration of the period of adjustment to post-thinning conditions. However slenderness adjustment continues for several years after the period of maximum height reduction and basal allocation. Given the shape of the HDR adjustment curves, the greater adjustment of more slender trees, and the relationship between HDR and safety factor under wind load, it would appear the pattern of post-thinning slenderness adjustment provides the best indicator of the state of acclimation with post-thinning conditions. Re-equilibration could be considered complete when HDR levels after the period of rapid downward adjustment.

For the Sitka spruce site, the adjustment of slenderness occurred over a period of 7 years with the period of rapid adjustment ending 5 years after thinning. For the Douglas-fir J78 site the period was 8 years with the period of rapid adjustment ending at 6 years. For the J84 site the period was 10 years with rapid adjustment ending 7 years after thinning. A conservative thinning strategy would be to wait for the period of slenderness adjustment to end prior to subsequent thinning entries. Studies by Valinger (1990) showed increased crown expansion and upper stem increment following fertilization. Laiho (1987) reported that recently thinned and fertilized stands experienced levels of damage three times higher than recently thinned stands and six times higher than un-thinned stands in his study of storm damage in Denmark. Waiting for stem form to re-equilibrate with post-thinning conditions prior to fertilizing would appear to be a wise strategy in stands which demonstrate large post-thinning form adjustments.

In the longer term, trees of various initial HDR's appear to have developed equivalent levels of windfirmness, and the period of time taken for the adjustment was similar for trees regardless of initial slenderness. However, during this time, the more slender trees were not only responding to a larger post-thinning increase in wind loads than the dominants. The positive slopes of relative radial increment versus slenderness indicate that they were also increasing in relative size faster than the larger trees after thinning. The larger adjustment in the initially slender trees would reflect responses to the larger initial increase in wind speeds due to canopy removal and increasing drag as they increase in relative size more quickly than the tapered trees. Given the estimated safety factors and the greater adjustment of these trees it would appear that they are in greater disequilibrium with early post-thinning conditions. In view of this, retaining the most tapered trees during thinning would be the more conservative strategy.

The results of this study demonstrate that the use of HDR could be extended from that of a static indicator of stand windfirmness (e.g. Cremer et al. 1982; Becquey and Riou-Nivert 1987) to that of a dynamic indicator for providing insights into post-thinning acclimation over time. Documenting the pattern of HDR adjustment would rely on accurate yearly measurements of breast height diameter and height. For smaller trees these could be determined from re-measurement of tagged sample trees using a dbh tape and height pole. The pattern of radial increment for the lower bole could also be obtained from increment cores taken from the windward and lee sides. For larger trees where accurate measurements of height are difficult, destructive sampling may be necessary. Documentation of the relationship between the magnitude and duration of the slenderness adjustment for codominant trees from stands representing a range of densities and heights in a given area would enable localized guidelines for thinning re-entry to be developed.

The diagnostic question for the stand hazard component in the diagnostic framework presented below is based on the premise that trees grown in more open stands are better acclimated to wind loads. They are therefore less liable to be windthrown during endemic peak winds or when their exposure is increased following treatment. Literature supporting the greater windfirmness of more open grown trees was reported earlier in this section. The modified growth patterns detected in this study and their net effect on HDR adjustment demonstrated the responsiveness of healthy trees and their ability to acclimate to post-thinning conditions.

The factors which constrain acclimative growth in stands should be further investigated. The British experience with Sitka spruce on uplands (e.g. Miller, 1985) and the Ontario black spruce on peatlands (Smith et al., 1987) are cases in which the development of individual windfirmness is sufficiently suppressed that over time whole stands become susceptible to annual peak winds. While these may be anomalous cases, they underline the fact that while trees are capable of acclimating to wind loads, there are combinations of stand and site conditions under which they do not acclimate sufficiently to withstand routine peak winds.

3.5 Conclusions

i) The predominant post-thinning growth responses included adjustment in height-diameter ratio through a combination of temporary reduction in height increment, increased radial increment and increased basal allocation. ii) Slenderness adjustment was most pronounced for the initially more slender trees, but the total period of adjustment was similar for all trees. iii) These responses occurred in two species growing on sites with very different ecological characteristics, suggesting that they are general responses. iv) The short term growth responses were consistent with acclimative responses reported in literature. v) The pattern of slenderness adjustment could be used as an indicator for both the duration of the period of post-thinning dis-equilibrium with wind loads, and the relative magnitude of this dis-equilibrium for trees of different initial slenderness.

CHAPTER 4 - A STRATEGY FOR WINDTHROW RISK ASSESSMENT AND MANAGEMENT IN BC[2]

4.1 Introduction

BC's public forest land is managed for multiple objectives through a public and multi-agency referral process. The proposed harvesting plans of the forest licensees are coordinated at the landscape level through Development Plans which are referred to government agencies and the public for discussion several years before harvesting is to commence. Once a proposed harvest area is approved in principle and stand level management objectives are identified, management at the stand level is guided by silviculture prescriptions. The silviculture prescription contains a description of site capability and constraints, identifies a desired future stand condition which meets local objectives and details the series of treatments necessary to produce the target stand (Hadley et al. 1990).

Foresters use a process of 'site and stand diagnosis' to classify sites and identify limiting conditions. The diagnosis is based on observation of soil, forest floor and vegetation attributes, interpretation of disturbance history, and comparison with known indicators (e.g. Hadley et al. 1990; Steen and Coupé 1997). The biogeoclimatic classification framework used in BC based on the work of Krajina (1973), greatly assists managers in identification and characterization of similar forest ecosystems and in predicting their response to treatment. The challenge for foresters developing silviculture prescriptions in areas of recurring windthrow is to predict the likelihood and severity of damage in proposed target stands.

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[2] **Modified versions of this chapter have been published in For. Chron. 71:446-450 (S.J. Mitchell 1995b), and For. Chron. 74:100-105 (S.J. Mitchell 1998).**

The general principles of vulnerability to damage and management strategies to reduce vulnerability have been well documented for forests of the Pacific Northwest since the 1950's (e.g. Ruth and Yoder 1953; Alexander 1964). In 1977, Moore provided a detailed analysis of the factors contributing to windthrow in coastal BC streamside leave strips and made a series of recommendations for assessment and management. Ruth (1976) reviewing his earlier work in coastal Oregon cautioned of the need for better incorporation of windthrow assessment and prescriptive actions into plans:

> 'blowdown is probably the most serious problem in managing hemlock forests... the forestry staff labors over a detailed management plan that calls for particular stands to be harvested at particular times... along comes a windstorm and the carefully prepared plan has to be held in abeyance and all efforts directed to salvage operations.'

However, in spite of the body of information on windthrow risk assessment and mitigation, and in spite of recurring disruption of stand and forest level plans by wind damage, no comprehensive approach to windthrow management has been adopted in BC to date. Identification of windthrow as a 'forest health factor' in the BC Forest Practices Code, the requirement for stand level assessment of windthrow risk in silviculture prescriptions, and the desire to extend the use of partial cutting silviculture systems has provided new impetus for development of windthrow assessment tools and management strategies.

In this chapter, the factors contributing to the lack of coordinated management of windthrow are reviewed, and the limitations of existing risk assessment approaches for current use in BC are discussed. A diagnostic framework for windthrow risk assessment designed to assist forest managers with prescription development is introduced. The principle of acclimative growth investigated in Chapter 3 provides the conceptual basis for the assessment of stand acclimation to windloads within this diagnostic approach. The components of a comprehensive approach to management and future windthrow research needs are outlined

4.2 Challenges in Managing Windthrow in BC

There are a number of factors which contribute to the difficulty of managing windthrow in BC and which have impeded adoption of a comprehensive approach to windthrow management. BC is diverse in climate, geography and forest types, with five physiographic regions (Valentine et al. 1978), twelve biogeoclimatic zones, and a landscape dominated by old-growth forests. The interactions between the climatic, edaphic, stand, and management factors which contribute to wind damage vary from region to region. This limits the use of standardized windthrow risk indicators and windthrow management prescriptions.

BC's forests are managed extensively. High rates of staff turnover combined with the lack of systematic monitoring of windthrow impacts on the success or failure of plans and prescriptions means knowledge is not accumulated or passed on to successive managers. From the responses to the BCMOF 1992 windthrow census it is clear that some managers perceive that windthrow is unpredictable, even in locations where recurring damage from wind is evident (Table A.2). Lack of recognition of the recurrent nature of windthrow, and its cumulative impact on management objectives means that the probable effects of windthrow on the outcome of forest and stand level plans are not incorporated into the planning process. Without accurate statistics on endemic and catastrophic damage and their impact, it is difficult for managers to build a case for more resources to be applied to the problem. Without careful and systematic analysis of windthrow events on a case by case basis, there is no separation of preventable from unpreventable cases, or successful from unsuccessful management actions.

Development Planning requires compromises in the design of harvesting areas in order to accommodate multiple objectives. If risk of damaging agents such as wind are not made explicit during this process, they are not incorporated into the plans. Even where the potential for damage is identified, the mitigative actions which are proposed may not be consistent with the desired outcome or with the legal constraints on cutblock size and adjacency.

4.3 A Comprehensive Windthrow Management Program

4.3.1 Benefits of a Program

The scale of the windthrow problem indicated by the BCMOF 1992 windthrow census underlines the need for a comprehensive approach to windthrow management. Collection of statistics on endemic and catastrophic windthrow would enable documentation of trends and justification for expenditures on staffing, training and mitigative action. Projection of endemic damage levels would assist planning and logistics for salvage operations. Identification of high hazard locations and high risk treatments would enable better design of landscape and block level plans. Overall, managers could take a strategic rather than reactive response to recurring wind damage.

4.3.2 Components of a Program

A comprehensive windthrow management program should contain the following components.

- Annual census of endemic and catastrophic damage including mapping and volume summaries by licence.
- Estimation of annual damage expected from endemic winds by district.
- Valuation and administrative procedures designed to facilitate windthrow salvage and implementation of prescriptions which reduce vulnerability to wind damage.
- Landscape level mapping of windthrow hazard to be used in conjunction with development planning.
- Stand level assessments during site and stand diagnosis where potential for wind damage or undue impacts is identified in development planning.
- Modification of silviculture prescriptions based on assessment results.
- Monitoring to check outcomes of prescriptions intended to reduce wind damage.
- Training program in windthrow assessment and prescription development.
- Research into windthrow mechanics and ecology, assessment methods and prescriptive strategies.

The 1992 BCMOF Windthrow Census provides a model for an annual census of damage. The primary source of information for the census would be spring windthrow flights or ground surveys conducted by licensees on their operating areas in which recent damage is mapped and damaged volumes estimated. These spring surveys are already routine in some districts. Statistics could be compiled by district and region and published in the BCMOF Annual Report along with summaries of damage from other agents such as fire and insects. Each licensee should maintain an overview map of their operating area on which recently detected damage is noted. Over time such maps would be useful in identifying the pattern of damage and its association with site, stand and management features. Averaging statistics for each district over several years would enable estimation of volumes affected by endemic winds.

Discussion of administration and valuation procedures is beyond the scope of this thesis, but it was clear from the comments of census respondents that recovery of damaged timber would be promoted if detection, integrated resource planning, and valuation procedures specific to windthrow salvage were developed and standardized from district to district. The Forest Practices Code enacted in 1995 now requires forest managers to use management strategies which reduce the risk of wind damage to riparian zones, gully reserves and areas of terrain instability. Stand edge treatments such as edge thinning and crown pruning or topping are being investigated in coastal BC (Gillies 1998), and recent changes to the valuation procedures in the Vancouver Forest Region now enable licensees to recover some of the additional cost of these treatments.

The next two components of a comprehensive windthrow management program are landscape level hazard mapping and stand level assessment of windthrow risk. In the following section existing methods of assessment are discussed and an alternative approach is suggested. Following this discussion, the remaining components of the windthrow management program are considered.

4.4 Approaches to Assessing Windthrow Risk

Windthrow risk refers to the probability of damage of a given level of severity occurring on a particular site. Knowledge of the mechanics and ecology of windthrow reviewed in Chapter 2 has enabled researchers to develop several methods for assessing windthrow risk in forests. These methods can be divided into three groups, 'observational', 'empirical' and 'mechanical'.

