

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

WIND STABILITY OF NATURALLY
REGENERATED AND PLANTED DOUGLAS-
FIR STANDS IN COASTAL WASHINGTON,
OREGON, AND BRITISH COLUMBIA

by

Jeremy Stuart Wilson

A dissertation submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

1998

Approved by

Charles D. Olin

Chairperson of Supervisory Committee

B. Bruce Ball

Thomas M. Hinckley

James H. Agee

Thomas J. Fain

Program Authorized

to Offer Degree

College of Forest Resources

Date

June 1, 1998

UMI Number: 9836278

**Copyright 1998 by
Wilson, Jeremy Stuart**

All rights reserved.

**UMI Microform 9836278
Copyright 1998, by UMI Company. All rights reserved.**

**This microform edition is protected against unauthorized
copying under Title 17, United States Code.**

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

© Copyright 1998
Jeremy Stuart Wilson

Doctoral Dissertation

In presenting this dissertation in partial fulfillment of the requirements for the Doctoral degree at the University of Washington, I agree that the Library shall make its copies freely available for inspection. I further agree that extensive copying of this dissertation is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for copying or reproduction of this dissertation may be referred to University Microfilms, 1490 Eisenhower Place, P.O. Box 975, Ann Arbor, MI 48106, to whom the author has granted "the right to reproduce and sell (a) copies of the manuscript in microform and/or (b) printed copies of the manuscript made from microform."

Signature

James S. W. L.

Date

6/1/98

University of Washington

Abstract

WIND STABILITY OF NATURALLY
REGENERATED AND PLANTED DOUGLAS-
FIR STANDS IN COASTAL WASHINGTON,
OREGON, AND BRITISH COLUMBIA

by Jeremy Stuart Wilson

Chairperson of the Supervisory Committee: Professor Chadwick D. Oliver
College of Forest Resources

Risk of wind damage is an important factor influencing forest management throughout the world. Managed forest landscapes of the coastal Pacific Northwest are undergoing a transition from dominance by naturally regenerated second-growth stands to Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) plantations. This analysis evaluates the impacts of the managed forest transition on risk of wind damage. Experimental plot data are used to compare tree size variability and stand stability between naturally regenerated and planted stands. In addition, a landscape-scale wind risk rating system is developed to evaluate the impact of stand and management transitions at both stand and larger spatial scales.

Naturally regenerated stands tend to develop greater variation of tree sizes compared to plantations. Limited size variation in plantations makes them more susceptible to developing high height to diameter ratios (H/D same units) in the dominant trees. The H/D of a tree is a relative measure of stability under wind and snow loads. H/D can be lowered in plantations through reduced planting densities or early thinning. The higher the initial density the shorter the period during which thinning can effectively lower future H/D values. Thinning requirements in dense plantations make their management inflexible. The flexibility with which a stand can be managed describes the rigidity of intervention requirements and/or potential range of stand development pathways.

Shorter rotations in plantations compared to naturally regenerated stands offset much of the increased risk of wind damage caused by higher H/D values. The transition from naturally regenerated to planted stands typically increases the diversity of stand ages within a landscape. Even-aged landscapes have distinct periods of high and low risk, as all stands in the landscape move through susceptibility stages together. Uneven-aged landscapes never reach the same levels of landscape risk; however, some portion of the landscape is typically at high risk. As the transition from naturally regenerated to planted stands continues wind damage may be more common but have a reduced potential for devastating a landscape.

TABLE OF CONTENTS

List of Figures	v
List of Tables	xi
Chapter 1: Introduction	1
1.1 Wind damage in forests	1
1.2 Organization of this dissertation	2
Chapter 2: A comparison of tree size variation and wind stability in naturally regenerated and planted Douglas-fir stands	4
2.1 Introduction	4
2.2 Background	6
2.2.1 Size distributions of individuals in a stand	7
2.2.2 Yield and mortality	9
2.2.3 Causes of size variation	11
2.2.3.1 Age	11
2.2.3.2 Spacing	12
2.2.3.4 Species mixtures	14
2.2.4 Measures of size variation	16
2.2.5 Tree size variation and allometry	17
2.3 Methods	19
2.4 Results	25
2.4.1 Size variation comparisons between stand types	25
2.4.2 Influences of tree size variation on stability	29
2.4.3 Impacts of spacing on size variation and stability	33
2.5 Discussion	35
2.6 Conclusion	39
Chapter 3: Wind stability and management flexibility of Douglas-fir plantations	40
3.1 Introduction	40

3.2 Background	41
3.2.1 Tree allometry and stand stability	41
3.2.1.1 Mechanistic models of tree stability under wind or snow loads	42
3.2.1.2 Empirical evaluations of wind or snow damage	47
3.2.1.3 Stem buckling models	51
3.2.2 Allometric measures of tree stability used in this analysis	52
3.2.2.1 Number of trees per hectare to evaluate for stand stability	52
3.4 Results	56
3.4.1 Height diameter ratio trends for unthinned plantations	56
3.4.2 Impacts of thinning on plantation H/D_{L250} trends	59
3.4.3 Comparing H/D_{L250} predictions with growth model projections and spacing trial results	60
3.5 Discussion	61
3.6 Conclusion	67
Chapter 4: Developing a rating system for landscape-scale wind risk	69
4.1 Introduction	69
4.2 Background	70
4.2.1 Wind risk modeling	70
4.2.1.1 Climate	71
4.2.1.2 Soils	72
4.2.1.3 Topography	72
4.2.1.4 Stand conditions	76
4.3 Methods	79
4.3.1 Rating stand and landscape wind risk	79
4.3.1.1 Spatial relationships between neighboring polygons	81
4.3.1.2 Exposure risk rating	84
4.3.1.3 Soil risk rating	84
4.3.1.4 Stand characteristic risk rating	84

4.3.2 Evaluating the wind risk rating system.....	86
4.3.2.1 Comparing exposure model ratings	87
4.3.2.2 Adjusting scenarios to reduce wind risk	87
4.4 Results.....	89
4.4.1 Comparison of exposure models.....	89
4.4.2 Wind risk ratings.....	92
4.4.2.1 Base scenario	92
4.4.2.2 Reduced planting density alternative	92
4.4.2.3 Revised harvest schedule alternative	92
4.4.2.3 Combined planting density and harvest schedule alternative	95
4.5 Discussion	97
4.6 Conclusion	99
Chapter 5: Comparing past and future landscape-scale wind risk in managed	
landscapes of the coastal Pacific Northwest	100
5.1 Introduction.....	100
5.2 Background	101
5.2.1 Forest stand attributes that determine susceptibility to wind damage	101
5.2.2 Effects of changing landscape patterns on stand risk factors.....	101
5.3 Methods.....	103
5.3.1 The wind risk rating system.....	103
5.3.2 Evaluating wind risk under changing landscape patterns	105
5.3.3 Comparing wind risk ratings using different H/D_{L250} predictors.....	106
5.4 Results.....	107
5.4.1 Comparison of wind risk between landscape periods.....	107
5.4.2 Comparison of stand risk factors	109
5.4.3 Range in wind risk ratings produced by different estimates of H/D_{L250}	112
5.5 Discussion	112
5.6 Conclusion	115

Chapter 6: The impact of wind stability on flexibility of forest management.....117

- 6.1 Introduction.....117
- 6.2 Wind stability and management flexibility.....119
 - 6.2.1 Stand-scale considerations120
 - 6.2.2 Landscape-scale considerations124
- 6.3 Conclusion126

References.....128

Appendix A: Experimental plot data used in the analysis145

Appendix B: Programs developed in Python for the analysis148

LIST OF FIGURES

Figure 1: Hectares harvested and planted on industrial forest tree farms in the Pacific Northwest (1949-1978) (Data from Wheat and Silen, 1985).....5

Figure 2: Growth patterns of dominant vs. suppressed trees. As trees become suppressed they lose horizontal growing space to fast growing dominants. From a suppressed tree's perspective the stand is becoming more crowded (reduced growing space) through time. $SDI = stand\ density\ index = (TPA * (Dq/25)^{1.604})$ (Reineke 1933)(Figure modified from Oliver and Larson 1996).10

Figure 3: Natural log of breast height age vs. natural log of DBH in a naturally regenerated 56 year-old Douglas-fir stand from Pack Forest in Eatonville, WA (Appendix A).....13

Figure 4: Relationship between Gini coefficient and both the (a) coefficient of variation and (b) Weibull shape parameter. All statistics based on Douglas-fir tree diameters in naturally regenerated and planted stands. (Note: The Weibull shape parameter was only calculated for the EP703 subset of the data).26

Figure 5: Comparison of the Gini coefficient (based on Douglas-fir tree diameters) in naturally regenerated and planted stands. Trend lines follow individual stands through repeated measurements.....27

Figure 6: Density management diagram showing self-thinning trends for naturally regenerated and planted stands. Q_{md} is the quadratic mean diameter. SDI is the stand density index (Reineke 1933).28

Figure 7: Height diameter ratio trends with dominant height for naturally regenerated (n) and planted stands (p). H/D_{L250} is the average height to diameter ratio of the largest 250 tph in a plot.30

Figure 8: Adjusted height diameter ratio (using height – breast height) trends $((H-bh)/D_{L250})$ vs. dominant height for naturally regenerated (n) and planted stands (p).....31

Figure 9: Comparison of height to diameter ratios corrected for breast height $((H-bh)/D_{L250})$ with initial density of Douglas-fir in naturally regenerated and planted stands.....31

Figure 10: Relationship between adjusted dominant height (ht-bh) and average dbh of the largest 250 (L250) Douglas-fir per hectare.....33

Figure 11: Transformed Ripley's K statistic trends for natural and planted stands from EP703 (radius is maximum neighbor distance evaluated in each run). Ripley's K calculated based on Douglas-fir coordinates from the first measurement period.....34

Figure 12: CV of maximum pie degrees free of neighboring Douglas-fir. (radius is maximum neighbor distance evaluated in each run). CV of maximum pie degrees based on Douglas-fir coordinates from the first measurement period.35

Figure 13: Comparison of dominant stand height (m) vs. (a) coefficient of variation, (b) Dominant H/D, and (c) trees per hectare between naturally regenerated and planted eastern white pine stands (Data from Deen 1933).....38

Figure 14: Five-year height increment (Douglas-fir site index curves) and the theoretical diameter and basal area (BA) increments needed to maintain the H/D ratio shown. This figure shows the dramatic increase in BA increment required to keep the H/D ratio relatively constant in trees between 10 and 30 meters tall.....49

Figure 15: Predicted H/D_{L250} vs dominant height of unthinned plantations $((h-bh)/d=63.72588+1.20446*(ht-bh-19.06629)+.00715*(iddf)$, adj. $r^2=.771$, $p < .0000$) Line labels (numbers on far right) correspond to initial

Douglas-fir density. Broken lines correspond to H/D trends for individual plots.....	58
Figure 16: Relationship between adjusted dominant height (ht-bh) and average dbh of the largest 250 Douglas-firs per hectare.	58
Figure 17: Predicted H/D_{L250} vs dominant height of thinned (20% ba at an average of 15 meters in height) and unthinned plantations ($h/d=61.01636+1.15625*(ht-bh-18.99)+.00750*(iddf)-.10961*(thinc)$, adj. $r^2=.74$, $p < .0000$) Line labels correspond to initial Douglas-fir density for thinned (below) and unthinned (above) plantations.....	60
Figure 18: Comparison of predicted H/D_{L250} values (gray lines) to results from (a) FVS-PN variant, (b) ORGANON-SWO variant and (c) ORGANON-SMC variant (black lines). Legend specifies initial Douglas-fir density (trees/hectare).....	62
Figure 19: Comparison of predicted H/D_{L250} for plantations and results from the Wind River (WR) and Haney, B.C.(H) spacing trials. Initial Douglas-fir densities (tph) in the spacing trials are numbers to the right in the legend. Grayed trend lines display predicted H/D_{L250} at initial densities specified by line labels. (Data for Wind River (Reukema 1970, 1979), Haney, B.C. (Reukema and Smith 1987).	63
Figure 20: H/D trends for the 2 largest (dbh) individual trees per plot when they had heights measured over several periods.....	65
Figure 21: Early H/D trends from Haney, B.C. nelder plot data. Numbers to the right of legend lines represent initial Douglas-fir density (tph) in particular arcs. (Data from Smith 1983, Reukema and Smith 1987).....	65
Figure 22. Matrices describing how risk rankings for soil, exposure, and stand characteristics are combined into an overall wind risk value. Values for Site Risk from the first matrix (A.) are used for Site Risk in the second matrix (B.) The values 1, 2, and 3 reflect low, moderate, and severe risk	

ratings for risk associated with site and stand conditions (modified from Mitchell 1995b).....	80
Figure 23: Flow of information to the wind risk rating system. Grayed area in the diagram represents limits of LMS. Modified from McCarter et al. (in press).....	81
Figure 24: Count of stands in each exposure rating under the different exposure models. Ratings are for winds from the southwest.	90
Figure 25: View of the case-study landscape from the southwest comparing exposure model ratings. Severe ratings = black, moderate ratings = dark gray, and low ratings = light gray. Ratings are for winds out of the southwest.	91
Figure 26: Landscape proportions assigned to each wind hazard class in (a) the base scenario and (b) the first alternative scenario with reduced Douglas-fir densities in planted stands. Plantation densities are 500-1,000 tph as opposed to 1,000-2,000 tph in the base scenario. Winds are from the southwest.....	93
Figure 27: Landscape proportions assigned to each wind hazard class in (a) an alternative harvesting schedule designed to reduce topographic exposure and (b) an alternative combining reduced topographic exposure and reduced Douglas-fir densities in planted stands. Plantation densities are 500-1,000 tph as opposed to 1,000-2,000 tph in the base scenario. Winds are from the southwest.	94
Figure 28: Number of times a windward edge was exposed in stands with moderate or severe exposure ratings in the base scenario (Figure 26a) and the alternative harvest schedule (Figure 27a).	95
Figure 29: Landscape proportions assigned to each wind hazard class in (a) an alternative harvest schedule designed to reduce topographic exposure and (b) an alternative combining reduced topographic exposure with reduced Douglas-fir densities in planted stands. Plantation densities are 500-1,000	

tph as opposed to 1,000-2,000 tph in the base scenario. Winds are out of the north.	96
Figure 30: Landscape visualization of the case study landscape depicting the transition period in the (a) long- and (b) short-transition scenarios. Scenarios are pictured halfway through the transition period (long-transition scenario 1990, short-transition scenario 1970). The landscape is viewed from the southwest using UVIEW (Ager and McGaughey 1997). ...	107
Figure 31: Proportions of the landscape assigned to different wind risk rankings for the (a) long- and (b) short-transition scenarios.	108
Figure 32: Average portion of the landscape assigned to each wind risk class during the three landscape periods in the (a) long- and (b) short-transition scenarios.....	110
Figure 33: Average proportions of the landscape assigned to each stand hazard class for the different landscape periods under (a) long- and (b) short-transition scenarios.....	111
Figure 34: Landscape wind risk rankings for the long-transition scenario when H/D_{L250} values are derived from growth models (a) FVS-PN and (b) ORGANON-SWO.	113
Figure 35: Landscape wind risk rankings for the long- transition scenario. In this scenario plantation densities range from 2,000 – 3,500 tph rather than 1,000 – 2,000 tph used in Figure 31a.....	115
Figure 36: Schematic diagram depicting tradeoffs between management flexibility and efficient use of growing space by a single tree species. Forest owners and managers must find an appropriate balance between how intensively they are willing to manage and how efficiently they wish growing space to be utilized by the planted species.....	118
Figure 37: Conceptual comparison of wind risk rankings: (a) when a single silvicultural approach is used across a landscape; (b) when prescriptions	

are altered to account for inherent site risk; and (c) low site and stand risk are combined to provide very low risk stands that are more suitable for long rotations. Overall wind risk is composed of equal parts site and stand risk.....125

LIST OF TABLES

Table 1: Organization of the dissertation.....	3
Table 2: Experimental studies providing data for this analysis.	20
Table 3: Regression coefficients, standard errors, and p-values of a model predicting values for the Gini coefficient. (adj. r-squared = .414, $p < .00000$, $n = 111$, standard error of estimate = .03688)	29
Table 4: Regression coefficients, standard errors, and p-values of a model predicting values for adjusted H/D of the largest 250 Douglas-fir/ha. (adj. r-squared = .702, $n = 111$, $p < .00000$, standard error of estimate = 5.1977).....	32
Table 5: Plantation plots from studies used in this analysis.	54
Table 6: Regression coefficients, standard errors, and p-values of a model predicting values for $(H - bh) / D_{L250}$ values for unthinned plantations. (adj. r-squared = .771, $n = 62$, $p < .00000$, standard error of estimate = 5.2370).....	57
Table 7: Regression coefficients, standard errors, and p-values of a model predicting values for adjusted H / D_{L250} values for thinned and unthinned plantations. (adj. r-squared = .738, $n = 90$, $p < .00000$, standard error of estimate = 5.3761).....	59
Table 8: Column formats for the neighborhood table. The relationship between a focus stand and all adjacent stands is reported. Degree represents the direction of a line perpendicular to the average border direction.	82
Table 9: Rating criteria used in this analysis for stand risk ratings.	86
Table 10: Comparison of exposure model ratings for stands in the Olympic Peninsula landscape. Ratings are for winds from the southwest.	90

Table 11: Impacts of the three managed landscape periods on the seven factors impacting wind damage susceptibility. Impacts are + = increases susceptibility, - = decreases susceptibility, 0 = neutral, or ? = unknown.102

Table 12: Years in each landscape period for the long- and short-transition scenarios...106

ACKNOWLEDGEMENTS

I thank Chad Oliver for his guidance and support throughout my studies at the University of Washington. I am also grateful to Jim Agee, Bruce Bare, Tom Hinckley, and Tom Quinn for their contributions as members of my Graduate Committee.