4.4.1 Observational Approach

In observational windthrow risk assessment, practitioners are provided with a list of indicators for the various environmental and management factors believed to be associated with windthrow risk. The indicators may be identified during local studies of windthrow or compiled from reviews of the international literature. The checklists provided at the ends of the studies of Ruth and Yoder (1953), Alexander (1964), Harris (1989) and Stathers et al. (1994) are examples of this approach (Appendix C). Practitioners use these lists to evaluate relative windthrow risk of different sites in a given location based on the presence and abundance of risk indicators. Predictions of damage are generally of the form 'damage more or less likely' or 'damage more or less severe'. The premises underlying observational methods of windthrow risk evaluation are: i) that risk of damage increases with increased presence of indicators, ii) that factors involved are similar from event to event and location to location within a given region, and iii) that topographic, soils and stand components contribute equally to the likelihood and severity of damage. There is generally no explicit feedback or confirmation step where the results of predictions are evaluated and indicators revised.

The observational approach has many advantages. Local windthrow research programs are not necessary. It is easy to teach to practitioners and is easy to apply. The method is generally used only in locations where there is a history of windthrow, and within these locations enables identification of the most vulnerable areas. This enables limited staff and financial resources to be focused on further evaluation or management in those areas. Using overview maps of topography and forest cover, areas with high risk indicators can be identified at the landscape level. Indicator checklists can be used during site and stand diagnosis for estimation of stand level hazard. The disadvantages of the observational approach are that the expected probability and severity of damage for each risk class are not defined, and generic indicators are not calibrated to local conditions. Unless a feedback step is included to check results of predictions, these refinements do not occur.

4.4.2 Empirical Approach

In the empirical approach to windthrow risk assessment, practitioners are provided with a quantitative model of windthrow risk which enables a prediction of the volume or proportion of wind damaged timber given particular environmental, stand and management factors. The models are developed for specific geographic areas and usually for specific management scenarios. The underlying premise is that the probability of damage of a particular severity can be predicted using an equation containing variables representing environmental and management factors.

The data are collected from a defined population using a sampling system which enables documentation of windthrow, environmental and management variables at a series of sample points. Multivariate techniques are used to screen the contribution of each independent variable and model the relationship between windthrow and selected variables. These models can be validated using a portion of collected data not used to build the model.

The studies of Elling and Verry (1978) and Fleming and Crossfield (1983) contain empirical models for prediction of volume losses due to windthrow in boreal black spruce strip cuts using stand and management variables (r^2 of 0.93 and 0.58 respectively). Steinblums et al. (1984) and Andrus and Froehlich (1992) present empirical models for prediction of volume losses due to wind damage in riparian buffer strips in coastal Oregon using topographic, soils, stand and management variables (r^2 of 0.74 and 0.57 respectively). Fridman and Valinger (1998) developed models for predicting snow and wind damage (probability of one damaged tree in plot) using tree, stand and site characteristics from permanent sample plots in Scots pine stands in Sweden. Their best model correctly predicted 81% of the undamaged and 82% of the damaged plots. These models illustrate that reasonable predictions of wind damage can be made when sufficient data are available for specific geographic areas with limited management scenarios. The specific nature of the variables used and dissimilarity of the variables between the buffer strip and strip cut models indicates the difficulty in generalizing such models.

When there are strong associations between damage and environmental or management variables, these models are powerful predictive tools, particularly for landscape level assessment of risk. Even when the association is weaker, identification of the relative contribution of environmental and management factors is an improvement on the observational approach where risk indicators are not weighted. Collecting the data and building models takes considerable resources, as comprehensive and detailed measures of damage, site and management attributes are needed. Large sample sizes are necessary because of the variability of conditions. Environmental variables may be hard to quantify, particularly topographic variables, and the association of damage with measurable variables may be weak.

The validity of the resulting model for areas outside the sample is unknown unless tested, and the model may not extend well to areas with dissimilar attributes.

The UK Forestry Commission windthrow hazard classification predicts critical heights for Sitka spruce plantations by combining wind zone, elevation, topographic exposure and soil scores, which were initially developed using results of empirical studies (Miller, 1985). Miller notes that the hazard classification is useful for operational planning at the forest level but does not provide a satisfactory basis for detailed stand level prescriptions. He advises practitioners to make modifications based on systematic observation of windthrow in order to improve local precision, a recommendation repeated by Quine (1994). The hazard classification is now considered pessimistic in its predictions (Quine 1995) and a new classification is being developed based on the mechanical approach.

4.4.3 Mechanical Approach

Mechanical models of windthrow are used to estimate the critical wind speed at which stands will fail, or the critical stand height at which frequently recurring winds will begin to cause damage. This approach is used for uniform canopied stands where trees are relatively uniform in characteristics and fail en masse, and typically in locations where it has been observed that stands become increasingly unstable as they grow taller. The underlying premise in building mechanical models for windthrow prediction is that the critical wind speed and probability of critical wind speed can be determined for trees within a stand at a particular location. Critical wind speeds are calculated from loading and resistance models using measured and estimated tree and stand attributes. Tree resistance is determined using static pulling tests and bending models. Windloads are determined using wind tunnel tests of tree crowns, measurements of within canopy wind speed profiles and drag equations. The probability of critical wind speed is determined from local climate data or from regional climate data adjusted for local topography. Environmental and management factors contributing to risk are individually weighted. The model results can be calibrated by comparing incidence of damage with predictions.

There are a number of examples of mechanical models in the literature. The study by Smith et al. (1987) was in response to their observation that mortality in growth and yield plots in black spruce stands on peatland sites was more closely correlated with stand height than with stand age. Subsequent studies of tree resistance and probable windloads indicated a pattern of declining critical wind speeds with increasing stand height. Peltola and Kellomaki (1993) studied the critical wind speeds for Scots pine along fresh clearcut edges using a similar approach. Blackburn and Petty (1988) studied stability within Sitka spruce plantations in Britain using both static and dynamic models of wind loading and resistance. The critical wind speeds obtained using static models were higher than those observed to cause damage. Recalculation of critical wind speeds using measured damping ratios and assuming resonant gust frequencies, reduced predicted critical wind speeds to within the range of observed damaging winds. Quine (1994, 1995) made a number of recommendations which address some of the determinism of mechanical models. He suggested that critical wind speed has persistent, progressive and episodic components. The site contribution (soil type, topography) is unchanging and therefore 'persistent'. Tree growth patterns result in progressive changes over time. Events which change vulnerability over short time periods, such as thinning treatments, soil saturation, snow loading, and leaf out for deciduous trees, comprise the episodic component. The resulting critical wind speed therefore varies throughout the life of an even-aged stand on seasonal, yearly and decadal time scales. As an alternative to using the probability of critical wind speed in any year, he suggested using a time series of peak annual wind speeds to demonstrate the importance of the annual variability in wind speed for the timing of first damage in stands with declining critical wind speeds.

Estimation of critical wind speeds enables scheduling and arrangement of cutting plans in locations with endemic windthrow histories, and enables modelling of the effects of different treatment strategies. The detailed evaluation of the loading and resistance components provides a functional understanding of windthrow and the role of environmental and management factors, which is useful for researchers and managers outside the locations tested. The mechanical method requires considerable research resources and expertise. For this reason it is best suited to areas where there are large holdings of uniform stands managed using a limited range of harvesting and thinning regimes. Knowledge of the return periods of different wind speeds and how they vary with topography is a key component of these models. Moore and Somerville (1998) describing their mechanical model for New Zealand reported that the correlation between areas of predicted high risk and actual damage was good for 2 locations with non-complex terrain, but poorer in 2 locations with complex terrain. Mechanical models have not been extended to stands with multi-storied structures or stands managed with partial cutting silvicultural systems. The accuracy of predictions made with mechanical models should be verified through empirical studies.

4.4.4 Requirements of a Windthrow Assessment Approach for BC

In order to be useful across BC in the short term, the windthrow assessment method needs to meet the following criteria:

- Provide accurate predictions of severity of damage from endemic winds.
- Contain a mechanism for verification of predictive accuracy and effectiveness of prescriptive actions.
- Be usable in all five physiographic regions, in stands of a variety of ages, compositions and structures which are managed under a variety of silvicultural systems.
- Use readily available landscape and stand level information.
- Make use of the expertise of local practitioners in site and stand diagnosis.
- Be relatively inexpensive.

The limitations of observational, empirical and mechanistic approaches for current use in BC are summarized in Table 4.1. The observational approach meets most of these criteria, but is inaccurate unless a feedback step is included. While the empirical and mechanical approaches provide the most quantitative predictions, they are expensive methods which require considerable research to develop. They provide predictions of unknown reliability when extended to site, stand or management conditions which were not used in building or testing the models. The mechanical model is not suited to stands of complex structure or composition and requires detailed wind information not generally available for forested areas in BC.

Table 4.1: Comparison of windthrow risk assessment approaches for use in British Columbia.

Approach	Damage Prediction	Verification of Prediction	Site/Stands/ Management Regime	Information Acquisition	Information Provider/User	Relative Cost
Observational	relative risk	none	any	indicators from literature; field observations; overview maps	researcher/ practitioner	low
Empirical	probability of damage; severity of damage	run with independent data; monitoring area	any (must be similar to those used to build model)	aerial photographs; maps; GIS database; field observations	researcher/ researcher & practitioner	high
Mechanical	probability of damage; critical height	monitoring area; test with empirical model	uniform canopy (must be similar to those used to build model)	winching, wind tunnel studies; climate data; windflow models maps; GIS database; field observations	researcher/ researcher & practitioner	high
Diagnostic	severity of damage	calibration step	any (need old edges with comparable conditions)	maps; field observations	practitioner/ practitioner	low

4.4.5 Acclimation and Diagnosis as the Basis for a New Approach

In mechanistic modelling of windthrow risk, the assumption is made that the magnitude and probability of critical wind speed can be determined from extrinsic measures of tree, stand and site attributes. The concept of acclimative growth provides an alternative conceptual basis for windthrow risk assessment. Endemic windthrow can be viewed as a problem of mal-acclimation in which certain trees in a given location are unable to withstand local routine peak winds. Risk prediction then becomes a problem of evaluating the degree to which trees are acclimated to local peak winds, and of estimating the increase in wind loading on residual trees likely to result from proposed treatments.

Combined with the field based diagnostic approach which is standard for the assessment of site capability and constraints in BC, the concept of acclimative growth provides an opportunity for a new approach to windthrow risk. Within a 'diagnostic framework for windthrow risk estimation', the diagnostic question for assessing stand hazard is based on the premise that the more open grown a tree is, the more likely it is to be acclimated to above canopy periodic peak winds. Using a 'mechanical' approach, a practitioner observes the stem, crown and canopy features in order to estimate the probable load and resistance of trees within a stand. Under the 'acclimative' approach, the practitioner uses these same observations to estimate the long term exposure of the trees within the canopy and their dependence on their neighbours for shelter and damping. Since stem and crown form reflect the long term position of trees within the canopy and their competitive interactions with their neighbours for space and light (e.g. Smith, 1986), this is a more direct interpretation for a practitioner to make. Observation of tree form can also provide insights into the local wind regime at a site. The form of well exposed dominants reflects their long term acclimation to the local wind and snow regime, and was found by Valinger and Fridman (1997) to be a good indicator of site susceptibility to damage. A greater contrast in mean slenderness between open grown trees and trees grown in nearby stands of a given density, implies a greater differential in acclimation.

For assessing the contribution of a given treatment to windthrow risk, it is necessary to evaluate the probable increase in wind load resulting from that treatment. In mechanical models, the effects of thinning or cutting unit shape on wind flow are measured or calculated. In the diagnostic approach the relative increase in wind loading on residual trees is evaluated using site indicators such as boundary orientation relative to damaging wind direction, or canopy removal level. The association of damage with treatment characteristics is then confirmed during calibration. Treatments which result in small changes in wind loading are low risk, whereas treatments which result in large changes are high risk. The net effect of these changes in wind loading on the overall risk of windthrow depends on the degree to which trees are acclimated to exposed conditions, and is evaluated in the diagnostic approach by integrating stand, soil, and topographic hazards with treatment risk.

Further potential for the use of intrinsic tree responses to wind loading within a diagnostic framework were identified in Chapter 3. The results of the study of post-thinning growth underlined the fact that stem slenderness is dynamic as trees modify height increment, radial increment and longitudinal allocation in response to sudden changes in their environment following thinning. Observing the magnitude and duration of short term changes in stem slenderness following removal of neighbouring trees, offers a diagnostic test for evaluating re-equilibration with post-treatment conditions which could assist with scheduling multi-entry treatments. Observing the relative adjustment of trees of different initial form classes provides insights into the vulnerability of different form classes in the years immediately following thinning.

4.5 A Diagnostic Framework for Windthrow Risk Estimation

4.5.1 Characteristics

The diagnostic framework for windthrow risk estimation (DFWR) introduced in this section combines elements of the observational, and empirical approaches. It maintains the simplicity, and cost effectiveness of the observational approach while adding a calibration step to localize generic indicators which makes it more empirical. As in the empirical method, a specific severity of damage is predicted. The DFWR is consistent with two of the principles of decision support systems systems for silviculture planning recommended by Thompson and Weetman (1995); it is based on presently available technical information, and through the calibration procedure it is refined with the active participation of practitioners. The DFWR was developed primarily as an instructional tool for training practitioners and was refined through interaction with workshop participants, and through application in windthrow assessment projects.

The DFWR provides practitioners with a framework for collecting observations during site and stand diagnosis for prescription development. The calibration and feedback step provides for continual refinement of predictions as new knowledge is gained. Practitioners ask and answer a series of simple questions in order to 'diagnose' site conditions, describe the severity of damage along nearby clearcut edges and predict post-harvesting wind damage. The diagnostic questions induce systematic observation and consideration of site indicators and management actions and their relationship with damage patterns. The premise underlying this approach is that the severity of endemic windthrow and its association with environmental and management factors in a given location is the best predictor of future endemic damage in nearby areas with similar attributes.

The topographic, soil and stand factors which contribute to windthrow risk were reviewed in Chapter 2 and form the basis for the checklist contained in the Windthrow Handbook for BC Forests (Stathers et al. 1994) contained in Appendix C. In the diagnostic approach, the observation and analysis of windthrow indicators is retained from the observational approach, however in this method the observations are used to answer diagnostic questions which are based on the principles which underly the contribution of these indicators to risk. These questions enable characterization of threshold indicator values for three levels of hazard (low, moderate and high) for each of the topographic, soil and stand components of biophysical hazard for windthrow. The calibration step is a form of empirical study in which the expected association of indicators with actual occurrence of damage is confirmed through observation. Results from the calibration are then used to check and if necessary revise the threshold indicator values for the topographic, soil and stand hazard components.

4.5.2 Applications

The DFWR provides estimates of the severity of damage from endemic winds to clearcut edges or within block reserves in areas with a history of recurring edge damage from endemic winds (e.g. Figure 4.1). This approach requires nearby treated area for calibration and is limited by the availability of comparable sites and the accuracy of site comparisons. If there are no existing clearcuts for calibration, evaluation of risk for a new cutblock could be conducted using 'best estimates' for answers to the diagnostic questions. The predicted severity of damage would be uncertain, but areas within the cutblock with relatively higher or lower relative risk could be identified.

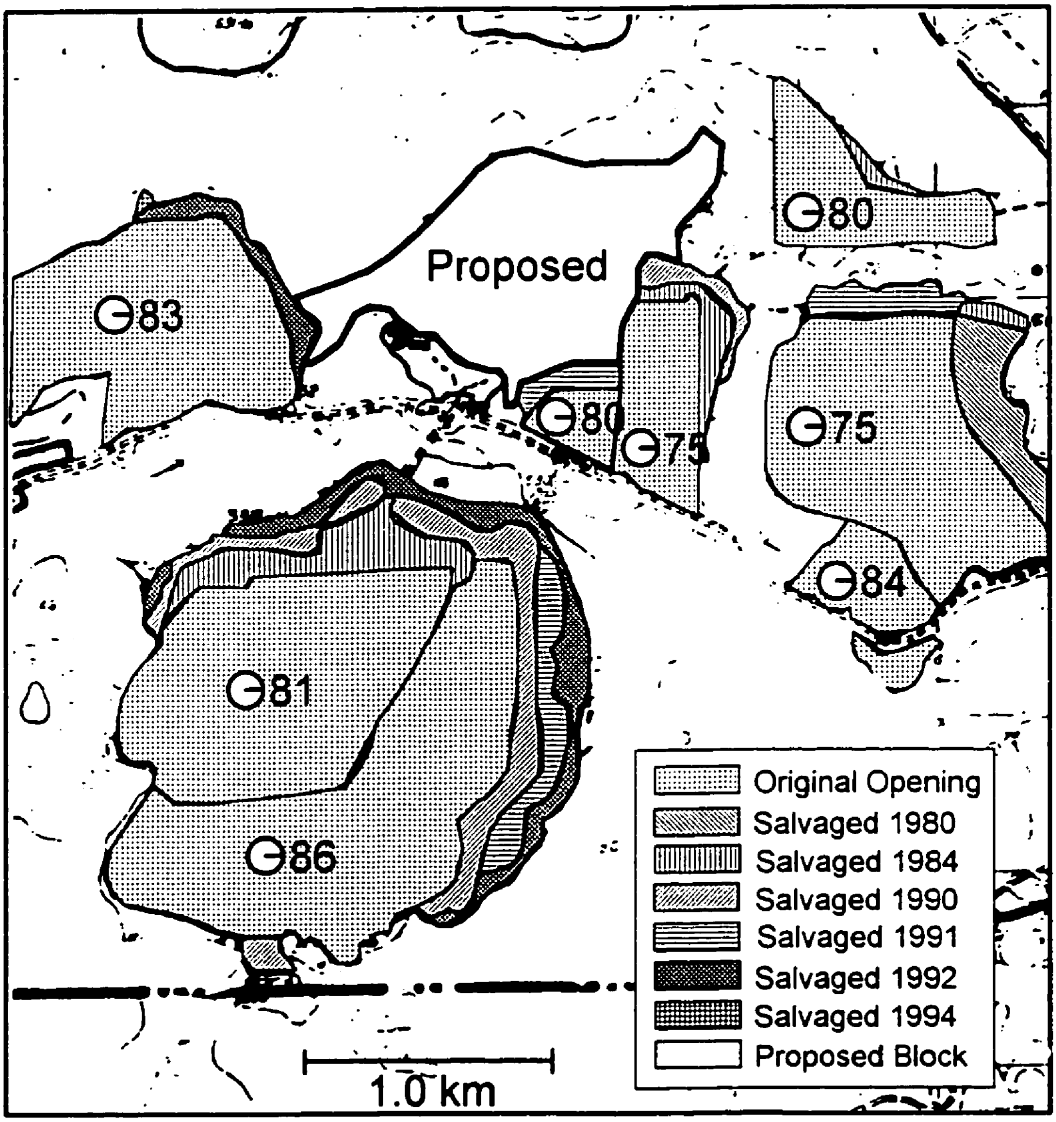

Figure 4.1: Overview map of an area on the central interior plateau (west of Quesnel, BC) showing example of recurring clearcut edge wind damage and salvage. Note the concentration of damage on north and east clearcut edges. The symbol 'ϴ' and adjacent number indicates year of harvest for the original opening.

4.5.3 Definitions

The DFWR focuses on the prediction of endemic damage for several reasons. By definition, endemic damage is caused by winds which recur frequently and are therefore highly predictable. If these frequently recurring winds are disrupting prescriptions and planning, managers should take steps to predict and reduce the damage. Where overview maps show a pattern of recurring salvage to cutblock boundaries, a pattern of endemic windthrow is implicated.

In this framework, 'Windthrow Risk' is the severity of damage expected from endemic peak winds. In a given location it is determined by the interaction of environmental factors and management factors. 'Severity of damage' at the stand level refers to the proportion of trees damaged within a given area. The environmental factors are termed 'Biophysical Hazard' and the management factors 'Treatment Risk'. Biophysical Hazard integrates topographic, soils, and stand features. It represents the vulnerability of the stand to windthrow. In other words, the differential between how windfirm the trees which form the stand are, and how windfirm they would need to be in order to survive full exposure to wind along a downwind clearcut edge. Treatment Risk is the degree to which a particular harvest pattern increases the wind loading on residual trees.

For the results of the assessment to be useful for practitioners it is necessary to define the severity of damage expected for each Windthrow Risk class. In Table 4.2, the expected severity of damage to freshly exposed boundaries which have a High Treatment Risk (at or near perpendicular to the direction of damaging winds at the downwind end of a large opening) is described for each Windthrow Risk class.

4.5.4 Steps

The assessment procedure can be used at both the landscape level and at the stand level. In both cases, managers start by observing windthrow patterns on overview maps and photographs, looking for evidence of recurring damage to cutblock boundaries from particular directions. This gives an indication of predominant damaging wind directions, and the boundary orientations which have a higher Treatment Risk. Biophysical information is obtained from forest cover maps, topographic maps, and ecosystem or soils maps for a landscape level analysis, and from inspection of existing and proposed cutblock boundaries for a field analysis. Boundaries should be divided into segments which have similar management and biophysical attributes. With overview map information the ability to interpret map information such as forest cover labels or contour lines in terms of the diagnostic questions is necessary.

The assessment process is iterative, with the first cycle focusing on High Treatment Risk boundaries of existing cutblocks which have been exposed to winds for several years. This enables calibration and adjustment of component hazard class thresholds. The second cycle focuses on the boundaries of cutblocks proposed for harvest. The third cycle occurs several years after harvest when damage is monitored and the assessment predictions are checked and re-calibrated if necessary. The steps in the assessment process are summarized in Figure 4.2.

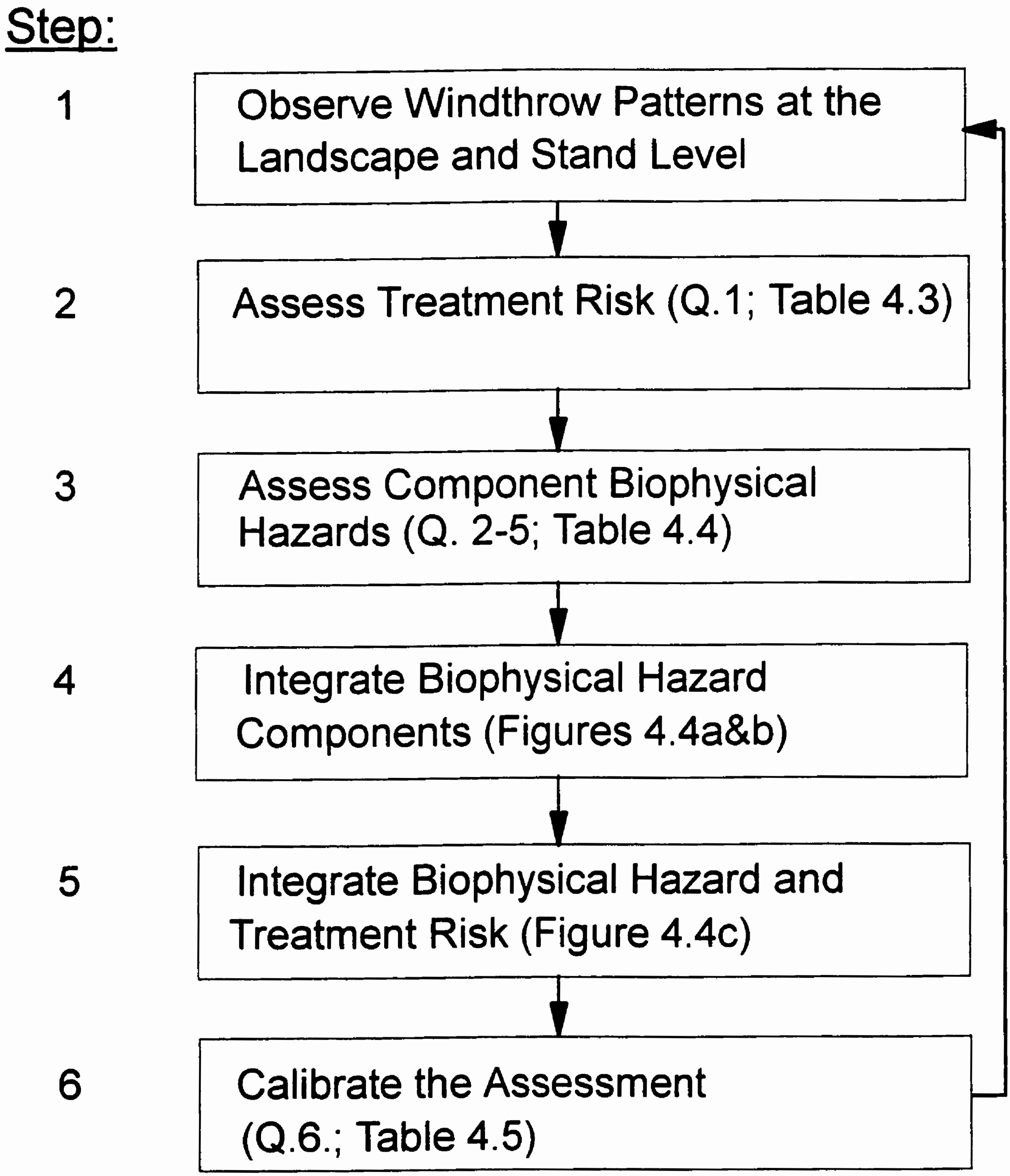

Figure 4.2: The steps in the diagnostic framework for windthrow risk estimation.