Past and present members of the Silviculture Lab have provided a stimulating and supportive work environment. In particular, I thank Jim McCarter, Scot Zens, Patrick Baker, and John Kershaw for their critical insights.

This project was supported by the Landscape Management Project, a cooperative research effort between the Silviculture Lab and the U.S. Forest Service.

Several agencies graciously provided data for the analysis.

British Columbia Ministry of Forests, Research Branch

Stand Management Cooperative

U.S. Forest Service, Pacific Northwest Research Station

Washington State Department of Natural Resources

Pack Forest and Champion International Corporation provided access to stands for exploratory data collection during the early development of this project.

I cannot imagine reaching this goal without the support and patience of Katie and Rowan.

CHAPTER 1: INTRODUCTION

Young managed forests in the coastal Pacific Northwest are dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) plantations. In most plantations, even-aged seedlings of a single species are planted in a regular pattern. This practice may limit variation of tree sizes, making plantations susceptible to stagnation and/or instability. The number of practical management options is limited in stagnant or unstable forest stands, making their management inflexible. To avoid stagnation, plantations are often thinned one or more times during a rotation. In the short term, thinning increases the risk of wind damage by allowing more wind to penetrate the canopy, creating more turbulent airflow and reducing the sway dampening that neighboring trees provide. As plantations mature and begin to dominate managed landscapes, their attributes may make wind damage increasingly common and more severe in this region.

1.1 WIND DAMAGE IN FORESTS

Forests in tropical and temperate regions are impacted by windstorms ranging from gales to cyclonic storms to tornadoes. Wind damage to forests can occur catastrophically as concentrated area-wide blowdowns or endemically as small windthrow pockets which grow slowly through time as new edges are exposed (Savill 1983, Miller et al. 1987, Greene et al. 1992). Although spectacular, catastrophic events may cause less damage through a typical rotation than endemic damage (Rollinson 1987).

In a recent review of the literature on wind damage to forests, Everham and Brokaw (1996) found references reporting on forest damage in all regions of North America, Great Britain, the Caribbean, Central America, Australia, New Zealand, the Pacific Islands, Sri Lanka and countries in Africa. There is also an extensive literature detailing

wind damage to forests throughout Europe (see Savill 1983, Bouchon 1987, and Ruel 1995 for reviews).

Severe windstorms that damage forests have been common in the Pacific Northwest. Hurricane-force windstorms hit the coast of Washington and Oregon every 20 years on average. Major windstorms are reported to have hit the region in 1788, 1880, 1895, 1921, 1923, 1929, 1955, 1961, 1962, 1979, 1981, and 1993 (Wiley 1965, Henderson et al. 1989). Of these, the 1921 and 1962 storms were the most serious. Damage caused by the 1921 storm was concentrated on the Washington coast. The storm is estimated to have blown down 23 to 28 million cubic meters of timber. The 1962 storm blew down an estimated 38 million cubic meters of timber in western Oregon and Washington (Wiley 1965, Lynott and Cramer 1966, Henderson et al. 1989). Gusts in the 1962 storm exceeded 170 miles per hour at some locations (Wiley 1965).

1.2 ORGANIZATION OF THIS DISSERTATION

This thesis is organized in five stand-alone chapters. The emphasis of the chapters builds from consideration of stand-scale stability measures to stand-, landscape-, and regional-scale wind risk evaluations. **Chapter 2** compares tree size variability and wind stability between naturally regenerated and planted Douglas-fir stands. Three large-scale experimental plot studies from the Pacific Northwest provide data for the analyses. **Chapter 3** begins with a review of tree and stand stability measures. A relationship describing the development of wind stability in thinned and unthinned plantations is developed using the experimental plot data introduced in Chapter 1. The relationship is compared to results from growth models and Douglas-fir spacing trials. **Chapter 4** details the development of a landscape-scale wind risk rating system. The system is developed from the wind hazard literature. An example landscape management scenario is developed and altered to evaluate the potential for reducing wind risk by adjusting harvest timing and modifying planting densities. In **Chapter 5**, the wind risk rating

system developed in Chapter 3 is employed to evaluate trends in wind risk for managed landscapes of the Pacific Northwest. As part of this analysis, the wind risks associated with even- and uneven-aged landscapes are compared. Finally, in **Chapter 6**, the implications of stand- and landscape-scale instability for management flexibility are discussed. Management flexibility is a stand attribute reflecting the rigidity of intervention requirements and/or potential range of development pathways. The organization of the thesis is summarized in Table 1.

Table 1: Organization of the dissertation.

Chapter	Topic	Scales	Key concepts
2	Comparison of tree size variation and wind stability between naturally regenerated and planted stands	Tree and stand	Age variation Spacing Species diversity Size variation Wind stability Stand development Stand management
3	Development and evaluation of a wind stability relationship for planted stands	Tree and stand	Wind stability Tree allometry Height to Diameter ratio Thinning Spacing trials Growth models Stand management
4	Development and evaluation of a landscape-scale wind risk rating system	Stand and landscape	Climate Soils Topographic exposure Stand characteristics Wind risk rating Risk reduction
5	Comparison of past, current, and future wind risk in managed landscapes	Stand, landscape, and region	Managed landscapes Landscape age diversity Rotation lengths Wind risk patterns
6	Evaluating the impact of wind stability on the flexibility with which stands can be managed	Stand, landscape, and region	Operational requirements Developmental constraints Tradeoffs

CHAPTER 2: A COMPARISON OF TREE SIZE VARIATION AND WIND STABILITY IN NATURALLY REGENERATED AND PLANTED DOUGLAS-FIR STANDS

2.1 INTRODUCTION

During the first two-thirds of this century, harvested forestlands in western Oregon, Washington and British Columbia generally were allowed to seed in naturally and develop without intervention. These naturally regenerated stands are often referred to as “second growth.” Second-growth stands have matured and, in turn, become the major source of timber in the coastal Pacific Northwest.

Inconsistency of seedling establishment and repetitive slash fires in large clearcut areas raised concerns over the adequacy of natural regeneration. In response, aerial seeding of cutover land became commonplace in the 1960's (Smith et al., 1997). More recently, planting has become the dominant means of regenerating forests after harvesting. Forest stands regenerated through planting of seedlings are called “plantations.” Plantation establishment became the dominant forest regeneration technique in the 1970's. Figure 1 shows the increasing proportion of harvested stands being planted in the late 60's and 70's on industrial forests in western Washington and Oregon. Planting became standard practice because of both economic considerations and regulations (Smith et al., 1997). Planting expedites the development of full stocking, increasing volume yields and shortening rotation lengths.

Early development is different in plantations than in the naturally regenerated stands they replace. Planted seedlings are all the same age or vary by 1 to 2 years. Natural seedlings re-invade a harvested site over a period of two decades or more, allowing wide variations in the ages of individual trees (Oliver and Larson, 1996). Attempts are made to space the

seedlings evenly when planting a stand. This pattern is not a perfect grid except in mechanically planted areas; however, it does reduce both aggregations of trees and

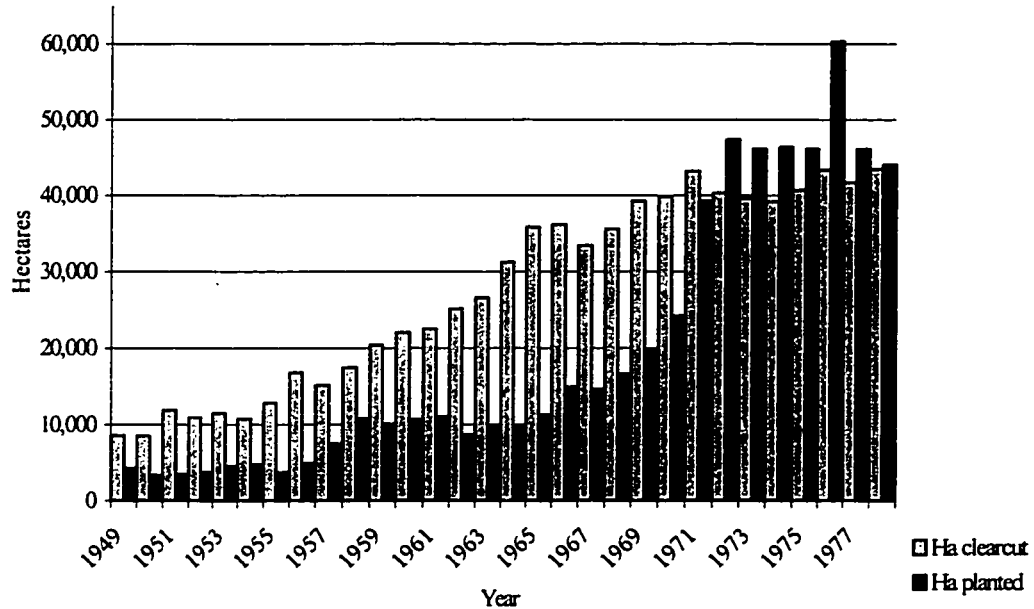


Figure 1: Hectares harvested and planted on industrial forest tree farms in the Pacific Northwest (1949-1978) (Data from Wheat and Silen, 1985)

openings commonly found in naturally regenerated stands. Usually, only one species is planted in a stand, although natural establishment of additional trees often prevents plantations from being true tree monocultures. The competitive advantage given to planted trees may reduce the importance of inter-specific competition in plantations compared to naturally regenerated stands. Two other attributes of plantations differ from stands that have regenerated naturally: intensive site preparation and genetics. In some areas, planting is preceded by extensive site preparation. Site preparation such as plowing or root raking tends to reduce micro-site variation by leveling local topography. This type of site preparation is uncommon in the coastal Pacific Northwest; therefore, it will not be considered in this analysis. Genetic variation among seedlings can result in differential growth rates and size variation. It is unclear whether genetic improvement programs

reduce or augment genetic variation in seedlings being planted. While the impacts of genetic variation are of obvious importance, they are beyond the scope of this analysis.

Age, spacing and species composition differences between plantations and naturally regenerated stands should all tend to reduce variability or differentiation of tree sizes within plantations. Stands with little differentiation or tree size variability may require intensive and time-sensitive management to avoid stagnation and to remain wind, snow, and ice firm. Well-differentiated second growth stands have not required management at specific times to avoid stagnation and instability (O'Hara 1995). Thinnings in well-differentiating stands can be delayed for better markets or increased labor availability. Alternatively, thinning operations can be avoided in an inaccessible stand.

The flexibility with which well-differentiating stands can be managed may make them a logical choice for many types of landowners and managers. Management flexibility is especially important in forestry where rotations are long and goals, regulations, markets, and techniques are continually changing.

This chapter begins with a discussion of plant size variability and its implications for stand development, including stand stability. Experimental plot data is used to compare tree size variation and measures of stand stability between planted and naturally regenerated stands. The chapter ends with a discussion evaluating the implications of differences between regeneration methods for plantation management.

2.2 BACKGROUND

Most research into plant competition and stand development occurs at one of two scales. The first scale characterizes and models the development of plant size distributions. This scale evaluates attributes of individuals within a stand or population (e.g., modeling the development of a stand diameter distribution through time). The second scale models changes in a population or a stand's mean plant size and density (density in this project

refers to plants per unit area). These models are used to understand and predict the yield and mortality of a population through time. This section provides a brief review of the research into plant competition and development. This review provides a framework for understanding how differences between naturally regenerated and planted stands might influence tree size variability and stand stability.

The bulk of research evaluating plant size distributions has dealt with annual plants in greenhouse and open field experiments (Mitchell-Olds 1987, Firbank and Watkinson 1987). The term population refers to a contiguous group of plants. A population of trees is a stand. In this discussion, the terms population and stand will be used interchangeably.

2.2.1 SIZE DISTRIBUTIONS OF INDIVIDUALS IN A STAND

Studies that evaluate the development of size distributions in stands of plants are common (Harper 1977, Benjamin and Hardwick 1986, Huston and DeAngelis 1987, Hara and Wyszomirski 1994). Of particular interest to researchers are mechanisms that produce observed size distributions in plant populations (Huston and DeAngelis 1987). Interest in size distributions has been sparked by two factors. One, size is positively correlated with survival and reproduction, making the development of size hierarchies important to the process of plant evolution. Two, uniformity of plant size within an agricultural crop is thought to use seed and land resources most efficiently (Hara 1988, Weiner 1984, Weiner 1988).

Populations of plants often develop positively skewed size and weight distributions soon after seedlings emerge (Mohler et al. 1978). Asymmetric size distributions of seedlings are not expected since seed weight tends to be normally distributed (Silvertown and Doust 1993). Many studies find plant size hierarchies, populations with a few large individuals and many small ones, become more positively skewed as stands age (Mohler et al. 1978, Hutchings and Budd 1981, West and Borough 1983, Cannell et al. 1984, Benjamin and Hardwick 1986, Kikuzawa 1988). Other research finds increases in size

inequality but not necessarily skewness of the distributions (Weiner and Thomas 1986, Knox et al. 1989). Weiner and Solbrig (1984) showed that inequality is a more appropriate measure of size hierarchies than skewness (see section 2.2.4 Measures of size variation for descriptions of inequality and skewness).

Individuals compete with their neighbors for growing space. If one of the individuals is taller, its stem and leaves shade those of its shorter neighbors. In this case the competition for light may be one-sided. In one-sided or **asymmetric competition**, growth of larger individuals is not impacted by close proximity of smaller ones. In contrast, growth of smaller individuals is curtailed by close proximity to larger ones. When the effects of neighbors are proportional to sizes, competition is termed **relative size symmetric** (Silvertown and Doust 1993). In two-sided or **symmetric** competition, a seedling retains control of any space it can grow into prior to its neighbors. Once all horizontal space is occupied, further increases in size are based on vertical expansion. Size inequality between individual plants increases until all horizontal space is filled and then remains static as the plants grow vertically (Ross and Harper 1972, Firbank and Watkinson, 1987).

Size inequality or skewness of individual sizes increases with higher densities and over time in most populations of annual plants (Harper 1977, Weiner and Thomas 1982, Benjamin and Hardwick 1986, Hara 1988, Stoll et al. 1994) and trees (Weiner and Thomas 1986, Knox et al. 1989). This finding is used to support the claim that the majority of plant competition is one-sided. In one-sided competition, effects of small differences in relative growth rates are compounded over time (Mohler et al. 1978, Ford and Diggle 1981, Cannell et al. 1984, Weiner and Thomas 1986, Schwinning and Weiner 1998). Plants interact with neighbors sooner in denser stands, increasing the time during which one-sided competition is occurring. As one-sided competition progresses, some individuals become dominant, and others suppressed in a process called “differentiation.” Differentiation in combination with continued growth of plants

typically leads to mortality of suppressed individuals (Benjamin and Hardwick 1986, Franco 1986, West and Borough 1983, Gibson and Good 1986, Silvertown and Doust 1993).

2.2.2 YIELD AND MORTALITY

Mortality caused by competition is often referred to as “self-thinning” (Ford 1975, Mohler et al. 1978). Self-thinning mortality connects the two levels of research in plant competition and stand development (Long and Smith 1983, Knox et al. 1989). The development of size hierarchies in distributions of individuals leads to self-thinning mortality. Self-thinning mortality is being modeled in research that evaluates mean growth (yield) and mortality in a stand through time.

Self-thinning mortality is density dependent. Mortality generally occurs earlier in plant populations that have greater number of individuals per unit area (Silvertown and Doust 1993, Oliver and Larson 1996). Self-thinning continues as the mean size of plants in a population increases. Mortality restricts the number of live plants in an area at a given mean size (Reineke 1933, Yoda et al. 1963, Curtis 1970). Trends in growth and mortality through time in an even-aged single-species population approach a constant slope. The relationship between mean plant weight and density is described in Equation 1.

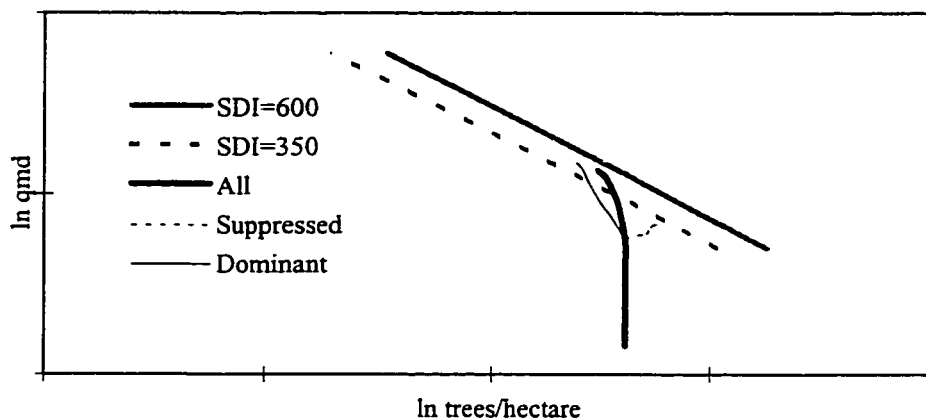
$$w = cN^{-k} \quad \text{or} \quad \log w = \log c - k \log N \quad (1)$$

where: c and k are constants N is the surviving density (Silvertown and Doust 1993).