Step 1. Identify Windthrow Patterns

Analyses of extreme wind events should be referred to if they are available and if they are representative of the area of interest (e.g. Murphy and Jackson, 1997). Windthrow salvage units and areas of known windthrow are identified from landscape level maps of cutblock openings. Cutblock edges on aerial photographs are examined and any damage is recorded on the overview maps. People with local experience are interviewed. Patterns in the direction, location, periodicity and intensity of damage caused by winds are noted. During field assessment work, the location and orientation of fresh, old and historic windthrow is observed and mapped. From this overview and field level assessment the predominant damaging wind directions can be identified for each location. For example, the area shown in Figure 4.1 shows a clear pattern of repeated windthrow salvage on north and east cutblock boundaries. These would be the 'high treatment risk' boundaries which would be inspected in the field for calibration prior to assessing the boundaries of the proposed cutblock to the north.

Step 2. Assess Treatment Risk

Treatment Risk refers to the effect of the treatment on the wind loading of remaining edge trees (Table 4.3). For openings, the size, location and orientation of the boundaries are the determinants of treatment risk, for uniform partial cuts the removal intensity and tree selection criteria are the determinants. The diagnostic question is:

Q1. ***Treatment Risk for Clearcut Boundaries:*** Will the proposed harvesting boundary increase wind loading on trees along the stand edge (for openings), or on retained trees (uniform partial cut)?

Step 3. Assessing Biophysical Hazard for Windthrow

The site and stand features which determine Biophysical Hazard for windthrow can be grouped into Topographic Exposure, Soils and Stand Hazard components, forming three sides of the 'Windthrow Triangle' (Figure 4.3). Each of these component hazards is assessed as having Low, Moderate or High hazard. The assignment of hazard class for each component is made by asking the following diagnostic questions for each proposed boundary segment or location within a proposed partial cut, in its pre-harvest condition:

Q2. ***Topographic Exposure Hazard:*** Are wind speeds normal for the area, or are they lower or higher due to the presence of a terrain obstacle or constriction?

Q3. ***Soil Hazard:*** Is root anchorage restricted by an impeding layer, low strength soil, or poor drainage?

Q4. ***Stand Hazard:*** Are the individual trees within the stand well used to wind loads, or are they dependent on their neighbours for shelter and damping?

Q5. ***Supplemental Stand Hazard question for very high density stands:*** During a wind event, would damaged trees simply lean back into the stand and be supported by their neighbours, or will they work down through the canopy to the ground?

The indicators for low, moderate and high hazard classes for each component of Biophysical Hazard are summarized in Table 4.4. The actual indicator values of each boundary segment should be recorded along with the initial estimate of component hazards. After calibration, these indicator values can be used to identify hazard class thresholds in areas with similar biophysical characteristics.

Step 4. Integrate Biophysical Hazard Components

The Biophysical Hazard components are integrated in two steps. Topographic Exposure and Soil Hazard are combined using the Site Hazard Grid in Figure 4.4a. Site and Stand Hazard are integrated using the Biophysical Hazard Grid in Figure 4.4b.

Step 5. Integrate Biophysical Hazard and Treatment Risk

Biophysical Hazard and Treatment Risk are integrated using the Windthrow Risk Grid in Figure 4.4c.

Step 6. Calibrate the Assessment

Checking and calibrating the assessment of Biophysical Hazard components for each location is a critical step in the assessment process. The edges of nearby cutblocks which were harvested in the last 2-5 years should be examined prior to assessing the proposed block. The edges of particular interest are those with a High Treatment Risk because these are the boundaries which have experienced the greatest increase in wind load following harvest. Biophysical Hazard is estimated by answering the diagnostic questions. For High Treatment Risk boundary segments, the estimated Windthrow Risk class can then be determined from the fourth column of Figure 4.3c. The severity of damage in these segments is observed and a final diagnostic question is answered:

Q6. ***Calibrating Windthrow Risk Classification:*** Is the severity of damage observed along the calibration boundary consistent with that predicted in Table 4.2 for the estimated class of Windthrow Risk?

If the observed damage is not consistent with that expected for the estimated risk class, then it is necessary to reconsider each of the component hazards and adjust the rating of the component which was most likely rated too high or low (Table 4.5). This is generally a component which appeared borderline between two hazard classes during the initial assessment.

Once calibration is complete, if the biophysical characteristics and boundary orientations in the proposed block are similar to those in the calibration block, then direct comparisons are possible. The component hazard class thresholds should be valid, and predictions of damage severity should be accurate. Where there are differences in topographic exposure, soil or stand characteristics, component hazards should be classified according to the diagnostic questions. It may take several iterations of assessment, treatment and monitoring before hazard class thresholds are identified with confidence in areas without a prior history of harvesting.

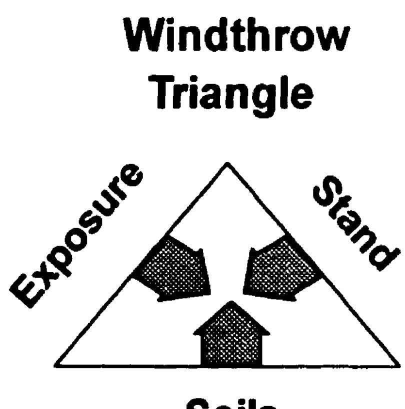

Figure 4.3: The component biophysical hazards which form the Windthrow Triangle.

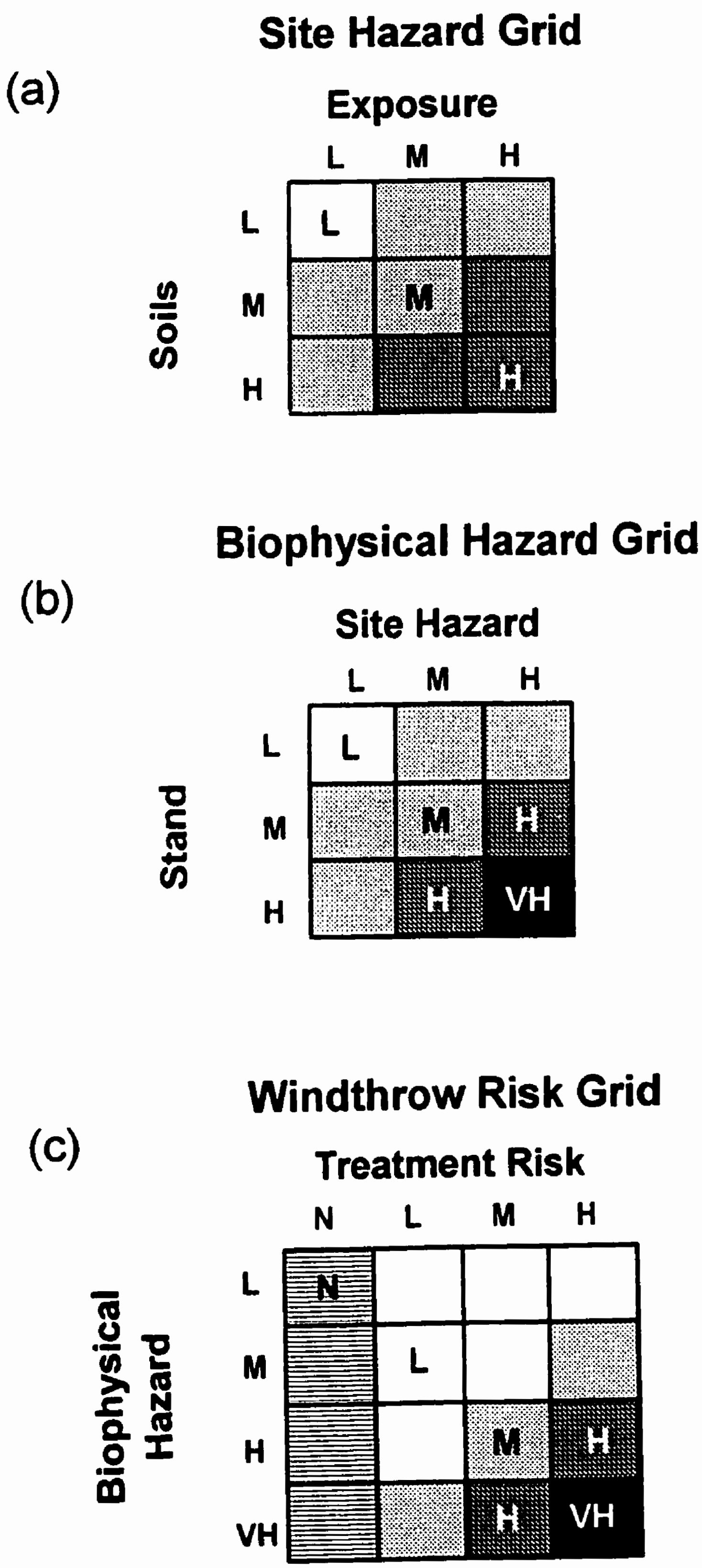

Figure 4.4: The grids used to integrate the components of Windthrow Risk. (a) Site Hazard Grid, (b) Biophysical Hazard Grid, (c) Windthrow Risk Grid.

Table 4.2: Descriptions of expected damage severity for Windthrow Risk classes

Windthrow Risk Class	Expected severity of damage from endemic winds to boundaries with high Treatment Risk
None	No stand present to be damaged by winds.
Low	Little or no damage along recent cutblock edges.
Moderate	Partial damage along recent cutblock edges. Between 10 and 70 percent of the trees are uprooted or snapped within the first tree length in from the edge.
High	Heavy damage along recent cutblock edges. More than 70 percent of the trees within the first tree length damaged.
Very High	Very severe damage along recent cutblock edges. More than 70 percent of the trees damaged in both the first and second tree lengths into the edge.

Table 4.3: Treatment Risk classes for cutblock boundaries.

Treatment Risk:	Answers to diagnostic question. Example indicators.
None	*Answer:* No edge trees. *Example:* Boundary extends to edge of non-timber type.
Low	*Answer:* Slight increase in wind load on edge trees expected following harvesting. *Example:* Boundary runs at or near perpendicular to the direction of damaging winds at the upwind end of a large opening.
Moderate	*Answer:* Moderate increase in wind loading on edge trees following harvesting. *Example:* Boundary runs at or near parallel to the direction of damaging winds.
High	*Answer:* Large increase in wind loading on edge trees following harvesting. *Example:* Boundary runs at or near perpendicular to the direction of damaging winds at the downwind end of a large opening.