In the log transformed form of the equation, $-k$ is the slope of the self-thinning trajectory (Hutchings and Budd 1981). Yoda et al. (1963) proposed that the value of $-k$ was $3/2$ for a number of species. Subsequent studies have also found tree and plant populations with slope values approximating $-3/2$ (White and Harper 1970, Drew and Flewelling 1977, 1979, Kikuzawa 1988, see Lonsdale 1990 for a thorough review). The self-thinning line

has been given many labels including the “-3/2 power law” (Oliver and Larson 1996, Silvertown and Doust 1993). The intercept in the equation (c) varies with different species and growing conditions (White 1985).

Working with Monterey pine (*Pinus radiata* D. Don) plantations in Australia, West and Borough (1983) found that a slope of -3/2 approximated suppression more closely than actual mortality. Oliver and Larson (1996) suggest that suppressed trees lose growing space through time to dominant trees (Figure 2). In effect, suppression reduces tree density for dominant trees and increases density for suppressed trees. Stand dominants can be following a self-thinning trajectory before any mortality has occurred.



*Figure 2: Growth patterns of dominant vs. suppressed trees. As trees become suppressed they lose horizontal growing space to fast growing dominants. From a suppressed tree's perspective the stand is becoming more crowded (reduced growing space) through time. SDI = stand density index = $(TPA * (Dq/25))^{1.604}$ (Reineke 1933) (Figure modified from Oliver and Larson 1996).*

In recent decades, there has been much criticism of the universality of the -3/2 power law and its underlying assumptions about plant architecture and form (Zeide 1987, Burrows 1991, Reynolds 1997). The observed -3/2 slope in self-thinning populations is probably

better thought of as a widely observed phenomena rather than a strict rule (Lonsdale 1990).

2.2.3 CAUSES OF SIZE VARIATION

Diversity of age (germination date), spacing, and species mixes are among the many factors that have been found to influence plant size variation (Harper 1977, Fowler 1984, see Benjamin and Hardwick 1986 for review of factors, Firbank and Watkinson 1987, Hara 1988, Silvertown and Doust 1993). The rest of this discussion will focus on the impact of these three factors since the type of regeneration, planted or natural, has strong implications for each of them.

2.2.3.1 Age

Older individuals in a population have time to gain a size advantage over their neighbors (Harper 1977, Watkinson 1985, Firbank and Watkinson 1987, Weiner 1988, Silvertown and Doust 1993). Large differences in emergence time allow for greater variability of individual plant yield at all densities (Watkinson 1985). Small differences in age under conditions of one-sided competition can be compounded with time (Weiner 1988, Palik and Pregitzer 1991). Alternatively, older individuals may simply preempt more growing space during their longer residence time under two-sided competition (Palik and Pregitzer 1991). Fowler (1984) found germination date had a significant impact upon plant weight and number of flowers in a greenhouse experiment with *Linum grandiflorum* Desf. var. *rubrum*. Firbank and Watkinson (1987) found that emergence time obscures the effects of local crowding in field experiments with *Agrostemma githago* L. and *Triticum aestivum* L. They found that comparing mean yield with overall plant densities averaged variation caused by emergence time and exposed the impact of density (seedlings per unit area) on yield (Firbank and Watkinson 1987).

If a stand has a range of tree ages, as is the case in many naturally regenerated second growth stands, stability is promoted in two ways. First, there are trees that establish early

and grow with little competition from neighbors, allowing them to develop large diameters. Figure 3 shows a relationship between breast-height age and diameter at breast height (dbh) in a naturally regenerated stand of Douglas-fir. In a linear regression, the natural log of breast height age alone explains 54% of the variation in the natural log of dbh. Second, trees that establish later develop in partial shade from above. Overhead shading slows both diameter and height growth of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) (Hoyer 1991, Wampler 1993). When trees establish at the same time, overhead shading is more limited. Side shade reduces the tree's diameter growth without a concomitant reduction in height growth (Omule 1985, Oliver and Larson 1996, Wagner and Radosevich 1991).

Extremes in age variation result when portions of an overstory survive a disturbance event or are retained during harvests. If remnants from the previous stand are unevenly distributed, their competitive influence on young trees may vary throughout the stand (Hoyer 1991). Height and diameter growth rates of Douglas-fir below an overstory are reduced compared to open grown trees (Wampler 1993). Young trees in portions of the stand less affected by a remnant overstory will grow larger than those in areas more strongly impacted by the older trees.

2.2.3.2 Spacing

There are two characteristics of a population described by spacing. The first is the average density of individual plants per unit area. The second is the variability in spacing around individual plants (Hara 1988). Non-spatial growth models predict an individual's growth based on relative sizes and numbers of competing plants in the population. Any spatial variation that exists between individuals is lost through averaging. Spatial growth models predict an individual's growth based on the relative sizes and distances of neighbors. Spatial models that predict growth based on space available to each individual (e.g. Voronoi polygons) assume two-sided or symmetrical competition (Hara 1988). Spatial models that account for competitive status of individuals by allowing larger

individuals to reduce the growth of smaller ones assume one-sided or asymmetric competition (Ford and Diggle 1981).

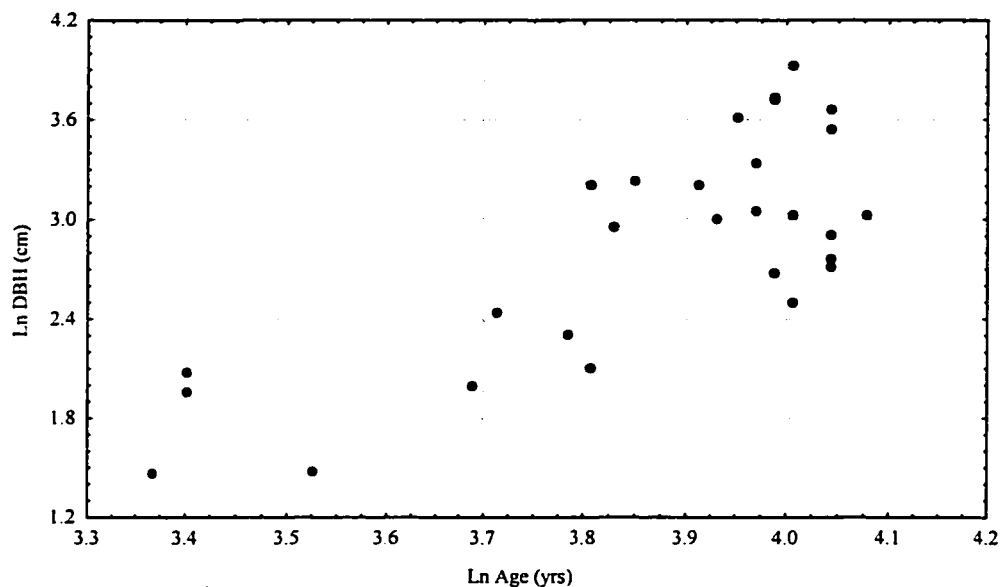


Figure 3: Natural log of breast height age vs. natural log of DBH in a naturally regenerated 56 year-old Douglas-fir stand from Pack Forest in Eatonville, WA (Appendix A).

There is a large range in the amount of variation in plant sizes explained by spatial growth models (Bella 1971, Daniels 1976, Waller 1981, Fowler, 1984, Martin and Ek 1984, Weiner 1984, Franco and Harper 1988, Miller and Weiner 1989, Vanclay 1994). Adding spatially explicit variables may only provide minimal increases in goodness of fit over non-spatial models (Hara 1988, Wimberly and Bare 1996). The small improvement in goodness of fit with spatial models has been attributed to the overwhelming importance of age, microsite variation, asymmetric competition, and genetic variation (Firbank and Watkinson 1987). Hara and Wyszomirski (1994) reviewed the literature and found the r^2 for spatially explicit models ranges from 0 to 90%. They attributed the wide range to levels of competitive symmetry in the populations being studied. In simulations and experiments involving plant populations, individual spacing explains greater proportions of size variation when competition is more symmetrical or when the density

of individuals is low (Firbank and Watkinson 1987, Hara and Wyszomirski 1994). Spatially explicit models have explained the most size variation among dune annuals where root competition is thought to be 2-sided. (Mack and Harper 1977, Firbank and Watkinson 1987, Wilson 1988). Miller and Weiner (1989) suggested that spatial variation may produce increasing size inequalities in plant populations even when competition is symmetric.

When a plantation is established in the coastal Pacific Northwest, attempts are made to plant seedlings on a grid. The grid is rarely perfect; however, the seedlings are relatively evenly distributed throughout the planted area. In most cases, there are no large openings without seedlings or areas where seedling density is much higher than others. Planted seedling mortality can still occur because of soil and other conditions, allowing for some differences in tree spacing. Trees are planted in a regular pattern to use land area and seedlings most efficiently. In naturally regenerated stands, seed dispersal and the availability of suitable germination sites determine seedling density and spacing patterns.

2.2.3.4 Species mixtures

Increasing species diversity in plant communities leads to greater variation of focus plant sizes (Hara and Wyszomirski 1994). Knowe (1992) found that size variation of loblolly pine (*Pinus taeda* L.) saplings rose as the surrounding basal area of competing hardwoods increased. Higher levels of inter-specific competition also increased size inequality among young Douglas-firs in the Coast Range of Oregon and Washington (Harrington et al. 1991, Knowe et al. 1992). Conversely, inter-specific competition reduced Douglas-fir size variation in the Siskiyou Mountains of southwestern Oregon. Knowe et al. (1992) proposed that species competing with Douglas-firs in drier regions were masking variation caused by microsite differences. Cannell et al. (1984) found that variation in relative growth rates of Sitka spruce (*Picea sitchensis* [Bong.] Carr.) and lodgepole pine (*Pinus contorta* Dougl. ex Loud.) saplings attributed to microsite decreased with time. At harvest, microsite accounted for only about 10% of relative growth rate variation. Higher

levels of grass competition increased skewness and size variation of stem volumes in widely spaced ponderosa pines (*Pinus ponderosa* Dougl. ex Laws [Petersen 1988]).

In general, Douglas-fir is the dominant species used in coastal Pacific Northwest plantations. Other species may establish naturally; however, if these species reduce the growth of Douglas-fir they are often removed through weeding or hardwood control. In naturally regenerated stands, species that overtopped Douglas-firs were generally not eliminated through management.

Some species can grow faster than Douglas-fir regeneration. Vine maple (*Acer circinatum* Pursh) causes suppression and some mortality in Douglas-fir but does not get very tall. Douglas-firs outside of a vine maple clump have a large gap to extend their branches when they eventually overtop the vine maple. Trees surrounding a vine maple clump have a competitive advantage over trees surrounded by other Douglas-firs. Clumps of red alder (*Alnus rubra* Bong.) and bigleaf maple (*Acer macrophyllum* Pursh) regeneration can also outcompete Douglas-fir (Knowe et al. 1995). They grow taller and create a larger opening than vine maple before being overtopped by surrounding Douglas-fir (Stubblefield 1979). This pattern is similar to what Oliver et al. (1990) found between cherrybark oak (*Quercus falcata* Michx. var. *pagodifolia* Ell.) and sycamore (*Platanus occidentalis* L.) and Clatterbuck and Hodges (1988) found between cherrybark oak and sweet gum (*Liquidambar styraciflua* L.).

Other species such as western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) grow more slowly in height than Douglas-fir; however, thick western hemlock regeneration, in clumps or throughout the stand, can limit the establishment of Douglas-fir (Stubblefield 1979). Douglas-fir grown at lower densities or around western hemlock clumps will grow with little competition and develop large diameters (Wierman and Oliver 1979).

2.2.4 MEASURES OF SIZE VARIATION

There are a variety of measures that can be used to describe size hierarchies within stands of plants. The coefficient of variation (CV) is a dimensionless ratio that allows comparison of variability in populations where standard deviation changes with the mean (Benjamin and Hardwick 1986). The Gini coefficient is a dimensionless statistic summarizing proportional areas in the Lorenz curve. The Lorenz curve plots cumulative percentage of size (e.g. Dbh, weight, or height) against cumulative percentage of a population. A forty-five degree line represents perfect equality. Inequality leads to a curve below the perfect equality line. The Gini coefficient is the proportion of area below the perfect equality line that is above the population's curve (Weiner and Solbrig 1984, Benjamin and Hardwick 1986).

Skewness measures departure from the symmetry around the mean of a normal distribution. The left and right tails of the distribution are asymmetrical in skewed populations. When distributions are skewed, the mean and median are not the same (Sokal and Rohlf 1981). Kurtosis measures departures in peakedness from normal distributions. Leptokurtic distributions have strong peaks with more observations around the mean and in the tails than normal distributions. Platykurtic distributions have reduced peaks with more intermediate observations than normal distributions. Bimodal distributions are highly platykurtic (Sokal and Rohlf 1981).

Parameters of a fitted distribution describe its shape and skewness. The Weibull distribution has been commonly used in describing tree distributions (Clutter et al. 1983). The shape parameter of a Weibull distribution describes its skewness (Shifley and Lentz 1985).

Studies comparing the usefulness of these various measures with plant populations have identified the coefficient of variation and the Gini coefficient as the most useful for comparing inequality between distributions (Weiner and Solbrig 1984, Benjamin and

Hardwick 1986, Knox et al. 1989). The two measures are highly correlated when used to describe plant populations (Hara and Wyszimorski 1994). Knox et al. (1989) found a close relationship between the Gini coefficient, the coefficient of variation, and the shape parameter of the Weibull distribution from 50 years of data in 16 even-aged loblolly pine stands.

2.2.5 TREE SIZE VARIATION AND ALLOMETRY

Trees in a stand differentiate or develop variation in their sizes when some individuals gain a competitive advantage over their neighbors (Oliver and Larson 1996). A small advantage early in a tree's life compounds with time (West and Borough 1983, Weiner 1988, Nilsson and Albrektson 1994). A tree that is taller or has a larger crown than its neighbors will have more access to sunlight and be able to produce more carbohydrates during the growing season. These carbon stores allow the tree to grow more than its neighbors, increasing its relative advantage during the next growing season. Trees can gain an early competitive advantage because of variations in conditions such as micro-site, genetics, spacing, species composition, and age (Oliver and Larson 1996).

Not all forest stands develop strong variations in tree sizes. Those stands that do not differentiate stagnate over time (Ford 1982, Oliver et al. 1986b). In stagnant stands, individual trees neither lose nor gain competitive advantage relative to their neighbors. As the trees grow taller, they gain respiring tissue without an accompanying increase in crown size. The live crown recedes as higher branches of neighboring trees shade branches in the lower canopy. Trees in non-differentiating stands develop respiration requirements for stored carbohydrates or photosynthates that can be equal or greater than the capacity for photosynthetic production (Oliver et al. 1986b).

The allocation of photosynthates in many conifers follows a set pattern of priorities (Assmann 1970, Kozłowski et al. 1991, Oliver and Larson 1996). If most of the available photosynthetic production is used by a high priority sink, sinks with lower priorities get

less. Trees allocate photosynthates in the following pattern of decreasing priority: 1) Maintenance respiration; 2) Production of fine roots; 3) Cone/flower and seed production; 4) Primary growth (height and branch); 5) Secondary growth (diameter growth), and disease and pest resistance (Oliver and Larson 1996). A tree that has slowed in diameter growth may still maintain rapid height growth (Kohyama et al. 1990). Diameter growth is more sensitive to reductions in photosynthate production than height growth because it has a lower allocation priority (Omule 1985, Oliver and Larson 1996, Wagner and Radosevich 1991). Cannell et al. (1984) found that tree height distributions in young planted stands of Sitka spruce and lodgepole pine had tendencies toward negative skewness, in contrast to diameters which were positively skewed. Photosynthate allocation patterns may change when trees grow under shaded conditions. Hara et al. (1991) found that shade intolerant *Betula ermanii* Chamb. maintains height growth when diameter growth was slowed because of shading. Conversely, shade tolerant *Abies veitchii* Lindl. and *Abies mariessii* Mast. slowed in height growth more than diameter growth when shaded. The trees studied by Hara et al. (1991) were suppressed saplings under an overstory, so the findings may not be transferable to even-aged stands.

These allocation patterns provide insight into the dynamics of non-differentiating stands. Respiration requirements (highest priority) increase while photosynthate production remains stable. Diameter growth (lowest priority) slows; however, height growth (medium priority) may continue at previous rates. Trees develop a large height to diameter ratio, making them unstable in wind, ice, or snow storms (Cremer et al. 1977, Oliver et al. 1986b, Oliver and Larson 1996). As the height-to-diameter ratio (H/D both measurements in the same units) increases trees become increasingly unstable (Petty and Worrell 1981, Cremer et al. 1982, Becquey and Riou-Nivert 1987, Laiho 1987, Lohmander and Helles 1987, Smith et al. 1987, Peltola and Kellomaki 1993; see Chapter 3 for a thorough review of stability measures). The high H/D that develops in non-differentiating stands makes thinning to promote growth risky. In two studies comparing matched naturally regenerated and planted Douglas-fir stands, age to achieve breast

height was reduced by 3 to 4 years and site index (50 year) was increased by 4 to 8 meters in the planted stands (Miller et al. 1993, Miller and Anderson 1995). If the more rapid height growth found in plantations is not accompanied by increased diameter growth, plantations may be prone to developing high H/D values at a younger age.