Table 4.4: Biophysical Hazard classes

Hazard Class	Answers to diagnostic questions. Example indicators.
	Topographic Exposure Hazard Component
Low	*Answer:* Winds are lower than normal in the area. *Example:* The site is in the lee of a major terrain obstacle which provides significant shelter.
Moderate	*Answer:* Winds are normal for the area. *Example:* The site is in flat terrain with no terrain obstacles to provide shelter or create wind speed up.
High	*Answer:* Winds are higher than normal for the area. *Example:* The site is on an upper slope or crest, on the shoulder of a ridge, in a constricted valley or pass, or near the shoreline of a large waterbody.
	Soil Hazard Component
Low	*Answer:* Root anchorage is unrestricted. *Example:* Root systems are bowl shaped and deep structural roots are unimpeded. Soils are not organic. Soils are well drained.
Moderate	*Answer:* Root anchorage is partially restricted. *Example:* Root wads are flat bottomed. Soils are moderately well to well drained.
High	*Answer:* Root anchorage is severely restricted. *Example:* Root systems are plate-like with little mineral soil penetration. Drainage may be poor. Organic soils.
	Stand Hazard Component
Low	*Answer:* Trees are well acclimated to above canopy winds. *Example:* Individual trees are open grown. Shade intolerants have live crown ratios in excess of 70 percent.
Moderate	*Answer:* Individuals are somewhat dependent on their neighbours for shelter and damping. *Example:* Shade intolerants have live crown ratios of 35-70 percent
High	*Answer:* Individual trees are very dependent on their neighbours for shelter and damping. *Example:* Shade intolerants have live crown ratios of less than 35 percent. Substantial root or stem decay present in stand.

Table 4.5: Calibrating the Windthrow Risk assessment

Answer to Question 6	Action
Yes, damage is consistent with expected level.	Use the values for the topographic, soils and stand indicators to identify the threshold values for high, moderate and low hazard classes for each of the Exposure, Soils and Stand Hazard components.
No, there is less damage.	Consider which of the component hazards, Exposure, Soils or Stand might have been rated too highly. Reduce the rating and raise the hazard class thresholds accordingly.
No, there is more damage.	Consider which of the component hazards, Exposure, Soils or Stand you might have rated too low. Increase the rating and decrease the hazard class thresholds accordingly.

4.5.5 Refinements

In areas with a prior history of harvesting, the calibration step should enable appropriate hazard class threshold values for Soil, Stand and Topographic Hazard to be identified for a particular location. The definition of expected severity of damage for each windthrow risk category makes the outcome of the assessment process quantitative, but the diagnostic questions are still based on relative measures of biophysical attributes.

The components of Biophysical Hazard are uniformly weighted during the integration steps, but the integration is conservative, so that a 'low' combined with a 'moderate' becomes a 'moderate'. In reality, the relative importance of topographic, soils and stand factors will vary from location to location. This can be accounted for during calibration by raising the hazard class thresholds for components which do not appear to contribute much to risk, and lowering them for components which contribute more. An alternative approach would be to weight the

Exposure, Soils and Stand components differently during the integration of Biophysical Hazard. This would require development of a scoring system in which individual components are scored and added to yield the overall Biophysical Hazard class such as in the UK windthrow hazard assessment method. Building landscape level empirical models for the area of interest would provide the appropriate weights.

4.6 Landscape Level Hazard Mapping

The discussion now returns to consideration of the components of a comprehensive windthrow management program for BC. Landscape level identification of hazard early in the planning process enables the resources available for more detailed stand level assessment to be focused on areas with higher hazard or where windthrow could seriously disrupt management. Identification of recurrent cutblock edge windthrow may encourage the multiple parties involved in development planning to design more realistic harvest unit layouts in areas with a history of recurrent damage. The size, shape and timing of proposed harvesting units can be modified to reduce post-treatment wind loading on residual trees, thereby compensating for lower windfirmness of trees on the site.

The DFWR requires assembly of local overviews of windthrow history in Step 1, and enables preliminary mapping of hazard using information from topographic, forest cover and soils or ecosystem maps to answer the diagnostic questions. Ideally, the preliminary mapping should be upgraded using the results from empirical studies. Empirical models could be developed using geographic information system databases combined with windthrow history maps or windthrow mapped from aerial photographs (e.g. Wright and Quine, 1993).

4.7 Incorporation of Assessment Results into Prescriptions

Where higher windthrow hazard or undue impacts are identified during landscape level hazard mapping or harvest planning, more detailed field based assessments of proposed harvesting or thinning units are warranted. Following estimation of the expected level of damage during stand level assessment, the challenge for the practitioner is to evaluate the potential impacts of this damage and where appropriate modify the prescription to reduce damage and impacts. Moore (1977) defined 'impacts' as the consequences of windthrow should it occur. This definition should be clarified to state 'consequences of windthrow for the *achievement of management objectives*'. Windthrow disturbance is a feature of unmanaged forest ecosystems, and where the management objective is simply to allow natural processes to proceed, windthrow disturbance could be considered as having a neutral or positive impact on management objectives. Where landscapes and stands are being managed for specific features and products, windthrow can disrupt the intention of the plans. In the latter case the impact would be negative.

The basic strategies for reducing windthrow risk at the stand level are summarized by Savill (1983), Ruel (1995) and Stathers et al. (1994). For clearcuts, they include reorientation of boundaries, movement of boundaries from higher hazard to lower hazard sites. Strategies such as edge feathering and crown reduction are also being used in BC (Gillies 1998). Wind tunnel modelling of stands in flat terrain indicates that wind speed on the downwind edge of an opening is relatively constant once opening width exceeds 6 tree heights, and decreases rapidly as opening width declines below 2 tree heights (Gardiner et al., 1997). For partial cuts with group removal, reducing opening size and cutting successive strips into the wind reduce wind loading on residual trees. For uniform partial cuts, removal intensity should be reduced as vulnerability increases in order to maintain mutual shelter. Groome (1988) recommends that uniform stands be left unthinned once they exceed 20m in height and that the vertical angle from the base of one tree to the top of the next not exceed 10%.

The challenge for practitioners is to correctly evaluate the risk to the proposed target stand and where necessary modify the layout or treatment regime in order to increase the likelihood of success. The identification of the separate contributions of topographic, soils, stand and treatment risk components during the DFWR assists practitioners in choosing among design and treatment options by promoting close examination of the limiting conditions on a particular site and the opportunities for avoiding or compensating for them. A series of field cards has been produced by the BCMOF (1998) to guide practitioners through the DFWR (Appendix C). Where management variables are included in empirical or mechanical models, the relative risks of different treatment strategies can be evaluated.

The use of individual tree growth patterns in assessing re-acclimation with post-thinning conditions was discussed in Chapter 3. Re-thinning or fertilizing stands which are still acclimating increases the potential for damage. Documentation of relationship between the magnitude and duration of the form adjustment for codominant trees from stands representing a range of densities heights in a given area would enable localized guidelines for thinning re-entry to be developed.

Acclimative growth can be managed for long term promotion of windfirmness through stand density management and manipulation of structure. Initial stocking and thinning treatments can be designed to maintain target height-diameter ratios within the stand. Crop planning tools such as stand density management diagrams (Farnden 1996) or TIPSY (K.J. Mitchell et al. 1995) enable prediction of average tree form development over time as a function of stand density and site quality. Under the acclimative premise, the difference in mean stand slenderness from pre-treatment density to target post-treatment density provides an indicator of potential disequilibrium with post-treatment conditions. Using a mechanical approach, the stand density, tree height and crown attributes in TIPSY could be used for estimating wind loading, and stem diameters could be used to estimate resistance. Gardiner et al.'s (1997) observation that wind loading for similar sized trees increases linearly with spacing factor (ratio of inter-tree spacing to top height) could be used to model short-term wind load increases resulting from thinning.

4.8 Monitoring, Feedback and Training

The predictions of landscape and stand level windthrow risk assessments should be monitored and the results used to refine prediction models to continuously improve the accuracy and detail of assessments. The outcomes of prescriptions should be monitored to ensure that wind damage and its impacts are within acceptable limits. The calibration step in the DFWR ensures that the initial association of damage with site features, and local interactions between topographic, stand and soil properties is observed and considered. In subsequent assessments, the calibration step enables refinement of the hazard class thresholds and provides feedback on the success of prescriptions. Establishing monitoring areas for the verification of empirical or mechanical models (e.g. Quine et al. 1995), and for testing windthrow mitigation treatments would provide feedback for practitioners and model developers. These monitoring areas could also be used during workshops on prescription development for training practitioners in windthrow assessment and management techniques.

4.9 Research into Assessment Methods and Prescriptive Strategies

While the diagnostic approach is well suited for current needs in BC and could continue to assist managers with prescription design, it should be viewed as a stepping stone to more quantitative methods of risk assessment in areas with substantial windthrow problems. A series of empirical studies of association of windthrow with biophysical and management regimes should be initiated in the different biogeoclimatic zones in areas of the province identified as having recurrent windthrow.

Major wind damage events have been attributed to combinations of unusually high winds and higher than average precipitation. Compilation of event records and AES climate data would enable the analysis of the frequency of damage events as function of wind speed and direction, and precipitation.

Studies into the efficacy of edge thinning and crown modification of trees along clearcut edges are underway on Vancouver Island (Gillies 1998). Windthrow is being monitored in silviculture system trials throughout the province (e.g. Coates 1997; Jull et al. 1997) and interpretation of the results of these studies in terms of the evaluation treatment risk in partial cuts is needed.

The work of Tripp et al. (1992) should be extended to documenting the impacts of windthrow on non-timber resources. This would require the establishment of long term monitoring sites, or conducting retrospective studies. Studies such as the work of Nowacki and Kramer in Alaska (1998) should be implemented to improve the understanding of windthrow ecology and the influence of wind damage on stand structure and distribution in different forest types.

4.10 Conclusions

Given the magnitude of wind damage in BC and the new requirements for assessment of windthrow a comprehensive program of windthrow management should be adopted in BC. Central to this program is the need for a method of assessing windthrow risk at the landscape and stand level which is suited to the diversity of conditions, quality of information available and skills of managers. Incorporating a framework for windthrow risk assessment based on the principle of acclimative growth into the system of site and stand diagnosis for silviculture prescription development currently used in BC provides a logical starting point.

CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. Following thinning, height growth was temporarily reduced, radial increment increased and allocation of radial increment to the stem base increased. These responses were consistent with acclimative growth responses observed in short term field and laboratory studies of tree growth under mechanical loading. The net effect of these growth responses was to reduce stem slenderness, with greater reductions in the initially more slender trees. The reverse-S pattern of slenderness adjustment and its association with relative height, radial increment and allocation responses, suggests that trees require a period of equilibration with post-thinning conditions and that the more slender trees are in greater disequilibrium initially.

2. The results suggest that monitoring the pattern of height-diameter adjustment could provide a useful tree-based diagnostic for managers designing tree selection guidelines and scheduling treatments in high density stands. They also support the principle of acclimation to routine windloads as the basis for the evaluation of stand hazard within the diagnostic framework.

3. While the 1992 windthrow census summarized in Chapter 2 is a point estimate of windthrow, the level of wind damage reported is of similar magnitude to that caused by wildfire and insects throughout the province in that year. This result, along with the comments of census respondents indicate that a more comprehensive program of windthrow management is warranted.

4. The review of windthrow assessment frameworks in Chapter 4 indicated that none of the current methods of assessment are well suited for general application given the diverse ecology and management of BC forests. By combining the principle of acclimative growth with the diagnostic approach to site and stand evaluation, the diagnostic framework for windthrow risk evaluation provides a means of enhancing practitioners' observation and understanding of the local components of windthrow, and improving stand level prescriptions in areas of recurring wind damage.

5.2 Recommendations

1. There are a number of areas for further investigation of the relationship between acclimative growth and windthrow risk: i) the concept of intrinsic safety factors and the mechanisms which control the allocation of resources to structural growth; ii) genetic variation in intrinsic safety factors and control mechanisms for trees from sites with different mechanical environments; iii) the relationship between safety factor, tree form and within-canopy wind profile for stands of different density and structure; iv) the relationship between site productivity and the problem of critical height on anchorage limited sites; v) the relationship between stem strength and anchorage, and how anchorage varies with age, tree size, soil characteristics, seasonal climate and soil moisture conditions; vi) the concept of thinning shock and the separation of reallocation of resources for mechanical equilibration from physiological equilibration.

2. A comprehensive program of windthrow management at the forest and stand level should be adopted. This strategy should include i) systematic local monitoring of windthrow and provincial compilation of annual damage statistics, ii) timber management policies which

facilitate prompt identification, agency review and salvage of windthrow where appropriate, iii) landscape and stand level assessments of windthrow risk in locations where a history of endemic damage is identified, iv) incorporation of landscape level assessments into development planning and stand level assessments into silviculture prescriptions, v) operational monitoring of the outcomes of development plans and prescriptions, assessment of windthrow impacts and feedback of results, vi) a research program to investigate operational methods of windthrow mitigation, document windthrow impacts on non-timber resources, and refine windthrow risk assessment methods.