That plantations have less size variation than naturally regenerated stands has been proposed but little tested (Oliver et al. 1986a, Oliver 1995). Equations based on the data used to develop the Douglas-fir Simulator (DFSIM) model predict higher coefficients of variation for thinned natural stands than unthinned or thinned plantations (Fight et al. 1987). Density management diagrams and mortality curves for coastal Douglas-fir have been developed for both planted and naturally regenerated stands using Tree and Stand Simulator (TASS/Wintipsy version 1.3 [Mitchell 1975, Mitchell 1986]) simulations (Farnden 1996). The curves show strikingly different mortality patterns up to the zone of imminent competition mortality. In natural stands originating at a density of 920 trees per hectare, only 650 are predicted to survive until the stand is 30 meters in height. In plantations originating at the same density, about 850 live trees are projected in a 30-meter tall stand (Farnden 1996).

Differentiation of tree sizes and the resulting dominance and suppression is the primary mechanism of tree mortality. The lower mortality rates predicted for plantations suggest that differentiation levels are lower in plantations than natural stands. Since spacing, age, and species are tightly controlled in planted stands, it appears logical that they may be important causes of differences between plantations and naturally regenerated stands.

2.3 METHODS

Data from repeatedly measured experimental plots were used to compare tree size variation and stand stability measures between naturally regenerated and planted stands. The data were pieced together from portions of three, large repeated measurement studies in the Pacific Northwest. Data sets were combined to increase sample size and to attempt

to cover similar ranges of Douglas-fir densities and stand ages in both stand types. Table 2 provides a list of the studies used; details about individual plots are shown in Appendix A. Plots were selected from Vancouver Island, British Columbia, and from areas west of the Cascade crest in Washington and Oregon. Data selected for the study included control plots or pre-treatment measurement periods from experimental plots.

Table 2: Experimental studies providing data for this analysis.

Study	Agency/reference	Locations	Plots
Experimental plot 703 (EP703)	BC Ministry of Forests (Stone 1994, Zens in prep)	Vancouver Island, B.C.	82
Levels of Growing Stock (LOGS)	USFS-PNW (Curtis and Marshall 1986, Curtis et al. 1997)	Oregon and Washington	9
Stand Management Cooperative (SMC)	Stand Management Cooperative (Collier and Haukaas 1996)	Oregon and Washington	18
Misc.	(Data collected during development of this thesis Appendix A)	Washington	2

All plots are dominated by Douglas-fir. Western hemlock and western red cedar (*Thuja plicata* D. Don ex Lambert) are the only other species with substantial representation in any of the plots. The range in 50-year site indices is 24 - 43 for planted and 23 - 41 for naturally regenerated plots. Plots range from .05 to .20 ha in size depending on the study. Diameters of all trees in every plot were measured. Heights were only measured on a subset of trees in most plots. Naturally regenerated plot ages range from 23 - 90 years. Plantation plots tend to be younger with an age range of 8 - 54 years. Plots from both types of stand cover a wide range of soil attributes, slopes, aspects, and elevations (< 1,000 m).

Unfortunately, long-term plots were never explicitly established and designed to evaluate differences between naturally regenerated and planted stands. Plot data from natural stands used in this analysis tends to be older than data from plantations. A relatively large

data set overcomes some of these data limitations; furthermore, the importance of evaluating differences between the two types of stand makes even an imperfect comparison worthwhile.

Naturally regenerated and planted stands were compared in three steps. First, measures of Douglas-fir tree size (dbh) variability were calculated and compared between stand types using graphical analysis and linear regression. Measures of size variability include the Gini coefficient (Equation 2), the coefficient of variation (standard deviation/mean), and the Weibull shape parameter (maximum likelihood estimates [StatSoft, Inc. 1997]).

$$\text{Gini coefficient} = \frac{\sum_{i=1}^n \sum_{j=1}^n |x_i - x_j|}{2n^2 \bar{x}} \quad (2)$$

where: x_i = dbh (cm) of the i th tree;
 x_j = dbh (cm) of the j th tree;
 n = number of trees; and
 \bar{x} = average dbh of stand (Weiner and Solbrig 1984).

Second, a measure of stand stability, average H/D of the largest 250 trees per hectare (based on dbh), was calculated for each stand. Including all trees in the analysis allows H/D values to be strongly influenced by suppressed and intermediate trees that are sheltered by more vigorous trees in the stand and so relatively unimportant to stand stability (Cremer et al. 1982). In addition, the largest trees tend to have the highest timber, aesthetic, and habitat values making their stability critical (see Chapter 3 for detailed justification of this measure). The experimental plots in this analysis range in size from .05 to .20 hectares. The largest 250 trees per hectare are determined by per hectare expansion specific to each plot. Height was not measured for every tree in the experimental plots. Average of measured heights within the largest 250 Douglas-fir trees was used for height and to calculate H/D_{L250} . Measurement periods for individual plots were excluded from the analysis when less than 20% of the largest trees had been

measured for height. Factors influencing H/D values including: size variation, height, regeneration type (categorical), initial densities of Douglas-fir, western hemlock, and western red cedar, plot size, and site index are evaluated using graphical analysis and linear regression.

Third, the spatial coordinates for trees in the EP703 data were used to generate stand level spatial statistics to evaluate the influence of spacing on size variability and stability. The influences of the limited species mixtures present in the combined data sets were examined in the first and second part of the analysis. Individual trees were not aged in the remeasurement experiments so the impact of age variation, although important (Figure 3), is not considered in this analysis.

Three stand-scale spatial statistics were examined. The first is a measure the regularity or clustering of point patterns, known as Ripley's K statistic (Equation 3) with translation edge correction (Getis and Franklin 1987, Moeur 1993, Batista 1994, Moeur 1997, Ward et al. 1996).

$$\hat{K}_1(r) = \frac{1}{\hat{\lambda} \cdot n} \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n \frac{I(\|x_i - x_j\| < r)}{w_i(x_i, x_j)} \quad (3)$$

where: r = a radius around a point (m);

$\hat{\lambda}$ = trees/area;

n = number of trees in plot;

$I()$ = indicator variable, 1 if true, 0 if false;

$\|x_i - x_j\|$ = Euclidean distance between points x_i and x_j ; and

w_i = translation edge correction.

The translation edge correction (Equation 4) is defined when the radius in the Ripley's K equation is less than the minimum plot side length (a or b) (Osher and Stoyan 1981, Batista 1994).

$$w_i = ab - \|x_i - x_j\|(2a + 2b - \|x_i - x_j\|) / \pi \quad (4)$$

where: a and b are lengths of rectangular plot sides (m).

The second spatial statistic was modified from an index of competition developed by Weiner (1984, 1995). The index sums the cross sectional area of neighbors weighted by distance of neighbor within a set radius (Equation 5).

$$W = \sum_{i=1}^n \frac{A_i}{d_i^2} \quad (5)$$

where: A_i = cross sectional area of neighbor i and
 d_i = distance of neighbor i from focus tree.

In this analysis, neighbor interference was evaluated at stand initiation so values for A_i were set to 1 for all trees. Focus trees less than the specified radius from a plot border are excluded. To scale this individual tree index to a stand spatial statistic the mean, standard deviation and coefficient of variation for the interference index were calculated for each plot at every radius specified.

The third stand-scale spatial statistic was developed for this analysis as an attempt to account for variation of gap size around trees. The statistic calculates degrees of the maximum pie wedge around each tree free from neighbors at a given radius. Focus trees that are less than the radius from a plot border are excluded. Maximum pie degrees are calculated for each tree. The mean, standard deviation, and coefficient of variation for maximum pie degrees are calculated for each plot at every radius specified. The influence of stand spatial statistics on both the Gini coefficient and H/D_{L250} is evaluated using linear regression and graphical analysis.

All of the spatial statistics were calculated using programs written in Python, an interpreted programming language with high-level built-in data structures (Watters et al.

1996, Lutz 1996). The spatial statistic programs and other Python programs developed for this project are included Appendix B.

The use of repeatedly measured plot data introduces the issue of repeated measures into the statistical analysis. Repeat measures on the same experimental unit (plot in this case) through time violate the assumption of independent errors that is central to traditional statistical analysis (Crowder and Hand 1990, Bence 1995, Vonesh and Chinchilli 1997). This violation can lead to underestimated errors for parameter estimates (Bence 1995). There have been a variety of techniques developed to address repeat measurements problems in univariate, multivariate, and regression analysis (Crowder and Hand 1990, Moser et al. 1990, Vonesh and Chinchilli 1997). Another technique used to analyze repeat measure studies is evaluating response curves using two-stage analysis (Meredith and Stehman 1991, Weiner 1995). Unfortunately, all of these approaches become impossible or exceedingly complicated with substantial losses of power when starting time or time increments are not equal between experimental units (Meredith and Stehman 1991, Vonesh and Chinchilli 1997). The pieced-together data set used in this analysis does not have similar starting times (height as surrogate for age) or equal time increments between measurements; therefore, only one measurement period from each plot is used in the linear regression analysis. A best subset approach was taken by generally selecting measurement periods for each plot with the maximum number of measured tree heights. In some cases measurement periods with the second or third most heights measured were chosen to provide a wide range of stand heights for the analysis.

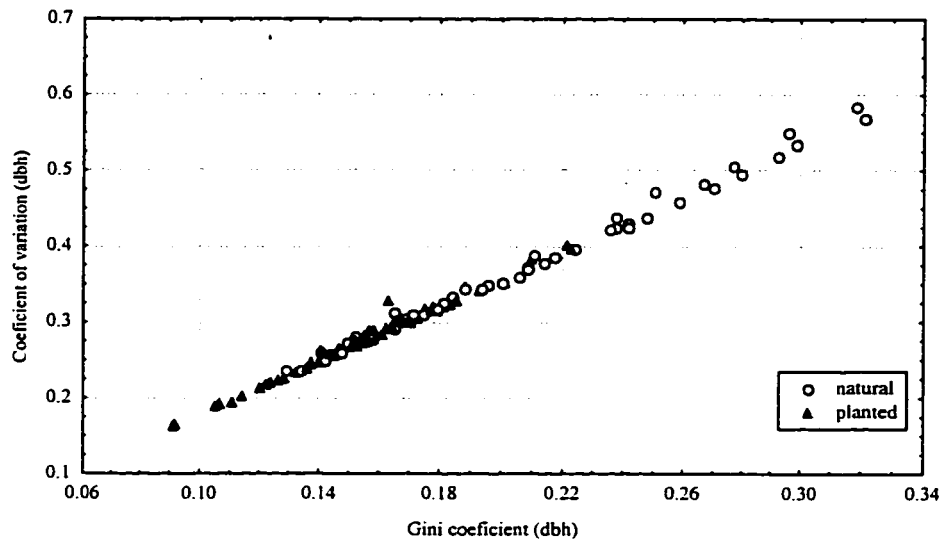
2.4 RESULTS

2.4.1 SIZE VARIATION COMPARISONS BETWEEN STAND TYPES

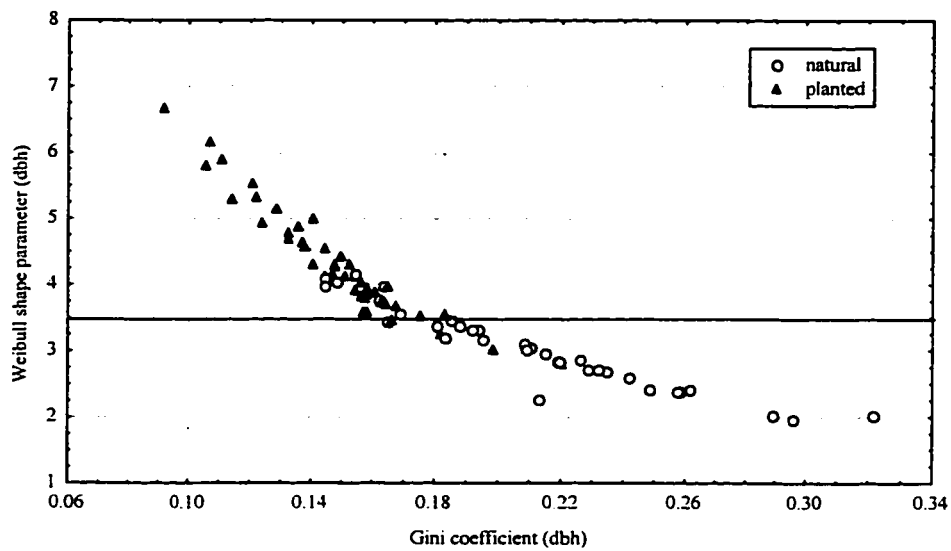
The Gini coefficient, the coefficient of variation and the Weibull shape parameter have been identified in past research as the most useful descriptors of size variation in forest stands (Weiner and Solbrig 1984, Benjamin and Hardwick 1986, Knox et al. 1989). In this study as in others these measures are closely related. Figure 4 demonstrates a high correlation between the Gini coefficient and both the CV and the Weibull shape parameter.

When values of the Weibull shape parameter are equal to zero the distribution is approximately normal. The distribution is negatively skewed if the Weibull shape parameter is greater than 3.6 and positively skewed if the parameter is between 1 and 3.6 (Shifley and Lentz 1985). The solid line in Figure 4b is placed at 3.6 on the y-axis, the transition between negative and positive skew. The data suggest that dbh distributions tend to be positively skewed in plantations and negatively skewed in naturally regenerated stands

The Gini coefficient is closely related to the CV and the Weibull shape parameter and is considered the most appropriate measure of inequality in plant sizes (Weiner and Solbrig 1984). Further comparisons of plant size variation between naturally regenerated and planted stands will focus on the Gini coefficient.



a.



b.

Figure 4: Relationship between Gini coefficient and both the (a) coefficient of variation and (b) Weibull shape parameter. All statistics based on Douglas-fir tree diameters in naturally regenerated and planted stands. (Note: The Weibull shape parameter was only calculated for the EP703 subset of the data).

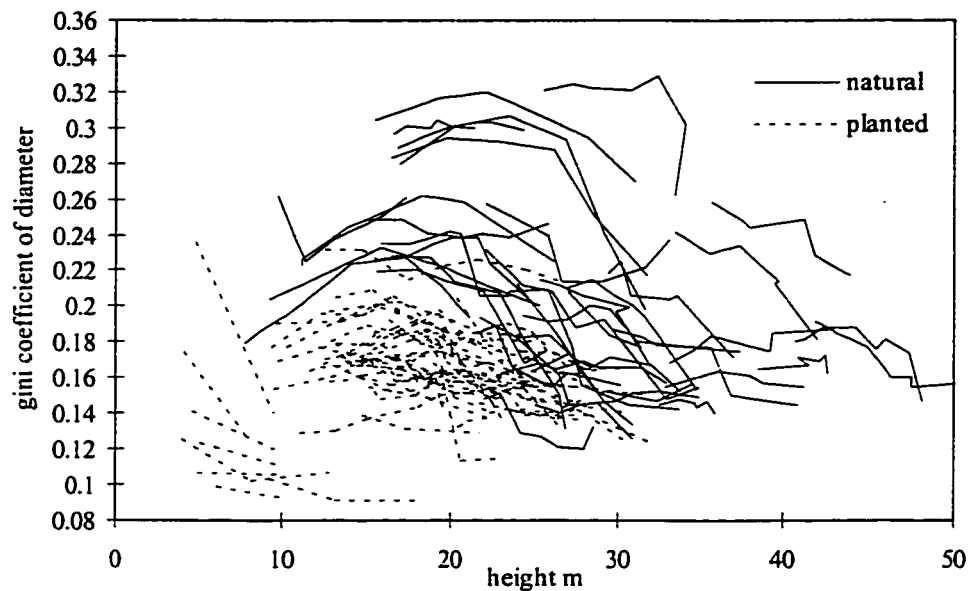


Figure 5: Comparison of the Gini coefficient (based on Douglas-fir tree diameters) in naturally regenerated and planted stands. Trend lines follow individual stands through repeated measurements.

Naturally regenerated stands tend to have larger values for the Gini coefficient for a given stand height (Figure 5). The trend lines for both types of stands follow a similar pattern, the plantation trends occurring at lower magnitudes. Trends for the Gini coefficient reflect a low at 10 meters, followed by a peak at 20-25 meters and a slow decline as stands grow ever taller.

The density management diagram displayed in Figure 6 may help to explain the trends in Gini coefficient values with height. Differentiation of tree sizes, measured by the Gini coefficient, increases up to the initiation of active self-thinning. Self-thinning mortality eliminates the smaller suppressed trees leading to a decline in measures of inequality.

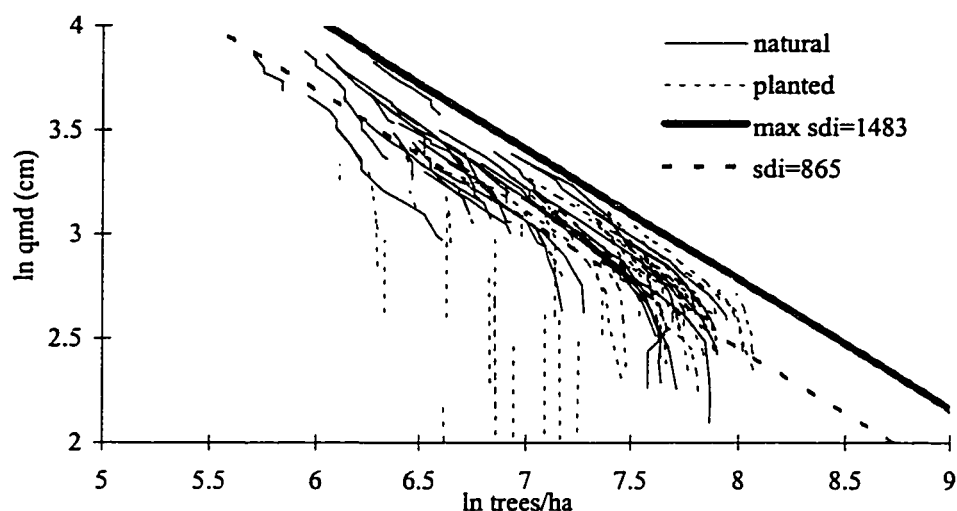


Figure 6: Density management diagram showing self-thinning trends for naturally regenerated and planted stands. Q_{md} is the quadratic mean diameter. SDI is the stand density index (Reineke 1933).

A backward stepwise linear regression procedure (StatSoft, Inc. 1997) was used to develop a predictive relationship for the Gini coefficient. Independent variables included: deviations from average stand height (mht), mht^2 , regeneration type (categorical), initial densities of each species (e.g. iddf-Douglas-fir), site index, plot size, and interaction terms between mht and initial densities. Height values were evaluated in terms of deviation from the average in order to reduce multicollinearity resulting from polynomial regression coefficients. All variables except regeneration type, iddf, and mht were removed from the model. The resulting relationship does not provide a good fit to the data (Adjusted R-Square = .41); however, the categorical variable for regeneration type is significant at $p < .05$ (Table 3). Residual analysis showed no substantial departures from normality. The value for the predicted parameter of regeneration type is negative, suggesting that the plantations in this data set have lower Gini coefficient values than the naturally regenerated stands.

Table 3: Regression coefficients, standard errors, and p-values of a model predicting values for the Gini coefficient. (adj. r-squared = .414, $p < .00000$, $n = 111$, standard error of estimate = .03688)

	B	Standard error B	p-value
Intercept	.191843	.011189	.000000
Regen. type (p=1, n=0)	-.069070	.008224	.000000
Iddf	.000017	.000005	.000576
Mht (ht-bh-23.06)	-.061440	.000481	.003400

2.4.2 INFLUENCES OF TREE SIZE VARIATION ON STABILITY

Trend lines in H/D of the largest 250 Douglas-fir per hectare vs. dominant stand height are shown in Figure 7. The trends in H/D_{L250} for both stand types follow a similar pattern. An initial dip in H/D_{L250} at around 10 meters of height is followed by a steadily rising values. H/D_{L250} values peak at stand heights of 25-30 meters and then decline slowly. This trend for H/D_{L250} values matches findings from wind stability studies that evaluated Monterey pine plantations in Australia (Cremer et al. 1982) and Norway spruce (*Picea abies* [L.] Karst.) plantations in France and England (Becquey and Rio-Nivert 1987). Cremer et al. (1982) attributed the leveling to a flattening of Monterey pine height growth curves at heights of approximately 25 meters.

The initial dip in H/D is an artifact of measuring the diameter at breast height. When trees are relatively short, breast height represents a considerable portion of total tree height. To correct for this, height can be adjusted to represent the height above breast height (H-bh). This correction for breast height eliminates the initial dip in H/D_{L250} values seen in Figure 7 (Figure 8).

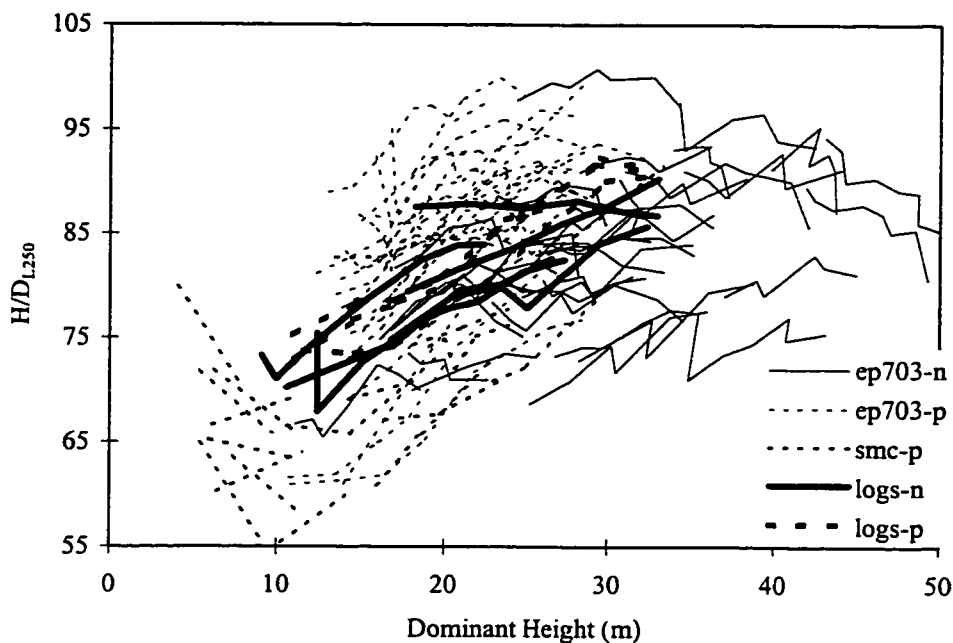


Figure 7: Height diameter ratio trends with dominant height for naturally regenerated (n) and planted stands (p). H/D_{L250} is the average height to diameter ratio of the largest 250 tph in a plot.

The graphical analysis suggests the two types of stands have similar $(H-bh)/D_{L250}$ trends through time; however, other factors such as initial density of Douglas-fir and species mixtures make interpretations of two dimensional graphical relationships difficult. A comparison of H/D_{L250} values with initial densities of Douglas-fir is shown in Figure 9. By combining three data sets it was possible to cover a wide range of initial Douglas-fir densities in both stand types. Unfortunately, combining data sets could not eliminate the general trend for experimental plantation plots to be younger and therefore shorter than the naturally regenerated ones (Figure 8).

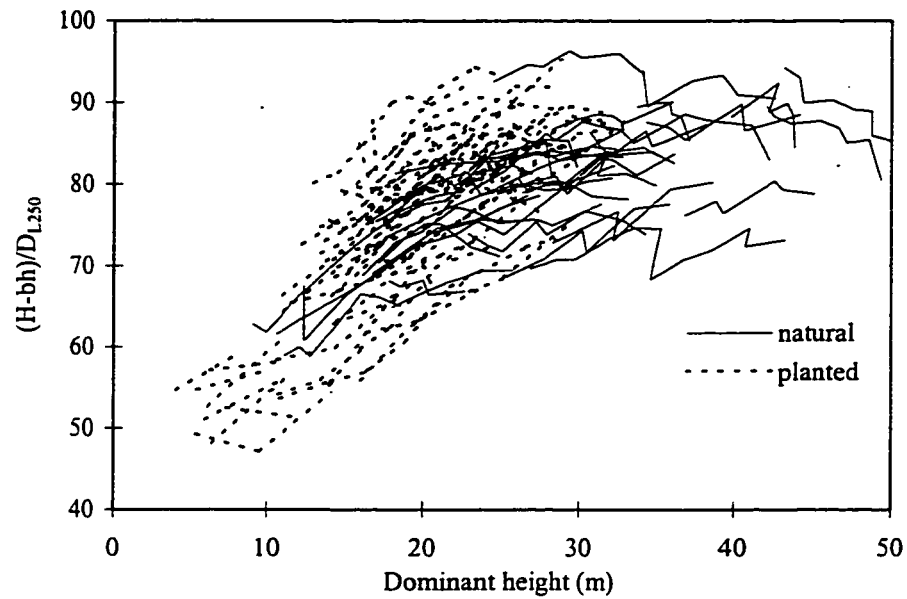


Figure 8: Adjusted height diameter ratio (using height – breast height) trends $((H-bh)/D_{L250})$ vs. dominant height for naturally regenerated (n) and planted stands (p).

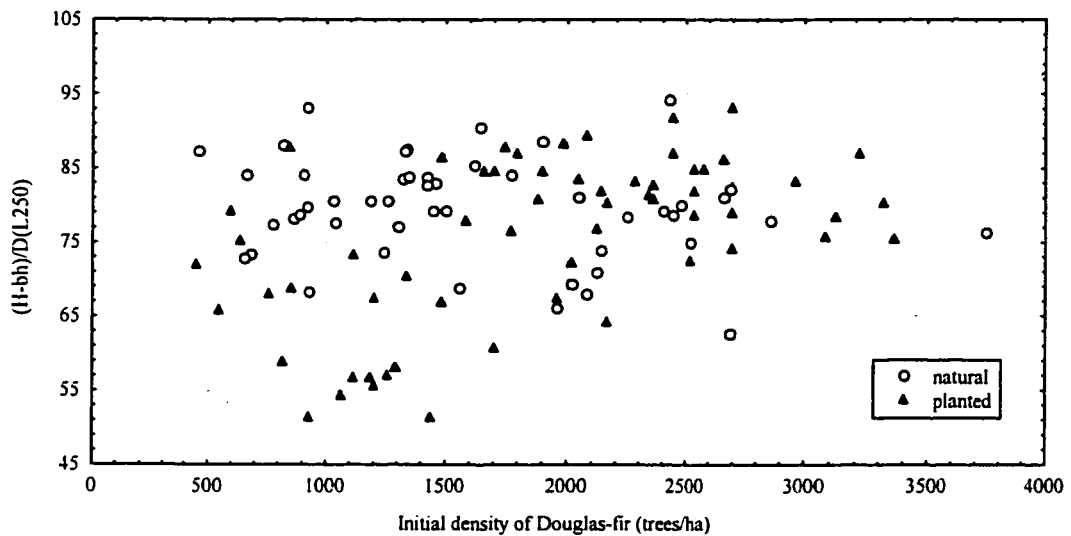


Figure 9: Comparison of height to diameter ratios corrected for breast height $((H-bh)/D_{L250})$ with initial density of Douglas-fir in naturally regenerated and planted stands.

A backward stepwise linear regression procedure (StatSoft, Inc. 1997) was used to develop a predictive relationship for the $(H-bh)/D_{L250}$ values. Independent variables included: deviations from average stand height – breast height (mht), mht^2 , regeneration type (categorical), deviations from average Gini coefficient (mgini), $mgini^2$, initial densities of each species (e.g. iddf-Douglas-fir), plot size, site index, and interaction terms between mht and both Gini coefficients and initial densities. Height and the Gini coefficient were evaluated in terms of deviation from the average in order to reduce multicollinearity with polynomial and interaction terms (Neter et al. 1989). All variables except iddf, mht, mht^2 , and $mgini*mht$ were removed from the model (Table 4). Residual analysis showed no substantial departures from normality.

Table 4: Regression coefficients, standard errors, and p-values of a model predicting values for adjusted H/D of the largest 250 Douglas-fir/ha. (adj. r-squared = .702, n=111, p<.00000, standard error of estimate=5.1977)

	B	Standard error B	p-value
Intercept	70.4301	1.52817	.000000
Iddf	.0050	.00073	.000000
Mht (ht-bh-23.06)	.8729	.06362	.000000
Mht ²	-.0234	.00501	.000009
Mgini (gini-.1783)	-28.9256	10.73723	.008222
Mgini*Mht	-5.1477	1.34587	.000222

Predicting H/D from height may appear inappropriate. Even if there were no relationship between H and D, a strong relationship between H and H/D could be expected. On the other hand, there is a clear understanding of how H/D_{L250} impacts tree stability, making it a useful measure to model. To evaluate this issue, a test data set was created where two variables (d and h) were unrelated. H was uncorrelated with h/d, h+d, or h*d. Typically, a positive and relatively linear relationship exists between height and diameter. In the data used for this analysis H_{L250} is highly correlated and has a positive linear relationship with dbh_{L250} (Figure 10). A second test data set was created where d rose with h but varied randomly around a linear relationship. In this case h is still uncorrelated with h/d but is

highly correlated with $h+d$ and $h*d$. When there is a ratio between two numbers, the value of the ratio does not automatically increase with numerator increases. Cremer et al. (1982) found H/D values for open grown Monterey pine remained constant in the 10 – 30 meter range of height. H_{L250} and the dimensionless ratio H/D_{L250} are not correlated simply because H_{L250} is present in both variables; therefore, H/D_{L250} and H_{L250} can be considered functionally independent.

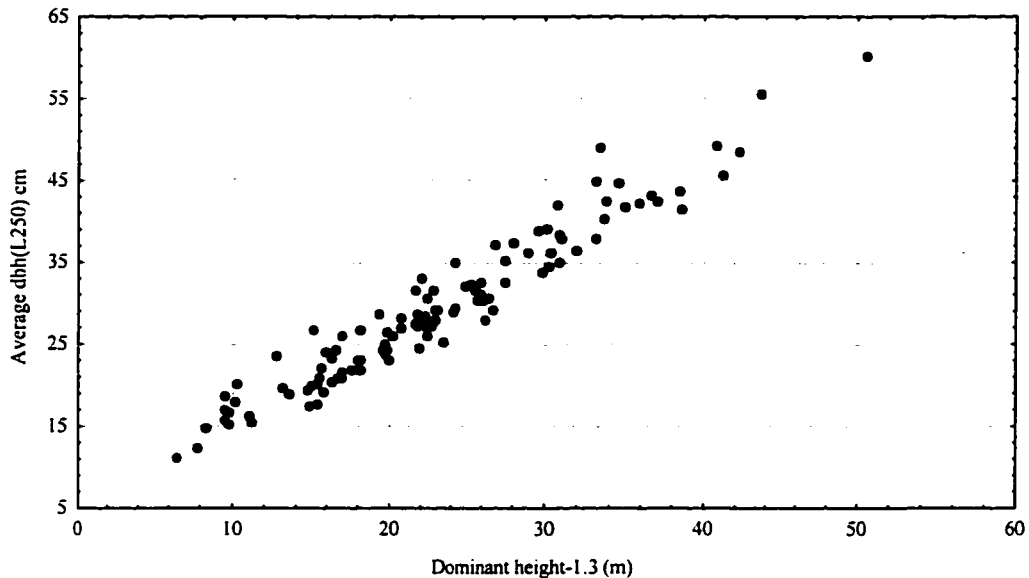


Figure 10: Relationship between adjusted dominant height ($ht-bh$) and average dbh of the largest 250 (L250) Douglas-fir per hectare.

2.4.3 IMPACTS OF SPACING ON SIZE VARIATION AND STABILITY

The Ripley's K statistic can be more easily interpreted by plotting a transformation of K (Equation 6) against radius (Batista 1994). A horizontal line at zero represents spatial randomness. Values above and below zero show spatial aggregation and regularity respectively (Moeur 1997).

$$\hat{L}(r) = \sqrt{\frac{\hat{K}(r)}{\pi}} - r \quad (6)$$

A comparison of transformed Ripley's K values for naturally regenerated stands and plantations is shown in Figure 11. At a radius of one meter, plantations have consistently negative values, most values below -0.2, suggesting regularly spaced trees. Naturally regenerated stands have both positive and negative values at a radius of 1 meter, suggesting they generally have more variation in small-scale spatial patterns than plantations. Consistent differences in spatial pattern between the two stand types disappear with radii above 2 meters.

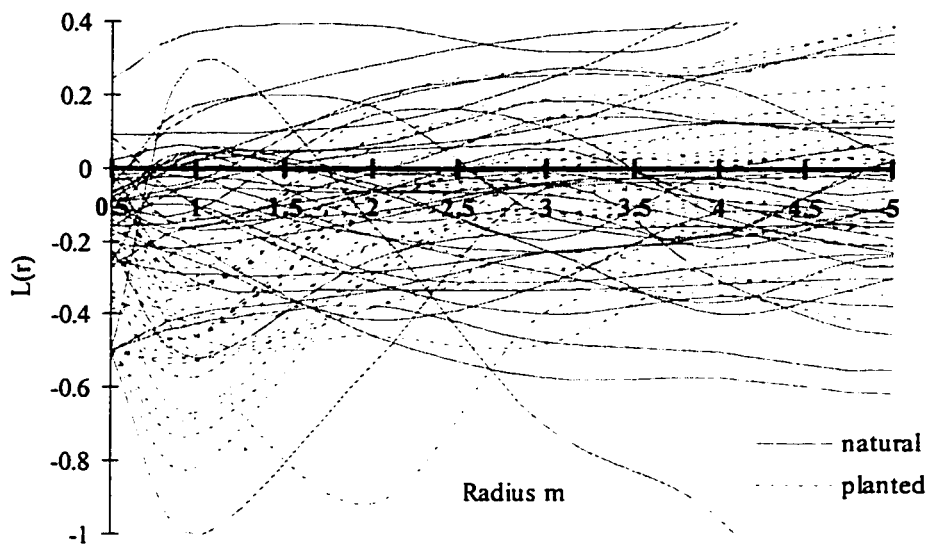


Figure 11: Transformed Ripley's K statistic trends for natural and planted stands from EP703 (radius is maximum neighbor distance evaluated in each run). Ripley's K calculated based on Douglas-fir coordinates from the first measurement period.

Graphical analysis did not expose any relationship between stand type and the mean, standard deviation, or coefficient of variation of maximum pie degrees or the Weiner neighborhood interference measure at radius measures ranging from 1-5 m. Figure 12 shows the coefficient of variation of maximum pie degrees at different radii.