3. Forest managers in BC should be trained to use a diagnostic approach to windthrow risk assessment in areas with a history of endemic windthrow until locally calibrated empirical or mechanical models with higher accuracy and utility are developed.

4. Form change patterns should be monitored in stands with a high windthrow hazard following thinning entries and subsequent entries be delayed until height-diameter ratios of residual trees stabilize.

5. Wind and snow damage should be accurately recorded in growth and yield studies and silviculture system research projects and compiled in a provincial database to assist in documenting stand attributes which are associated with higher windthrow risk.

6. Modules should be developed for crop planning tools such as TIPSY and Stand Density Management Diagrams which demonstrate the relationship between stand density, tree slenderness and vulnerability to wind damage.

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Appendix A

BCMOF 1992 Windthrow Census Questions and Comments

Table A.1: Questions asked in BCMOF 1992 Windthrow Census

	Question
1.	Blowdown analysis planned/unplanned:
a)	Is all commercially viable blowdown volume within your district under development plan? [by Tenure type in m^3] If no, explanation required by Tenure type.
b)	How much blowdown volume in your district is not commercially viable and therefore not planned for harvest? [by Tenure type in m^3] Comment as to why it is unviable.
2.	Harvest schedules (total planned volume to be harvested as a result of blowdown). [a) 1st year in m^3; b) 2nd year in m^3] If volume planned for harvest after 1st year, explanation required by tenure type.
3.	Of the planned volume, in Question 2, what is the volume of greenwood that was included to ensure salvage of blowdown became commercially viable? [by Tenure type]. Comment.
4.	Are you experiencing difficulties ensuring blowdown volumes are harvested within reasonable time frames? Why?
5.	Additional comments.

Table A.2: Summary of census respondents' written comments[1].

	Question 1a. Is all commercially viable windthrow under development plan?
Cariboo	WL: virtually all is viable except small isolated patches CH: May/June blowdown addressed before DP submitted QU: - HF: -
Kamloops	R: No - blowdown only just discovered, will be covered under DP
Nelson	BO: all identified merch under some harvest plan IN: - GO: - RE: fresh blowdown in next years DP CR: - AR: no, blowdown in TSA subsequent to preparation of DP's KL: volumes detected throughout field season; will be added to next years DP
Pr.George	PG: - RB: - VF: no, majority of blowdown logged prior to DP preparation FJ: no, DPs submitted prior to field season MA: - DC: - FJo: currently do not have a blowdown problem that can be mapped; most is fringe in non merch types FN: not commercially viable due to $1.25 and company selective in timber requirements
Pr.Rupert	R:
Vancouver	R: not in DP

[1] Abbreviations: R=Regional summary, Districts: WL=William's Lake CH=Chilcotin QU=Quesnel HF=Horsefly BO=Boundary IN=Invermere GO=Golden RE=Revelstoke CR= Creston AR=Arrow Lake KL=Kootenay Lake PG=Prince George RB=Robson VF=Vanderhoof FJ=Fort St. James MA=Mackenzie DC=Dawson Creek FJo=Fort St. John FN=Fort Nelson

	Question 1b. Why is windthrow salvage non-viable?
Cariboo	WL: virtually all is viable except small isolated patches; can't estimate volume; patches <0.3 ha CH: <2ha and random blowdown of MPB attack QU: all areas with access addressed; small isolated patches if volume justifies road costs; landowners get adjacent if no CL access HF: fringe or single tree windfall on edges of planted blocks; small isolated patches which do not warrant roading costs
Kamloops	R: <2ha; scattered isolated small patches with high access/mob costs
Nelson	BO: <1ha; isolated pockets with no developed access; inoperable IN: <1.5ha; access problems, small volumes, steep slopes GO: scattered and inaccessible RE: poor road and logging chance CR: scattered with low blowdown percentage and major development required AR: inoperability; small undeveloped areas KL: scattered blowdown (1-3% of stand); within Wilderness Areas; watersheds which are unavailable due to access, planning or political restraints
Pr.George	PG: small remote inaccessible patches; individual trees along roadsides; cutblock fringes RB: all detected volumes viable VF: inaccessible; low quality; IRM concerns; road sides and cutblocks; low volumes FJa: inaccessible; discovered too late and deteriorated MA: small patches far from roads; small volumes that don't pay for mob and de-mob costs DC: small timber; steep broken terrain; late detection (poor wood quality) FJo: TSA plan indicates approx 10500m^3 unsalvaged annually due to remoteness and small areas FN: [50000m^3 not commercially viable due to $1.25 and company selective in timber requirements]; old; <50m^3/ha; endemic blowdown content 10%; too far from present operations

Pr.Rupert	R: protection of non-timber resource values has constrained salvage of 60000m^3 in Morice TSA; accessibility problem in North Coast and Kalum TSA's; establishment or re-establishment of infrastructure to harvest isolated blowdown may limit operations to more valuable timber or require inclusion of a greater percentage of greenwood; scattered patches may preclude harvest; catastrophic events dealt with through non-replaceable major licences (e.g. FLA16889 North Coast TSA)
Vancouver	R: blowdown areas too small; site degradation associated with development too great to warrant exploitation; poor timber quality coupled with high development costs; agency constraints such as streamside management zones; scarce time and dollars prohibit comprehensive blowdown management; areas locked-up through protected area strategy (e.g. Power River in CRFD);

	Question 2. Why is windthrow scheduled for salvage after year 1?
Cariboo	WL: none CH: none QU: summer ground harvested after breakup HF: windthrow recurring problem, yr2 based on volumes of past yr.
Kamloops	R: extent of blowdown in some districts; some districts also dealing with MPB infestations
Nelson	BO: to meet operational requirements; no threat to forest health IN: none BO: none RE: fresh blowdown, higher priority areas first CR: time to complete SP's and CP administration; seasonal constraitns-snow AR: DP is not an appropriate gauge of our sensitivity to addressing blowdown as is submitted annually; blowdown occurs with unpredictable frequency and magnitude and therefore does not lend itself to formal planning procedure KL: extensive road development required for access; majority of development in high elevation areas where operating season restricted; blowdown priorized with good licensee cooperation

Pr.George	PG: massive blowdown in 1990 some salvaged in second year; historically all viable blowdown salvaged in first year RB: - VF: harvest as soon as possible after it occurs; is more blowing down as this is written; do not plan blowdown volumes year to year FJ: normally salvaged in same year as occurrence MA: none DC: none FJo: fringe areas of merch timber salvaged once identified FN: none
Pr.Rupert	
Vancouver	R: remoteness prohibits speedy extraction; much blowdown generated by winter storms and may remain undetected until following summer; by the time approvals and access development in place several operating seasons may have passed

	Question 3. What percentage of green wood is included to ensure commercial viability?
Cariboo	WL: none included for comm viability but patches usually clearcut so includes some standing green CH: negligible QU: - HF: -
Kamloops	R: ave 25% greenwood to rationalize boundaries, appropriate prescriptions for silvics of species, safety, road and landing development
Nelson	BO: only green standing within blowdown patches IN: greenwood only removed to facilitate the removal of the blowdown volume and/or for safety reasons. BO: greenwood within blowdown areas clearcut RE: greenwood within blowdown areas clearcut CR: most blowdown in timber types conducive to clearcut silv system AR: no green timber added to ensure commercial viability; green timber to be removed to accomodate operability, safety and logical development KL:greenwood within blowdown patches 30-40%

Pr.George	PG: greenwood not included for viability only to provide windfirm boundaries. RB: greenwood logged to ensure windfirm boundaries VF: - FJ: - greenwood accounts for 50% volume in blowdown MA: 50% DC: FJo: n/a FN: 50%; $1.25 influences ratio; little incentive for licensee to harvest poor quality stands
Pr.Rupert	R: [re-establishment of infrastructure to harvest isolated blowdown may limit operations to more valuable timber or require inclusion of a greater percentage of greenwood]
Vancouver	R: a significant volume may be required in order to make the opportunity more economically viable and to effect more windfirm boundaries

	Question 4. Are you experiencing difficulties ensuring blowdown volumes are harvested within reasonable time frames? Why?
Cariboo	WL: No; harvest when ground is snow free CH: No QU: No; licencees issued only blowdown permits until it was addressed HF: licencees reluctant some areas with high logging costs and poor wood.
Kamloops	R: administrative difficulties in processing SP's over many small blocks (<2ha) and single tree selection hampers recovery; use generic SP's for salvage but still require mapping, approval and tracking; should streamline or waive SP process for small blocks
Nelson	BO: ability to locate, track and sell blowdown is hampered by lack of additional human resources IN: no GO: summer access needed for late 1991 blowdown RE: some areas summer access only CR: have had extreme opposition to logging by local citizens AR: due to economics of blowdown salvage, some licensees must be prompted to take action KL: no

Pr.George	PG:- RB: no VF: logged 450000m^3 in 1990 resulting from severe windstorm; excellent licensee cooperation FJa: quick identification; establishment of low stumpage rate to ensure economic viability; extra staff time to identify and layout; use of blanket salvage permits for licensees has greatly improved utilization of small blowdown patches; attempting similar approach for SBFEP MA: blowdown program working fairly well but could be improved DC: majority of blowdown (fringe) occurs after operations have been completed and licensee is often reluctant to return for small volumes due to mob and de-mob costs FJo: no real blowdown problems in this district FN: yes, blocks added to current years harvesting as discovered; $1.25 stumpage does not encourage licensee to harvest problem stands because they can harvest the best material at the same price
Pr.Rupert	
Vancouver	R: remoteness prohibits speedy extraction; much blowdown generated by winter storms and may remain undetected until following summer; by the time approvals and access development in place several operating seasons may have passed

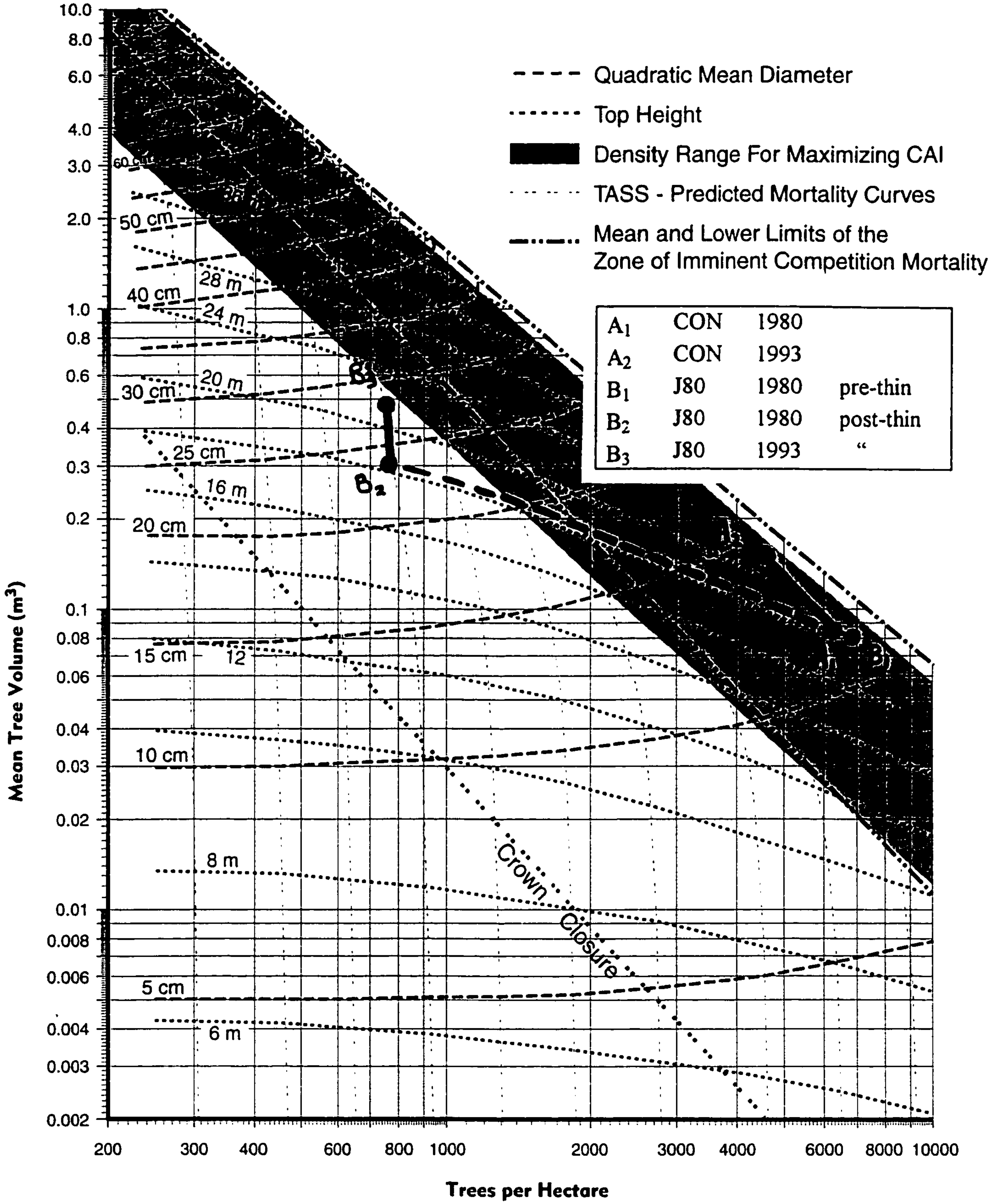
	Question 5. Any additional comments?
Cariboo	WL: formerly had small operators detect blowdown and apply for direct sales; Forest Act limits these to special circumstances CH: Fd blowdown salvage for FBB more successful than Pl QU: >1.5million m^3 blowndown May 5, 1990; addressed. Now working on current blowdown; little deterioration of merch during the 2 years it took to salvage, little staining and bark firm. HF: salvage licences for geographic areas under SBFEP ensure windfall volumes not lost.
Kamloops	R: valuation related concerns: lack of expedient and accurate way of quantifying blowdown damage; failure to recognize in appraisals the high costs of mob and de-mob associated with logging small isolated patches; need provincial concensus on how to cruise and appraise blowdown; using detection and direct award in one district
Nelson	BO: temporary staff increases should be available to deal with unusual situations like the Oct.1991 storm which created much of the blowdown IN: expediate removal of blowdown treated as a priority RE: licensee cooperating in salvage by modifying plans and overcutting with MOF permission CR: experiencing areas of continuous fringe blowdown which may result in linking clearcuts, or we may consider foregoing blowdown removal with the hope of ensuring a windfirm boundary. Also local trappers are concerned with removing blowdown adjacent to creeks especially when one side has already been clearcut KL: District has hazard rated all known blowdown and ranked priorities in terms of fire hazard, timber quality and potential insect buildup; good cooperation with licensees; majority of blowdown from 91 storm harvested (289,249m^3)

Pr.George	R: occurrence of blowdown varies between districts; early detection needed for prompt salvage; in remote districts with isolated operations and undeveloped areas licensee cooperation more difficult to attain, stumpage rates negotiated; where salvage not possible risk of bark beetle outbreaks assessed and appropriate prevention measures initiated; harvesting of blowdown a priorit, effort made to salvage commercially viable blowdown within one year; if majority of stand blowndown, then clearcut; logging boundaries designed to be as windfirm as possible; in remote locations is pressure to include greenwood outside of affected stand to improve economics; Appeal Board in Dunkley case ruled that can not use abbreviated appraisal system for small volumes of blowdown, does not help in taking timely action, recommend Appraisal Manual be amended. PG:- RB: past history have experienced only minor volumes of blowdown MA: incentives needed to encourage harvesting of very small volumes adjacent to new cutblocks, especially in spruce types to prevent spruce beetle buildups FJo: not had a significant blowdown problem since early 1980's; annual reconnaissance is conducted following spring breakup to assess and map blowdown; in 1991 salvaged less than 1000m^3 primarily along road corridors; no other significant areas detected FN: difficult to get problems addressed because licensee will not go very far of current block designs to recover blowdown areas; will take blowdown adjacent to existing logging but cull is extremely high.
Pr.Rupert	
Vancouver	R: there is a general absence of incentives like charges for cut-control and stumpage or royalty concessions, reducing the attractiveness of blowdown salvage for licensees; with AAC's decreasing and the potential for blowdown increasing due to the trend toward smaller cutblocks, there is an implicit need to have a formal structure in place to adequately address salvage.In the VFR this matter will be further investigated and direction will be given to DM's and Licensees; a current thought is that blowdown should be identified on all five year development plan submissions and salvage proposals incorporated.

Appendix B

Stand Density Management Diagrams

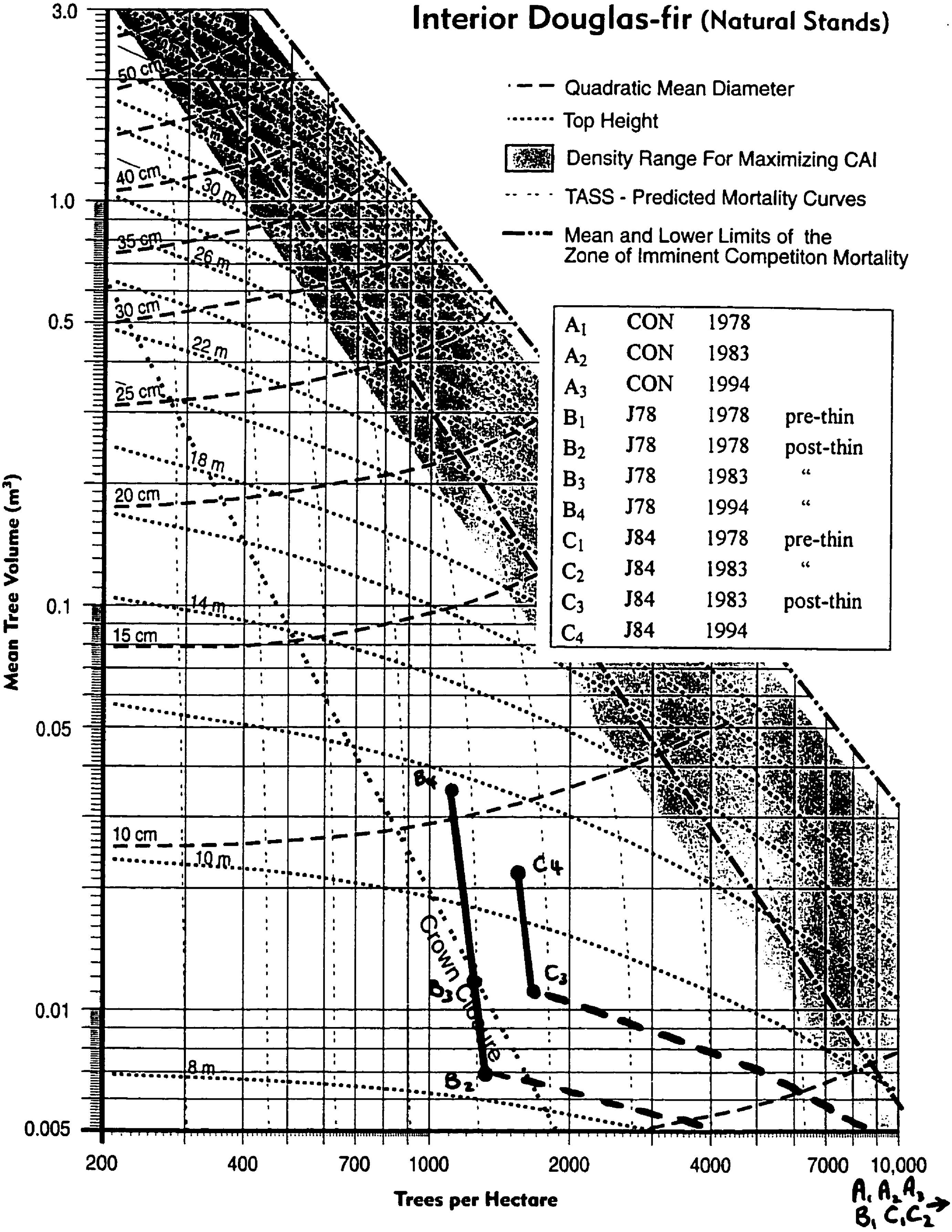
Stand Density Management Diagram
Sitka Spruce (Natural Stands)



Produced by Craig Farnden R.P.F., May 31, 1996.
Produced for Silviculture Practices Branch, B.C. Ministry of Forests
Funding provided by Forest Renewal B.C.

Data Source: TASS generated managed stand yield tables contained in the computer program WINTIPSY version 1.3 (B.C. Ministry of Forests, Forest Productivity and Decision Support Section)

Stand Density Management Diagram
Interior Douglas-fir (Natural Stands)



Produced by: Canadian Forest Service
Pacific Forestry Centre
Feb. 26, 1996

Data Source: TASS generated managed stand yield tables contained in the computer program WINTIPSY version 1.1 (B.C. Ministry of Forests, Forest Productivity and Decision Support Section)

Appendix C

Windthrow Risk Indicator Checklist from Windthrow Handbook for BC Forests;
BCMOF Field Cards

WINDTHROW HAZARD EVALUATION - EXAMPLE FIELD CHECKLIST

District: ____________________ **Licence:** ____________________ **C.P.:** ____________ **Block:** ______

Boundary Section: ____ **Surveyor:** ________ **Date:** ________

Wind Force Indicators

Topographic Exposure:

- ☐ Crest
- ☐ Saddle
- ☐ Upper Slope
- ☐ Shoulder
- ☐ Bowl
- ☐ Valley bottom perpendicular to prevailing winds

Boundary Orientation:

- ☐ Windward
- ☐ Sub-parallel
- ☐ Lee

Stand Attributes:

- ☐ Uniform - high density
- ☐ Uniform - moderate density
- ☐ Uneven - high density
- ☐ Uniform - low density
- ☐ Uneven - low density
- ☐ Uneven - moderate density

- ☐ Taller than average
- ☐ Intermediate
- ☐ Shorter than average

Tree Attributes:

- ☐ Taller than average
- ☐ Average
- ☐ Shorter than average

- ☐ Large dense crowns
- ☐ Moderately dense crowns
- ☐ Small open crowns

Overturning Resistance Indicators

Tree Attributes:

- ☐ Low taper
- ☐ Moderate taper
- ☐ High taper

- ☐ No butt flare
- ☐ Moderate butt flare
- ☐ Large butt flare

- ☐ Root or stem rot
- ☐ No root or stem rot

Rooting Depth:

- ☐ Shallow (<0.4 m)
- ☐ Moderately Deep (0.4-0.8 m)
- ☐ Deep (>0.8m)

Soil Drainage:

- ☐ Poor
- ☐ Imperfect
- ☐ Moderate
- ☐ Good

Other Indicators

Windthrow in stand:

- ☐ Extensive
- ☐ Moderate
- ☐ Minor
- ☐ None

Windthrow along adjacent edges:

- ☐ Extensive
- ☐ Minor
- ☐ Moderate
- ☐ None

Pit and mound microtopography:

- ☐ Extensive
- ☐ Minor
- ☐ Moderate
- ☐ None

Windthrow Hazard Class

- ☐ High
- ☐ Moderate
- ☐ Low

Windthrow Field Card Reference Page A

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Windthrow Field Cards: Reference Pages A & B, Assessment Pages A & B, Calibration Page and Prescription Pages can be used in conjunction with the Forest Service Windthrow Management Training, or on a stand-alone basis.

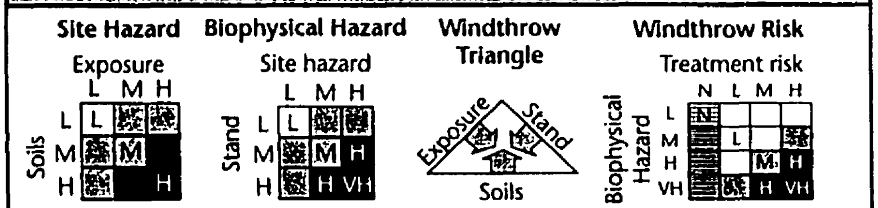
Definitions

- 'Biophysical Hazard' is the combination of the topographic, soils, and stand hazard components. It represents the intrinsic windloading and wind stability of trees on the site prior to treatment.
- 'Treatment Risk' is the way in which a particular treatment increases or decreases the windloading or wind resistance of trees. (For example, boundaries that run at right angles to damaging wind direction at the downwind end of a clearcut are high-risk treatments.)
- 'Windthrow Risk' is the likelihood of damage from endemic winds. It is the combination of Biophysical Hazard and Treatment Risk.
- 'Endemic' winds are peak winds expected to recur every year or so in a given location, as distinct from 'Catastrophic' winds, which recur very infrequently. If a portion of your operating area shows a pattern of repeated edge windthrow or salvage over a period of several years, you have a problem of endemic windthrow.
- 'Impact' is the consequence of wind damage. If wind damage conflicts with your management objectives, the impact is negative. Depending on your objectives, some level of damage may be acceptable.