A backward stepwise linear regression procedure (StatSoft, Inc. 1997) was used to develop predictive relationships for both the Gini coefficient and H/D values for the

EP703 data. Independent variables entered into the analysis included those used in the previous analysis as well as all three spatial statistics for radii 1-5. All of the spatial statistics at all radii were removed from the models by the backward stepwise procedure.

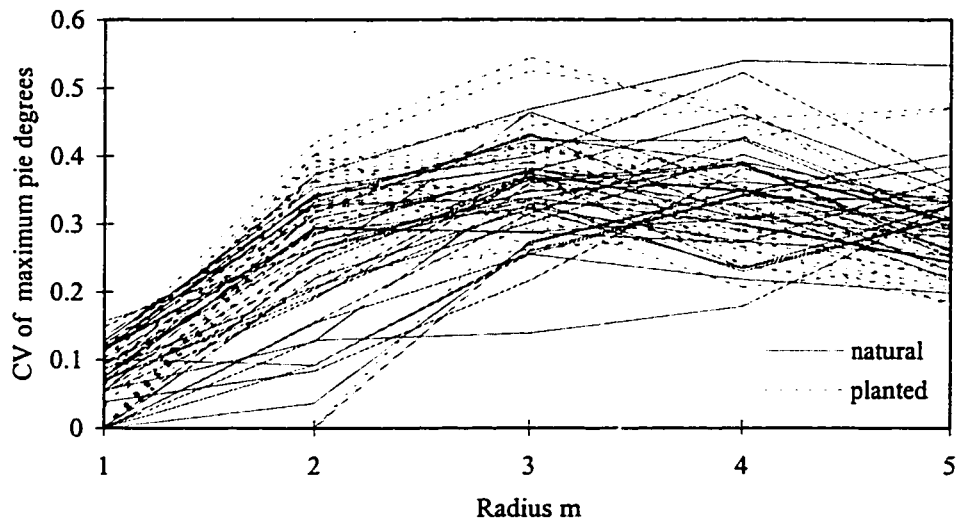


Figure 12: CV of maximum pie degrees free of neighboring Douglas-fir. (radius is maximum neighbor distance evaluated in each run). CV of maximum pie degrees based on Douglas-fir coordinates from the first measurement period.

2.5 DISCUSSION

The graphical and statistical comparison of the two stand types shows that naturally regenerated Douglas-fir stands have substantially more inequality of tree sizes as measured by the Gini coefficient. The relationship developed in the analysis predicted that naturally regenerated stands have Gini coefficient values that are 0.0691 lower than plantations, when the two stands initiate with the same Douglas-fir density (tph) and have equal dominant heights. This seems like a small quantity; however, Gini coefficient values in the combined data sets only ranged from 0.09 to 0.32.

The level of variation in tree sizes (Gini coefficient) is in turn a useful predictor of a measure of stand stability ($(H-bh)/D_{L250}$). The predictive equation developed in the analysis suggests $(H-bh)/D_{L250}$ increases with higher initial densities and with height. The negative relationship with squared height reflects the trend for $(H-bh)/D_{L250}$ values to peak and then decline after stand height reaches 25-30 meters (Figure 8). A similar pattern is reported for H/D trends in other studies (Cremer et al. 1982, Becquey and Riou-Nivert 1987). Stand stability concerns can be addressed by maintaining reasonably low H/D_{L250} values up to stand heights of 30 meters. The negative relationship with the Gini coefficient suggests that greater inequality in tree diameter results in lower H/D_{L250} values. In addition, the negative parameter for the interaction term between the Gini coefficient and height reflects the trend for Gini coefficients to decline after stands reach 20 meters in height (Figure 5). Evaluating the 0.0691 Gini coefficient difference between stand types in the $(H-bh)/D_{L250}$ relationship results in a 2.2 point increase in stand stability as defined by $(H-bh)/D_{L250}$ for planted stands when stand height equals 25 meters. Initial density determinations are likely to be underestimates in the older naturally regenerated stands. Initial density underestimates may result in a conservative prediction of Gini coefficient impacts on $(H-bh)/D_{L250}$ values.

Plantations develop less differentiation of tree sizes, making them prone to developing higher H/D_{L250} values than naturally established stands when all other variables are equal. Fortunately, initial density of Douglas-fir is a powerful determinant of future H/D_{L250} values. The relationship predicts a 5-point drop in $(H-bh)/D_{L250}$ for every 1,000 trees per hectare reduction in initial Douglas-fir density. Future stand stability can be easily adjusted by altering planting densities rather than devising some means to increase variability in tree sizes. A comparison of naturally established and planted eastern white pine (*Pinus strobus* L.) stands from the 1930's (Figure 13) highlights the importance of initial densities on future stand stability (Deen 1933). The naturally regenerated white pine stands tend to have more variation in tree sizes than the planted ones (Figure 13a). Unlike the Douglas-fir data sets used in this analysis, the natural stands have very high

dominant H/D ratios compared to the planted stands (Figure 13b). Figure 13c shows the likely cause of high H/D values in the naturally regenerated stands; they have extremely high initial densities of white pine. In this case, relatively high levels of tree size variability in the naturally regenerated stands could not compensate for stand stability lost because of high initial stocking levels

The relative importance of age, spacing, and species mixtures on tree size variation and stability remain somewhat unclear. Lack of age measurements made it impossible to evaluate the impact of age variation; however, Figure 3 suggests that the influence of age variation may be quite substantial. Age has been an important determinant of size variation in other studies.

Spacing, as reflected by initial density of Douglas-fir, is shown to be an important predictor of future stand stability. This result mirrors many other studies evaluating stand stability (Cremer et al. 1982, Becquey and Riou-Nivert 1987). Evaluating patterns of spacing in the data (i.e. Ripley's K) shows a clear trend for the Douglas-fir in planted stands to be more regularly spaced than naturally regenerated stands. The impact of this difference on tree size variability or stand stability is too subtle to be detected by the techniques used. The impact of local competition on individual tree growth, although intuitively enticing, has been difficult to determine in many studies (Bella 1971, Martin and Ek 1984, Wimberly and Bare 1996). In light of this difficulty, it seems unlikely that a stand-level spacing statistic, such as Ripley's K statistic or mean neighborhood indices, would highlight the impacts of initial spacing patterns on future stand size variation or stability.

The impact of other species on Douglas fir size variation and stability remains somewhat unclear. The only species besides Douglas-fir with substantial presence in the combined data sets were western hemlock and western red cedar. Initial densities of all three species show no trends based on stand type. Initial density values for both hemlock and cedar were dropped by the backwards stepwise procedure from both the Gini coefficient and

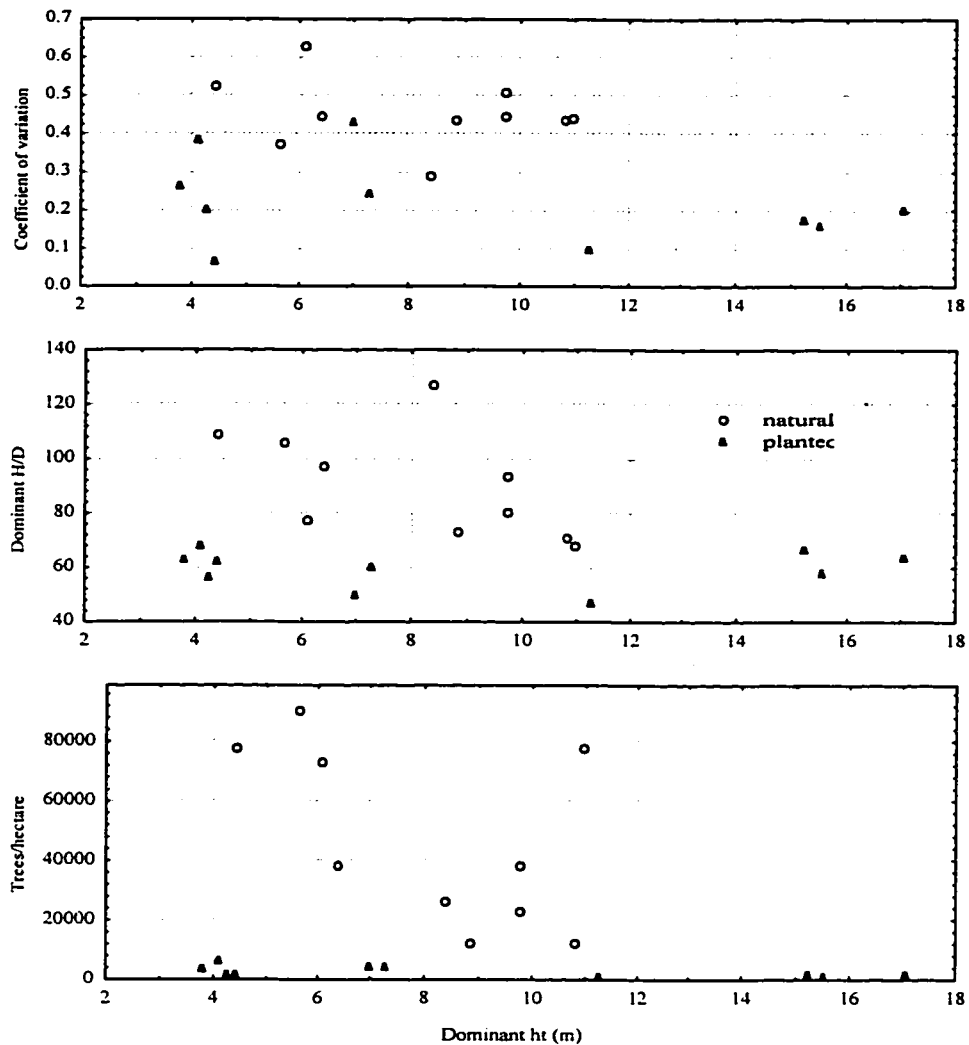


Figure 13: Comparison of dominant stand height (m) vs. (a) coefficient of variation, (b) Dominant H/D, and (c) trees per hectare between naturally regenerated and planted eastern white pine stands (Data from Deen 1933).

(H-bh)/ D_{L250} relationships, suggesting their influence on Douglas-fir size variation and stability is not substantial. Both western hemlock and western red cedar tend to be quickly overtopped by Douglas-fir in even-aged stand development (Wierman and Oliver 1979). The presence of species that are more robust competitors with Douglas-fir, such as

western white pine (*Pinus monticola* Dougl. ex D. Don), red alder, bigleaf maple, or grand fir (*Abies grandis* Lindl.), might have greater impact on Douglas-fir development.

2.6 CONCLUSION

Naturally regenerated stands have a tremendous range in stand characteristics such as size variability and wind stability. This range is promoted when stand establishment factors vary widely. Plantations represent a subset of this larger stand universe in which three stand establishment factors (age, spacing, and species) are tightly controlled. The skewing of establishment characteristics towards one extreme in planted stands results in substantial reductions of size variation and more limited reductions in stand stability. Attempts to increase size variability in Douglas-fir stands to promote future stand stability, such as planting seedlings with a range of ages or irregular planting patterns, seem like complicated management endeavors for relatively small gains in future stand stability. A much simpler management approach with greater possibilities for stability gains is to reduce the initial density of Douglas-fir or to thin stands very early (the impacts of thinning and timing of thinning are addressed in Chapter 3). If wider spacings raise wood quality concerns (e.g. large branches, juvenile wood core, and weed competition) species such as western hemlock and western red cedar, that appear to have a minimal impact on future dominant Douglas-fir stability, can be used to augment overall stand density.

CHAPTER 3: WIND STABILITY AND MANAGEMENT FLEXIBILITY OF DOUGLAS-FIR PLANTATIONS

Tree size variation and stand stability between naturally regenerated and planted stands were compared in Chapter 2. This chapter reviews tree and stand stability measures and evaluates stability trends in Douglas-fir plantations over time and at different stand densities (tph). Chapter 3 ends with a discussion of potential interactions between stand stability and management flexibility in planted stands.

3.1 INTRODUCTION

Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) plantations dominate young managed forests in the coastal Pacific Northwest (PNW). Plantations are forest stands regenerated through planting of seedlings. Plantation establishment became the dominant forest regeneration technique in the 1970's because the rapid use of all growing space in planted stands increases total stand volumes and shortens rotation lengths compared to naturally regenerated stands (Smith et al., 1997). In addition, state forest practice regulations began to require reforestation in the 1970's. In most plantations, even-aged seedlings of a single species are planted in a regular pattern. This practice limits variation of tree sizes, making plantations more susceptible to stagnation and/or instability than the naturally regenerated second growth they replace (Chapter 2). The traditional management response to plantation stagnation and instability has been to thin planted stands, increasing the growing space for remaining trees before they become unstable (Reukema and Bruce 1977, Oliver et al. 1986a, Oliver et al. 1986b, Smith and Reukema 1986, Wierman and Knapp 1986, Slodicak 1995). This costly, intensive, and time-sensitive approach may be unsuitable for some forest lands.

This chapter begins with a thorough literature review of tree allometry as it relates to wind stability. Experimental plot data are used to develop stand stability relationships in thinned and unthinned plantations. Predicted values for stand stability are compared to results from growth models and Douglas-fir spacing trials. The chapter ends with a discussion of how results can impact the flexibility with which plantations can be managed.

3.2 BACKGROUND

3.2.1 TREE ALLOMETRY AND STAND STABILITY

Instability of trees in windy conditions is related to individual tree characteristics such as height, species, diameter, crown size, and root/stem rots as well as site characteristics such as rooting depth, soil moisture, exposure, and slope (Cremer et al., 1982, Ruel 1995, King 1986, Becquey and Riou-Nivert 1987, Kimmins 1987, Foster 1988, Kozlowski et al. 1991). This section describes allometric measurements of individual trees that are associated with wind stability. Although site characteristics (e.g., rooting depth, exposure, and slope) are important contributors to wind risk, they are not generally modified through plantation design or tending. Site characteristics are more useful for determining where particular types of management may be limited (Quine 1995). The influence of site characteristics on wind risk and the interaction of site and stand characteristics will be discussed in Chapters 4 and 5.

There have been three general approaches to evaluating tree stability. These are: development of mechanistic models of tree stability in relation to wind or snow loads; empirical evaluations of tree or stand damage after storm events; and theoretical models of tree buckling in the absence of wind or snow.

3.2.1.1 Mechanistic models of tree stability under wind or snow loads

Several authors have developed theoretical or mechanistic models of tree stability in relation to wind and/or snow loads. All of them make the assumption that trees with conical or paraboloid stem shapes bend along curves that produce uniform strain in the outer wood. This assumption makes it possible to approximate a tree as a uniform resistance cantilever beam (Metzger cited in Mergen 1954). Stress on the outer fibers at any height in a uniform resistance circular beam is calculated in Equation 7:

$$\text{stress} [Pa] = \frac{32 \cdot F_x}{\pi \cdot D_x^3} \quad (7)$$

where: D_x = diameter at distance x from the free end [cm] and
 F_x = bending moment at distance x [Nm²] (Mergen 1954).

The ability for a uniform resistance beam to support a load is then directly proportional to D_x^3 (dbh of a tree) and inversely proportional to x or the height of a tree [H] (Mergen 1954, Cremer et al. 1982). The H/D^3 measure takes account of height and diameter but ignores the effect of crown size on stability. As crown size increases, drag on the tree increases. Crown size is highly correlated with basal area or D^2 (Siemon et al. 1980). Including a simplistic correction for drag associated with tree crowns (D^2) in the numerator of Equation 7 produces a description of stem strength that reduces to H/D . (Cremer et al., 1982).

Galinski (1989) included a correction for windspeeds at different heights in the canopy and added total length of needled branches in each whorl in order to develop a windthrow risk model (Equation 8) for dominant and suppressed Scots pine trees (*Pinus sylvestris* L.). Individual whorl contributions to the bending moment are corrected for their height in the tree (lever effect) and reductions in windspeed that occur from the top of the canopy to the bottom. Whorl values are then summed to produce a total crown contribution to the bending moment.

$$\text{windthrow risk} = \frac{\sum_{i=1}^n L_i \cdot H_i \exp[-a \cdot (1 - H_i / H_{\max})]}{dbh^3} \quad (8)$$

where: L_i = needed branch length of the i th whorl [m];
 H_i = height of the i th whorl [m];
 H_{\max} = height of the forest canopy [m]; and
 a = constant (2.5) (Galinski 1989).

To simplify the model and make it consistent for individual trees, Galinski has removed a constant, $32/\pi$, and removed the contribution of windspeed to the total bending moment. He found windthrow risk predicted by the model strongly related to H/D in dominant trees but not in the suppressed trees he evaluated. Galinski's model accounts for the force of wind drag but does not consider the force associated with the displacement of stem and crown weight when trees bend in the wind. The contribution of displaced stem and crown weight is proportionally larger in suppressed trees (Peltola and Kellomaki 1993). The omission of displacement weights has a larger influence on windthrow risk rating for suppressed than dominant trees and may contribute to the poor relationship Galinski found between suppressed trees and windthrow risk.

Petty and Worrell (1981) developed a model for stability of 20-meter tall conifers under snowloads, and Petty and Swain (1985) modified that model to account for wind loads. Their model accounts for snow or wind loads as well as the forces associated with stem and crown weights when trees bend. A maximum resistive moment in a bending stem is associated with the breaking stress of green timber in Equation 9.

$$\text{critical resistive bending moment [kNm]} = \frac{P_c \cdot \Pi \cdot a^3}{4} \quad (9)$$

where: P_c = breaking stress for green timber [Nmm^{-2}] and
 a = radius of the stem [cm]
 note: the divisor is 4 instead of 32 since the radius rather than the diameter is in the numerator (Petty and Worrell 1981).

The authors compared the critical resistive bending moment (using a range of breaking stresses) to applied bending moments caused by snow and wind loads for a range of diameters and stem forms. For both wind and snow they found that tree taper or H/D was the most important characteristic determining tree stability in their model. Increasing H/D ratios lead to reduced stability (Petty and Worrell 1981, Petty and Swain 1985). Their results matched empirical results from tree damage data gathered after wind and snowstorms. For the wind and snow loads they tested in 20 meter tall trees, an H/D value of 60 resulted in stable trees while values of 100 were unstable.

Petty and Worrell's model shows that as tree heights increase, H/D ratios must be reduced in order to maintain constant stability. If the height and diameter are increased proportionally by g , the H/D ratio is kept constant. The resistive bending moment increases by a factor of g^3 since the radius is cubed. The applied bending moment increases by a factor of g^4 since the lever length and the weights of stem, crown, and snow/wind are increased by a factor g . This result matches findings from empirical wind damage studies (Cremer et al. 1982, Becquey and Riou-Nivert 1987, Laiho 1987, Lohmander and Helles 1987) and other mechanistic model formulations (Smith et al. 1987, Peltola and Kellomaki 1993).

Peltola and Kellomaki (1993) developed a windthrow model for Scots pine. This model was expanded to evaluate the combined impacts of snow and wind on Scots pine, Norway spruce (*Picea abies* [[L.] Karst.), and birch (*Betula sp.*) by Peltola et al. (1997). The model includes the same critical resistive bending moment as Petty and Worrell (1981). In addition, Peltola and Kellomaki (1993) included an evaluation of root anchorage (Equation 10) to evaluate windthrow as well as windsnap.

$$\text{Supporting moment of root-soil anchorage [Nm]} = \frac{g \cdot \text{Mass} \cdot RS_{\text{mean}}}{A_{\text{rsw}}} \quad (10)$$

where: g = gravitational constant [ms^{-2}];
 Mass = mass of root-soil plate [kg];
 RS_{mean} = mean depth of soil-plate volume [m]; and
 A_{rsw} = proportion of root-soil plate weight to total anchorage (Peltola and Kellomaki 1993).

As with the Petty and Worrell model displaced stem and crown weight are included in the evaluation of applied turning moment on the stem. The model also adjusts for reductions in windspeed lower in the crown. The authors compared the critical resistive bending moment and supporting moment of the root-soils to applied bending moments caused by wind and snow wind loads for a range of tree heights and diameters. For wind as well as snow and wind they found that H/D and tree height were effective predictors of windsnap and windthrow risk. Windthrow risk can be predicted from H/D because root-soil size and weight are highly correlated with stem diameter (Peltola and Kellomaki 1993, Mattheck et al. 1995). Empirical studies of storm damage support the claim that H/D is a useful measure of both windsnap and windthrow risk (Cremer et al. 1982, Becquey and Riou-Nivert 1987, Lohmander and Helles 1987).

Critical windspeeds or snowloads required for uprooting averaged about half of those required for stem breaking. Coutts (1986) and Smith et al. (1987) suggested that uprooting tends to occur before stem snapping. Alternatively, Petty and Worrell (1981) using data from tree pulling experiments, found equivalent resistive bending moments at failure for uprooted and snapped trees, suggesting stem strength was closely related to root-soil resistance. The root-soil resistance moment computations are sensitive to soil properties (e.g., resistance, weight, and depth [Peltola and Kellomaki 1993]). Estimates used in Peltola and Kellomaki's analysis may have led to the large differences they found

between the two types of damage. In addition, Peltola and Kellomaki use a critical breaking stress for green timber of 32 MPa while Petty and Worrell evaluated a range of values from 16 to 32 MPa. Using the lower value in their model would make the resistive bending moments at failure more similar for uprooted and snapped trees.

The mechanistic models discussed previously evaluate stability under static or mean wind loads. When the drag force on trees has the same periodicity as tree sway, resonance occurs. Stresses in tree stems under dynamic (resonant) wind loads are much increased (Papesch 1974, Blackburn and Petty 1988). Blackburn and Petty (1988) modified the Petty and Worrell (1981) model to evaluate tree stability in a variety of plantation spacings including an evaluation of both static and dynamic wind loads. Wider tree spacings resulted in lower H/D ratios for trees and increased critical windspeed for windthrow or windsnap under static wind loadings.

When dynamic wind loads are considered the situation is more complex. Stands of widely spaced trees tend to have greater canopy roughness, generating more turbulence when wind flows through the canopy. Turbulent air movement has reduced periodicities that are closer to the sway period of trees, increasing the potential for resonance (Blackburn et al. 1988). Concurrently, sway periodicities are reduced with lower H/D values (Blackburn and Petty 1988). Wind energy periodicity's tend to be greater than tree sway periods, so trees with lower H/D values will be less likely to achieve resonance (Papesch 1974, Blackburn and Petty 1988). Blackburn and Petty (1988) concluded that increased turbulence at wider spacing is compensated by the reduced sway periods of lower H/D trees. Wider spacings promote wind stability under dynamic wind loads although the increased stability is proportionally less than under static wind loads (Blackburn and Petty 1988, Milne 1995).

Gardiner et al. (1997) argued that the findings described above are accurate for stem breakage but not for uprooting. They used data from a Sitka spruce (*Picea sitchensis* [Bong.] Carr.) pulling study by Fraser and Gardiner (1967) to establish a relationship

between stem weight and resistive moments of trees. They then compared increases in stem weights to applied bending moments for trees at wider spacings. Stem weight increases with wider spacing but not as much as, the increase in applied bending moment. Applied bending moments rise with wider spacings because of increased wind penetration of canopies. They concluded that trees grown at wider spacing are more susceptible to windthrow than trees grown at narrow spacings (Gardiner et al. 1997). It should be noted that the fit of the stem weight relationship with resistive moment is poor ($r^2 = .52$). In addition, the analysis only evaluated Sitka spruce trees that were roughly 12 meters in height. The relationship of spacing to stem weight may be quite different at greater heights. The poor fit and short trees may help to explain inconsistencies between the Gardiner et al. (1997) analysis and empirical studies described in the next section.

Under either static or dynamic wind loads, a proportional reduction in root-soil resistance through cultural activities (e.g., furrow ploughing) will have a relatively greater impact on tree stability's at wider spacings than narrow ones because of increased wind penetration into the canopy (Blackburn and Petty 1988, Maccurrach 1991)

3.2.1.2 Empirical evaluations of wind or snow damage

Several studies have found H/D values are highly correlated with stem bending, windsnap, and windthrow (Petty and Worrell 1981, Cremer et al., 1982, Becquey and Riou-Nivert 1987, Lohmander and Helles 1987, Slodicak 1995). Including both tree height and H/D in linear regression models predicting windthrow and windsnap improves the relationship (Cremer et al., 1982, Becquey and Riou-Nivert 1987, Lohmander and Helles 1987). Greater wind risks for taller trees with the same H/D as shorter trees results from increasing wind velocity with distance from the ground (Foster 1988, Galinski 1989, Peltola and Kellomaki 1993) and a relative increase in applied moments over resistive moments with increasing height (Cremer et al. 1982, Petty and Worrell 1981, Peltola and Kellomaki 1993).

Four papers provide detailed evaluations of wind risks at different H/D values. Cremer et al. (1982) evaluated varied data from several Australian Monterey pine (*Pinus radiata* D. Don) plantations to establish patterns of stable H/D ratios. Evaluating the 200 largest trees per hectare (tph), they found high levels of stem breakage and uprooting from particular wind and snow events occurring when stand dominant H/D_{L200} values ranged from 90 to 100. Minimal damage occurred in stands with H/D_{L200} below 80. When stands had been thinned, producing a sparser canopy, the high-risk ratio dropped to 85. Carter (1988) also found increased risk of damage from cyclone Bola for recently thinned stands of Monterey pine. Open grown Monterey pines were undamaged and had an average H/D of 38. Cremer et al. (1982) examined how H/D_{L200} develop in plantations over time. H/D_{L200} values were higher in denser stands and increased as stands grew in height. This pattern occurs because density reduces diameter growth while height growth is unaffected except at extremely low and high stockings (Cremer et al. 1982; Omule 1985, King 1986, Wagner and Radosevich 1991, Knowe 1991, 1994). H/D_{L200} values peaked in all stands at heights of 25-30 meters. This trend was attributed to a flattening of Monterey pine growth curves at these heights. Becquey and Riou-Nivert (1987) also found that H/D values peaked at this height range in French and English Norway spruce plantations. Thinning only lowered H/D_{L200} values substantially when it was performed early in Monterey pine plantation's development (Cremer et al. 1982). Both Slodicak (1995) and Becquey and Riou-Nivert (1987) found early thinnings critical to reducing mean H/D values in Norway spruce plantations.

It is possible to develop the theoretical allometric relationships between tree height, diameter, basal area, and H/D based on Douglas-fir height growth curves (Mitchell and Polsson 1988). This relationship has been evaluated for this study. Figure 14 compares theoretical allometric relationships in an individual Douglas-fir tree and helps to explain both the requirements for very early thinnings to reduce H/D values and the peaking of H/D ratios at 25-30 meters.

Five-year height growth increments (htinc) are based on height growth curves for a stand with a site index of 36 m (Mitchell and Polsson 1998). To maintain relatively stable H/D values when the tree is between 10 and 30 meters of height requires that diameter increments (dbhinc) match those shown in Figure 14. Required diameter increments are used to determine matching basal area increments (bainc). The rapid decline in H/D values in the first 5 m of height reflects diameters being measured at breast height (bh). The shorter the tree the greater the proportion of total tree height that breast height represents (Chapter 2).

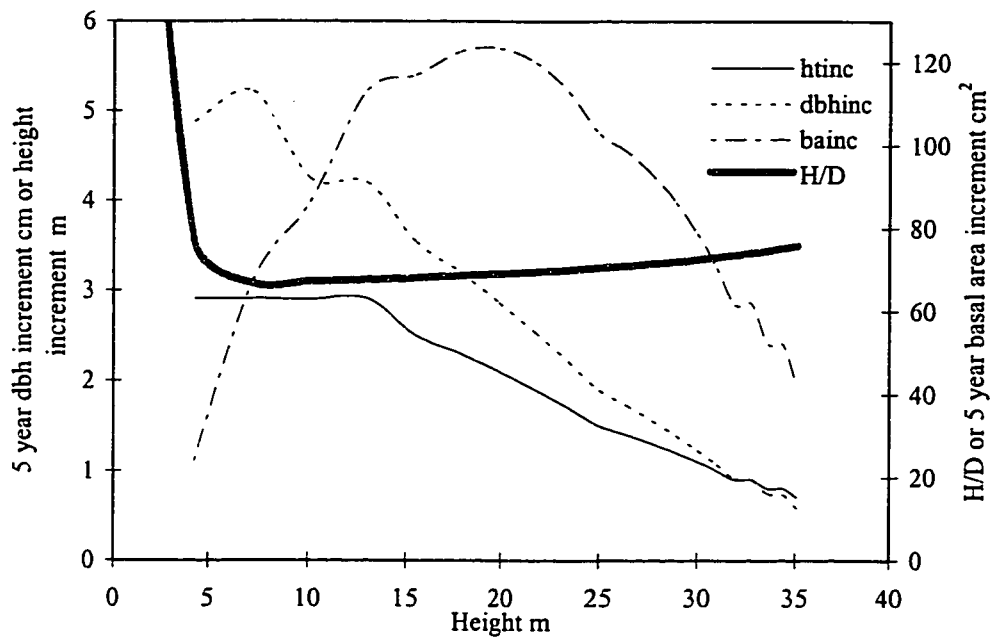


Figure 14: Five-year height increment (Douglas-fir site index curves) and the theoretical diameter and basal area (BA) increments needed to maintain the H/D ratio shown. This figure shows the dramatic increase in BA increment required to keep the H/D ratio relatively constant in trees between 10 and 30 meters tall.

Rapid height growth and basal area increments being a function of squared diameter $(dbh/2)^2$ combine to assure rising H/D values between 10 and 30 meters in all but open grown trees. To maintain relatively stable H/D values between stand heights of 10 to 30

meters requires substantial basal area increments (double and triple what they were prior to 10 meters). Tree height-growth increments decline beyond 25-30 m of stand height. The resulting reductions in basal area increment requirements help explain why studies have found H/D values peak in this height range.

Becquey and Riou-Nivert (1987) established zones of stability for Norway spruce plantations in France after a 1982 storm. The H/D cutoff for inclusion in a stability zone decreases with greater tree heights. For stands with heights ranging from 20 to 30 meters, unstable mean H/D values are those above 90; stable stands have mean H/D values below 60.

Lohmander and Helles (1987) developed a model predicting windthrow probability from data collected after a severe windstorm in Denmark in 1981. Their model predicts 100% probability of windthrow for Douglas-fir trees with H/D values greater than 67 and heights greater than 25 meters. Windthrow probability is 50% when the trees are 20 meters tall. Windthrow probabilities in their model only drop substantially when H/D values approach 50. This particular storm was very severe, blowing down three times the annual softwood harvest of Denmark (Lohmander and Helles 1987).

Thomasius et al. (1991 [cited in Bouchon 1987]) provided windrisk guidelines for Norway spruce plantations based on soil drainage and percentage canopy closure. Average H/D values for stands can be over 100 on well drained sites with 80% canopy closure but must be below 100 on poorly drained sites. At canopy closures of 40%, H/D values must be below 100 on well-drained sites and below 80 on poorly drained ones. Presence of root or butt rot in a stand requires lower H/D values for stability (Thomasius et al. 1991 [cited in Bouchon 1987]).

In an assessment of wind and snow damage in a Swedish Scots pine stand, Valinger et al. (1993) found damage to individual trees was best predicted by clear bole height and local density of neighbors. Reducing clear bole height and increasing the number of

neighboring trees increased the risk of wind/snow damage. H/D values were not found to be a significant predictor of damage. A potentially confounding aspect of this study is that the tree damage occurred over two winters with several wind and snowstorms. In a Norway spruce study, trees with very high H/D values were most susceptible to snow damage while trees with moderate H/D values were most susceptible to wind damage (Slodicak 1995). This discrepancy was attributed to high H/D trees being the most suppressed trees. Their canopy position and tiny crowns protected them from wind, but not snow damage (Slodicak 1995). The Swedish study may have averaged H/D for trees damaged by wind and snow. In another study of snow and wind damage in Swedish Scots pine stands, Valinger and Fridman (1997) found stand damage probabilities were higher when sample trees had relatively small upper diameters (diameter at 3 or 5 m) and higher when sample trees had relatively low H/D values. The apparent discrepancy with other study findings may result from combining wind and snow damage and/or from height confounding impacts of H/D values. Younger (shorter) stands had lower H/D values and appear much more susceptible to snow damage (Valinger and Fridman 1997). Greater susceptibility to snow damage in young stands may result from lowered breaking stress in juvenile wood (Cremer et al. 1982).

3.2.1.3 Stem buckling models

Complex models of branching, stem shape, and wood elasticity have been developed to evaluate stem buckling in the absence of wind or snow (e.g., McMahon 1973, 1975, McMahon and Kronauer 1976, King 1986, Holbrook and Putz 1989, Niklas 1994). These models predict the minimum stem diameter required to prevent stem buckling. Stem buckling is an extreme case of instability that represents the absolute limits of tree allometry. Although stem-buckling models are interesting from a theoretical perspective, their exclusion of wind or snow loading make them poorly suited for applied uses.

3.2.2 ALLOMETRIC MEASURES OF TREE STABILITY USED IN THIS ANALYSIS

This analysis is an attempt to develop a relationship between plantation initiation and future stand stability. Use of H/D values and height has proved a useful measure in studies evaluating tree stability in windstorm events. The utility of H/D values and height as a wind hazard measure in empirical studies has been well supported by results from complex mechanistic models. In addition, most of the more complicated buckling, wind, and snow damage models require detailed stem and crown measurements that were not obtained in the long-term data sets being used in this study, nor are they commonly obtained in forest inventories. Consequently, complex models predicting wind and snow damage or stem buckling are impractical for use in this analysis.

There is no single H/D value that determines whether a tree will blow down. The speed of wind gusts or severity of an ice/snow storm determines what stability level is adequate for trees to weather a particular storm event. Consequently, a method for defining wind stability must be developed that is based on simple measures but does not assume a single stable H/D value.

3.2.2.1 Number of trees per hectare to evaluate for stand stability

Average rotation lengths for coastal Pacific Northwest plantations are about 60 years. There is tremendous variation around rotation length based on site index and forest ownership. A 60 year rotation on land with an average site index of 36 meters (50 year index age) produces crop trees that are about 39 meters tall at harvest. Tree height can be used as an approximate measure for the combination of age and site conditions (Oliver and Larson 1996). This measure is most realistic in trees with consistent height growth such as coastal Douglas-fir (Assmann 1970, Mitchell and Cameron 1985, Mitchell and Polsson 1988). Tree height can be used instead of age for many measures because two stands planted at the same spacing, one with a site index of 36 and the other 30, will be essentially identical in height, diameter, crown size and other measures important for stability when the first is 50 years old and the second is 70. The substitution of height for

age and site index is suitable for many tree and stand measures (Oliver and Larson 1996) and makes the specification of rotation length easier.