Assessment Steps

1. Observe windthrow patterns at the landscape and stand level to determine orientation and recurrence of damaging winds.
2. Where there are nearby harvested blocks, calibrate the assessment on a High Treatment Risk boundary, then compare expected damage for the estimated Windthrow Risk Class with the observed damage and adjust Component Biophysical Hazard Classes if necessary.
3 Divide the boundary of a proposed clearcut into segments, or the interior of a proposed partial cut into portions that have similar biophysical and treatment characteristics.
4. i) Assess Treatment Risk for each segment/portion (boundary segments include adjacent stand).
   ii) Assess Biophysical Hazard Components for each segment/portion.
   iii) Integrate Biophysical Hazard Components using Grid.
   iv) Integrate Biophysical Hazard with Treatment Risk to estimate Windthrow Risk
5. Consider the management objectives for each segment/portion, the acceptability of damage, and the level of damage expected for the Windthrow Risk class you have estimated.
6. If the level of expected damage exceeds the acceptable level, recommend treatment modifications.
7. Set up a feedback loop where damage, assessment predictions, and treatments are monitored to enable improved windthrow prediction and management in your area.

Grids



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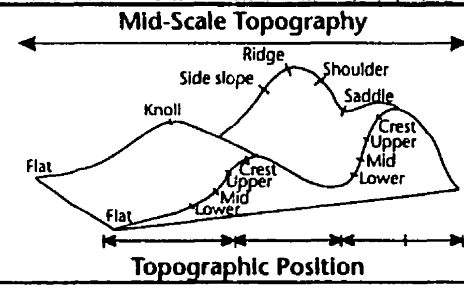
Windthrow Risk Class	Expected Damage Caused by Endemic Winds
None	No stand present to be damaged by winds.
Low	Little or no damage along recent cutblock edges.
Moderate	Partial damage along recent cutblock edges. Between 10 and 70 percent of the trees are uprooted or snapped within the first tree length in from the edge.
High	Heavy damage along recent cutblock edges. More than 70 percent of the trees within the first tree length damaged.
Very high	Very severe damage along recent cutblock edges. More than 70 percent of the trees damaged in both the first and second tree lengths into the edge.

Notes on Field Cards

The field cards can be filled out for each clearcut edge segment or partial cut portion, or simply use these cards as a checklist.

- In the boxes for recording Topography, Soil, and Stand attributes, indicator values are grouped into three columns representing High, Moderate, and Low hazard. This grouping is made to suggest the relative hazard of these indicator values. The relationship between indicators and hazard class will vary from place to place so common sense and local experience (assisted by the Diagnostic Questions) should be used in estimating the component Biophysical Hazards.
- The calibration step is important in refining the Biophysical Hazard classification. The logic underlying the assessment framework is as follows. Where site conditions and management actions in an area proposed for treatment are similar to those of an area treated in the past, a similar pattern of damage is expected.
- A more detailed discussion of the assessment framework can be found in '*A diagnostic framework for windthrow risk estimation.*' S.J.Mitchell in Forestry Chronicle 74 : 100-105 (January/February 1998).
- Card users wanting to improve their knowledge of windthrow assessment and management are referred to the BC Forestry Continuing Studies '*Windthrow Management Workshop*' and '*Windthrow Prescription Workshop.*'

Topographic Terms



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Windthrow Field Card Assessment Page A

Administrative

Location	Opening	Block #	Examiner/Date	Segment/Portion

Topographic Exposure Description

	High Hazard	Moderate Hazard	Low Hazard
Large-scale Topography	☐Coastal plain ☐Plateau ☐Rolling plateau ☐Major coastal inlet ☐Near large water body	☐Large valley ☐Hilly	☐Mountainous ☐Small coastal inlet ☐Far from large water body
Mid-scale Topography	☐Ridge ☐Saddle ☐Knoll ☐Shoulder	☐Flat ☐Side slope	☐Side valley
Topographic Position	☐Crest ☐Upper slope	☐Mid slope ☐Flat	☐Lower slope
Elevation (________m)	☐High	☐Middle	☐Low

Diagnostic question: Are wind speeds normal for the area, or do they vary due to the presence of a terrain obstacle or constriction?

Topographic hazard rating	☐High (higher)	☐Moderate (normal)	☐Low (lower)

Soil Description

	High Hazard	Moderate Hazard	Low Hazard
Parent material	☐Organic ☐Rock ☐Fine alluvial	☐Till ☐Moderate alluvial	☐Coarse alluvial ☐Colluvial
Texture	☐Fine	☐Medium/ ☐V.Coarse	☐Coarse
Coarse fragment %	☐>70	☐30–70	☐<30
Rooting depth (cm) and pattern	☐< 40 ☐Plate roots	☐40–80 ☐Flattened base	☐>80 ☐Rounded base
Impeding layer	☐Water table	☐Surface fractured rock	☐Deep fractured rock
Soil drainage	☐Poor	☐Moderate	☐Good

Diagnostic question: Is root anchorage restricted by an impeding layer, low strength soil, or poor drainage?

Soil hazard rating	☐High (severely restricted)	☐Moderate (somewhat restricted)	☐Low (unrestricted)

Stand Description

	High Hazard	Moderate Hazard	Low Hazard
Structure	☐Uniform	☐Two-layer ☐Uniform with vets	☐Multi-layer
Height (m)	☐>30	☐15–30	☐<15
Live crown Ratio	☐<30	☐30–70	☐>70
Height diameter ratio	☐>90	☐70–90	☐<70
Stand density	☐Dense	☐Moderate	☐Open
Root/stem rots	☐Significant	☐Some	☐Minor
Species			

Diagnostic question: Are the individual trees within the stand adapted to wind loads?

Note: If damaged stems would lean back into canopy and be supported by their neighbours instead of working down through the canopy to the ground, then stand hazard is low for clearcut edges.

Stand hazard rating	☐High (poorly adapted)	☐Moderate (somewhat adapted)	☐Low (well adapted)

Windthrow Field Card Assessment Page B

Existing Windthrow Pattern

	Recent	Older	Direction	Comments
Existing edge				
Within timber				

Treatment Description

Openings: Group selection, patch cut, clearcut, etc.

Treatment risk	High Risk	Moderate Risk	Lower Risk
Orientation relative to damaging winds	☐Downwind at right angle (Wind)	☐Parallel (Wind)	☐Upwind at right angle (Wind)
Width of Opening: Upwind Direction	☐>5 Tree lengths	☐2–5 Tree Lengths	☐<2 Tree Lengths
Influence of opening shape on windspeed	☐Funnels or projects into wind (Wind, Wind)		☐Straight (Wind)

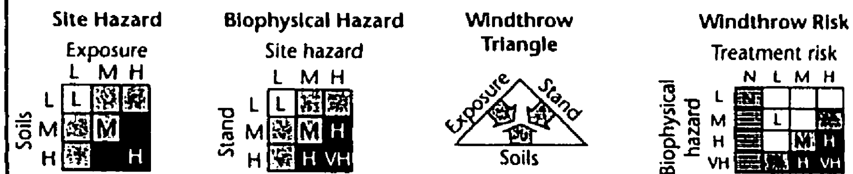
For Uniform Retention: Commercial thin, single tree selection, etc.

Treatment risk	High Risk	Moderate Risk	Lower Risk
Removal level (% basal area)	☐>50	☐30–50	☐<30
Removal criteria	☐Remove veterans, healthy dominants ☐Thin from above	☐Remove across all crown classes	☐Retain veterans, healthy dominants ☐Thin from below
Species	☐Least windfirm		☐Most windfirm

Diagnostic question: Will the proposed harvesting strategy increase wind loading on trees along the stand edge (opening) or retained trees (partial cut)?

Treatment risk rating summary	☐High (large increase)	☐Medium (moderate increase)	☐Low (minimal increase)

Windthrow Risk Evaluation



Estimated Windthrow Potential:

	Very High	High	Moderate	Low	None
Topographic Hazard	•	☐	☐	☐	•
Soil Hazard	•	☐	☐	☐	•
Stand Hazard	•	☐	☐	☐	•
Biophysical Hazard	☐	☐	☐	☐	•
Treatment Risk	•	☐	☐	☐	☐
Windthrow Risk	☐	☐	☐	☐	☐

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Windthrow Field Card Calibration Page

Observed Damage

1. Complete Windthrow Field Card Assessment Pages A and B in a nearby 2–5 yeard old cutblock on a High Treatment Risk Boundary.
2. Record initial evaluation of windthrow from Assessment Card Page B.

Initial Evaluation (from Assessment Card Page B):

	Very High	High	Moderate	Low	None
Topographic Hazard	•	☐	☐	☐	•
Soil Hazard	•	☐	☐	☐	•
Stand Hazard	•	☐	☐	☐	•
Biophysical Hazard	☐	☐	☐	☐	•
Treatment Risk	•	☐	☐	☐	☐
Windthrow Risk	☐	☐	☐	☐	☐

Calibration of Windthrow Risk Classification

3. Record observed damage on calibration boundary.

Trees Damaged (%):			
First Tree Length	☐>70	☐10–70	☐<10
Second Tree Length	☐>70	☐10–70	☐<10
Third Tree Length	☐>70	☐10–70	☐<10
Describe Damage:	☐Extensive	☐Partial	☐Minimal ☐None

Characteristics of Downed Trees:			
Size (compared to mean tree)	☐Same	☐Smaller	☐Larger
Species Composition	☐Same	☐Different: (describe)______________	
Rot (compared to average in stand)	☐Same	☐Less	☐ More

4. Look up the expected level of damage for your initial Windthrow Risk Class on Reference Page B, and compare with actual damage recorded above.

Diagnostic question: Is the level of damage observed along the calibration boundary consistent with that predicted for the estimated class of Windthrow Risk? (See top of Reference Page B)

If	Action
Yes, damage is consistent with expected level. ☐	Use the values for topographic, soils, and stand indicators to identify threshold values for high, moderate, and low hazard classes for each of the Exposure, Soils, and Stand Hazard components.
No, there is less damage. ☐	Consider which of the component hazards (Exposure, Soils, or Stand) might have been rated too highly. Reduce the rating and raise the hazard class thresholds accordingly.
No, there is more damage. ☐	Consider which of the component hazard (Exposure, Soils, or Stand) might have been rated too low. Increase the rating and decrease the hazard class thresholds accordingly.

5. Use the revised thresholds for classifying Soils, Topographic and Stand Hazards for nearby areas.

FS 712-3 HFP 98/05

Windthrow Field Card Prescription Page

Summary of Management Objectives and Acceptable Damage

Management Objectives for Outside Segment/Within Portion

Environmental	Recreation/Visual/ Property	Timber
☐Riparian area ☐Terrain stability area ☐Gully ☐Wildlife tree patch ☐Wildlife corridor ☐______________	☐Recreation area ☐Visual reserve ☐Powerline ☐Structure ☐Road ☐Trail ☐Property ☐______________	☐Value ☐Bark beetle ☐__________
Acceptable amount of damage: ☐None ☐Up to ___% of stems	☐None ☐Up to ___% of stems	☐None ☐Up to ___% of stems

Expected Level of Damage

Windthrow risk:	☐High ☐Very High	☐Moderate	☐Low
Expected damage:	☐Extensive	☐Partial	☐None-Minimal
Is this expected level Acceptable?	☐Yes ☐No	☐Yes ☐No	☐Yes ☐No

Recommended Treatment Modifications

Recommended treatment	Comments:
General:	
☐No treatment	
☐Salvage if damage exceeds acceptable amount	
For clearcuts:	
☐Adjust boundary	
☐Feather	
☐Top	
☐Top-prune	
☐Feather and top/top-prune	
For partial cuts:	
☐Leave more trees	
☐Change leave tree criteria	
☐Other	

Comments:

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