Douglas-fir density management diagrams are one method of determining the theoretical maximum number of trees that could be planted on land with a particular site index and harvested at a particular height without natural mortality or silvicultural thinning. (Drew and Flewelling 1979, Farnden 1996). Density management diagrams are based on extensive growth and mortality data from regions where they are developed. In the diagrams, 250 trees per hectare (tph) will pass into the “zone of imminent competition” at 39 meters. A harvest height of 39 meters (60 years of age on site 36 land) means there should be at least 250 crop tph to use all available growing space. Evaluating H/D values for the largest 250 tph provides an estimate of crop tree stability for an average Pacific Northwest rotation.

Generating mean height and H/D values for all trees in a stand allows these measures to be strongly influenced by suppressed and intermediate trees that are sheltered by more vigorous trees, making them poor predictors of total stand stability. In addition, the largest trees tend to have the highest timber, aesthetic, and habitat values, making their stability the critical factor. It is rare for smaller trees to overtake larger trees in DBH or height (crossover) (Oliver and Murray 1983, Nilsson and Albrektson 1994). In the absence of “crossovers,” the largest trees in a young stand will retain dominance and be the crop trees at harvest age (Cremer et al., 1982). Growth of co-dominant and dominant Douglas-fir trees is most responsive to thinning, making it logical to retain the largest trees during partial harvests (Oliver and Murray 1983, O’Hara 1988). Stable and rapidly growing trees are particularly important for shelterwood harvests or heavy thinnings designed to promote the formation of vertical stratification in the canopy or large diameter trees. In these cases, stability of leave trees is critical because trees are left with few neighbors to help buffer the wind and may be retained for long periods. Several other

studies have concentrated analysis on the largest 100-250 tph (Reukema 1970, Reukema 1979, Cremer et al. 1982, Slodicak 1995).

3.3 Methods

Data from repeatedly measured experimental plots were used to develop a stand stability model for plantations. The data was compiled from portions of three large studies in the Pacific Northwest. Data sets were combined to increase sample size and to attempt to cover a wide range of initial Douglas-fir densities and stand ages. Table 5 provides a list of the studies used, and details about individual plots are shown in Appendix A. Plots were selected from Vancouver Island, British Columbia, and from areas west of the Cascade crest in Washington and Oregon.

Table 5: Plantation plots from studies used in this analysis.

Study	Agency/reference	Locations	Plots
Experimental plot 703 (EP703)	BC Ministry of Forests (Stone 1994, Zens in prep)	Vancouver Island, BC	60
Levels of Growing Stock (LOGS)	USFS-PNW (Curtis and Marshall 1986, Curtis et al. 1997)	Oregon and Washington	3
Stand Management Cooperative (SMC)	Stand Management Cooperative (Collier and Haukaas 1996)	Oregon and Washington	18
Misc.	(Data collected during development of this thesis Appendix A)	Washington	1

Data selected for the study included control and some thinned plots (Ep703 only) dominated by Douglas-fir. Western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and western red cedar (*Thuja plicata* D. Don ex Lambert) are the only other species with substantial representation in any of the plots. The range in 50-year site indices is 24 - 43. Plots range from .05 to .20 ha in size depending on the study. Diameters of all trees in every plot were measured. Heights were only measured on a subset of trees in most plots.

Plot ages range between 8 - 54 years and cover a wide range of soil attributes, slopes, aspects, and elevations (< 1,000 m).

A direct measure of stand stability, average H/D of the largest 250 trees per hectare, was calculated for each stand. The experimental plots in this analysis range in size from 0.05 to 0.20 hectares. The largest 250 trees per hectare are determined by per hectare expansion factors for plot trees. Height was not measured for every tree in the experimental plots. Average of measured heights from the largest 250 Douglas-fir trees was used for height and to calculate H/D_{L250} . Measurement periods for individual plots were excluded from the analysis when less than 20% of the largest trees had been measured for height. Factors potentially influencing H/D values included size variation, height, thinning, initial densities of Douglas-fir, western hemlock, and western red cedar, plot size, and site index. These were evaluated for this study using graphical analysis and linear regression.

Using repeatedly measured plots in this analysis brings the issue of repeated measures into the statistical analysis. Measuring the same experimental unit (plot in this case) repeatedly through time violates the assumption of independent errors that is central to traditional statistical analysis (Crowder and Hand 1990, Bence 1995, Vonesh and Chinchilli 1997). This type of violation can lead to substantial underestimates of parameter estimate errors (Bence 1995). There are a variety of techniques used to address repeat measures in univariate, multivariate, and regression analyses (Crowder and Hand 1990, Moser et al. 1990, Vonesh and Chinchilli 1997). Another appropriate analysis for repeat measure studies has been to examine response curves using two-stage analysis (Meredith and Stehman 1991, Weiner 1995). All of these approaches become impossible or difficult with substantial losses of power when starting time or time increments are unequal between experimental units (Meredith and Stehman 1991, Vonesh and Chinchilli 1997). The piecemeal data set used in this analysis does not have similar starting times (height as surrogate for age) or equal time increments between measurements; therefore,

only one measurement period from each plot is used in the linear regression analysis. A best subset approach was approximated by selecting measurement periods for each plot with the greatest number of measured tree heights. In some cases, measurement periods with the second or third most heights measured were chosen to provide a wide range of stand heights for the analysis.

Results from the H/D_{L250} relationship being developed in this analysis were compared graphically with projections from the Stand Management Cooperative (SMC) and Southwest Oregon (SWO) variants of ORGANON (Hester et al. 1989) and the Pacific Northwest variant of the Forest Vegetation Simulator (FVS-PN [Donnelly 1996, Teck et al. 1996]). All three models are individual-tree, distance-independent growth models developed for the region. The growth model projections are made for a representative plantation at a variety of initial Douglas-fir densities. Model predictions are also compared to H/D_{L250} values obtained in the Wind River (Reukema 1970, 1979) and Haney, B.C. (Reukema and Smith 1987) Douglas-fir spacing trials.

3.4 RESULTS

3.4.1 HEIGHT DIAMETER RATIO TRENDS FOR UNTHINNED PLANTATIONS

A backward stepwise linear regression procedure (StatSoft, Inc. 1997) was used to develop an equation predicting $(H-bh)/D_{L250}$ values for unthinned plantations using data from control plots. Correcting height for breast height dbh measurements produces a more linear relationship between height and H/D (See Chapter 2 for details). Independent variables evaluated included: deviations from average stand height - bh (mht), mht^2 , deviations from average Gini coefficient (mgini), $mgini^2$, initial densities of each species (e.g., iddf-Douglas-fir), site index, plot size, and interaction terms between mht and both Gini coefficients and initial densities. Height and the Gini coefficient were evaluated in terms of deviation from the average in order to reduce multicollinearity with polynomial

and interaction term coefficients (Neter et al. 1989). All variables except iddf and mht were removed from the model (Table 6). Residual analysis showed no consistent or substantial departures from normality.

Table 6: Regression coefficients, standard errors, and p-values of a model predicting values for $(H-bh)/D_{L250}$ values for unthinned plantations. (adj. r -squared = .771, $n=62$, $p<.00000$, standard error of estimate=5.2370)

	B	Standard error B	p-value
intercept	63.72588	1.808932	.000000
Iddf	.00715	.000877	.000000
Mht (ht-bh-19.07)	1.20446	.104018	.000000

The family of curves produced by the $(H-bh)/D_{L250}$ relationship (Table 6) developed for unthinned plantations are shown in Figure 15. $(H-bh)/D_{L250}$ values are multiplied by $H/(H-bh)$ to convert them to H/D_{L250} . This conversion generates the complex behavior of the curves below 10 meters in height.

Using height to predict H/D may appear inappropriate. Even if there were no relationship between H and D , a strong correlation between H and H/D would be expected; however, there is a clear understanding of how H/D_{L250} impacts tree stability, making it a useful measure of stability to model. Fortunately, when there is a ratio between two numbers, the value of the ratio does not automatically increase when the numerator increases (Chapter 2). This result is true even when there is a positive relationship between the two variables. In the data used for this analysis H_{L250} is highly correlated and has a positive linear relationship with dbh_{L250} (Figure 16). Cremer et al. (1982) found H/D values for open grown Monterey pine remained constant over a height range of 10 – 30 meters. H_{L250} and the dimensionless ratio H/D_{L250} are not related simply because H_{L250} is present in both variables; therefore, H/D_{L250} and H_{L250} can be considered functionally independent.

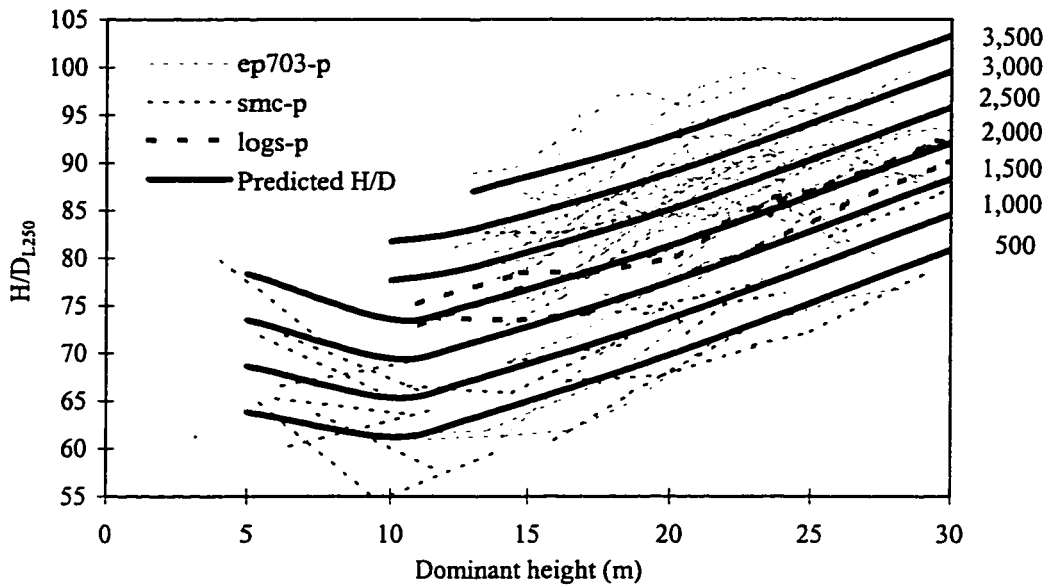


Figure 15: Predicted H/D_{L250} vs dominant height of unthinned plantations ($(h-bh)/d=63.72588+1.20446*(ht-bh-19.06629)+.00715*(iddf)$, adj. $r^2=.771$, $p < .0000$) Line labels (numbers on far right) correspond to initial Douglas-fir density. Broken lines correspond to H/D trends for individual plots.

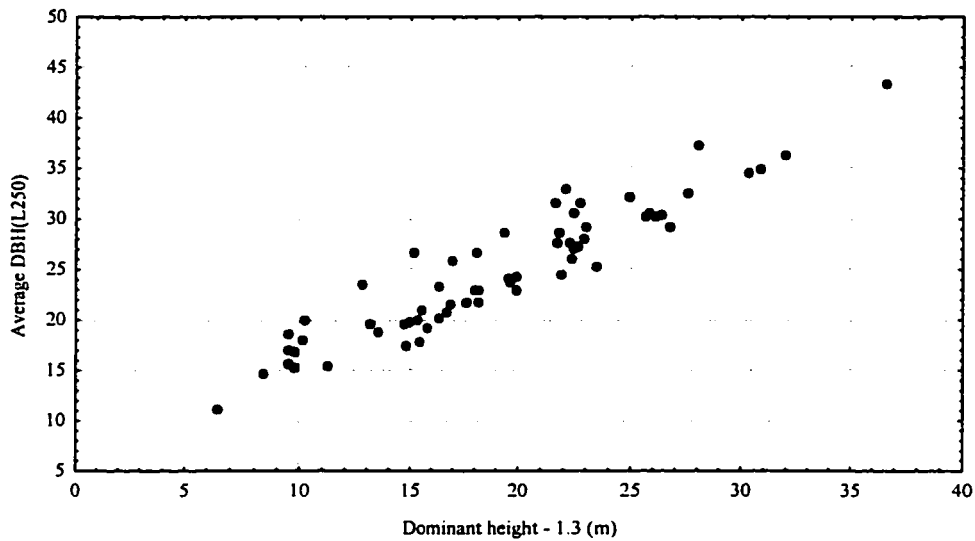


Figure 16: Relationship between adjusted dominant height ($ht-bh$) and average dbh of the largest 250 Douglas-firs per hectare.

3.4.2 IMPACTS OF THINNING ON PLANTATION H/D_{L250} TRENDS

A second $(H-bh)/D_{L250}$ predictive equation was developed using a combination of unthinned (i.e., control plots) and thinned stand data from the EP703. A backward stepwise linear regression procedure (StatSoft, Inc. 1997) was used to develop a predictive relationship for H/D_{L250} values. Independent variables evaluated included: deviations from average stand height-bh (mht), mht^2 , deviations from average Gini coefficient (mgini), $mgini^2$, initial densities of each species (e.g., iddf-Douglas-fir), a thinning code (thinc = 0, 20, 35, or 50 [percent basal area removed from below]), plot size, site index, and interaction terms between mht and mgini, initial densities, and thinc. Height and the Gini coefficient were evaluated in terms of deviation from the average to reduce multicollinearity with polynomial and interaction term coefficients (Neter et al. 1989). All variables except iddf, mht, and thinc were removed from the model (Table 7). Residual analysis showed no consistent or substantial departures from normality.

Table 7: Regression coefficients, standard errors, and p-values of a model predicting values for adjusted H/D_{L250} values for thinned and unthinned plantations. (adj. r-squared = .738, n=90, $p < .00000$, standard error of estimate=5.3761)

	B	Standard error B	p-value
Intercept	61.33741	1.646650	.000000
Iddf	.00750	.000803	.000000
Mht (ht-19.34)	1.15262	.091230	.000000
Thinc (0, 20, 35, 50)	-.10961	.035353	.003430

The family of curves predicted by the thinned $(H-bh)/D_{L250}$ relationship at different initial densities of Douglas-fir is shown Figure 17. Stands were thinned at an average stand height of 15 meters. Predicted $(H-bh)/D_{L250}$ values are again multiplied by $H/(H-bh)$ to convert them to H/D_{L250} . The broken lines in the diagram represent predictions for H/D_{L250} .

trends when 20 % of the stands basal area has been removed in thinnings. The two lowest thinned H/D_{L250} trend lines have been excluded because none of the thinned plot data had initial densities of Douglas-fir below 1,500 tph.

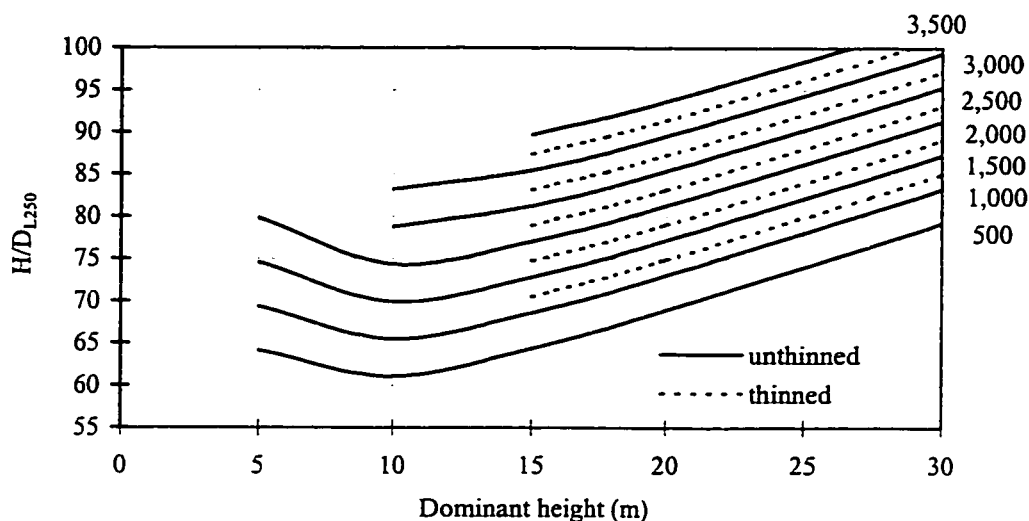


Figure 17: Predicted H/D_{L250} vs dominant height of thinned (20% ba at an average of 15 meters in height) and unthinned plantations ($h/d=61.01636+1.15625*(ht-bh-18.99)+.00750*(iddf)-.10961*(thinc)$, adj. $r^2=.74$, $p < .0000$) Line labels correspond to initial Douglas-fir density for thinned (below) and unthinned (above) plantations.

3.4.3 COMPARING H/D_{L250} PREDICTIONS WITH GROWTH MODEL PROJECTIONS AND SPACING TRIAL RESULTS

Predictions made with the unthinned H/D_{L250} equations are compared to FVS-PN growth model projections in Figure 18a, ORGANON-SWO variant in Figure 18b, and ORGANON-SMC in Figure 18c. H/D_{L250} values derived from FVS-PN projections are considerably lower (beyond 15 meters of height) than the predictive equation developed in this analysis. In contrast, projections from both variants of ORGANON tend to be considerably higher (beyond 15 meters of height). H/D_{L250} values derived from the SMC variant predictions are higher than SWO. Heights, diameter, and mortality projections

were compared between the growth models to evaluate where they diverged. Height projection differences between the models were inconsistent and small (less than a meter) up to 30 meters in height; however, diameter and mortality projections were consistently higher from FVS-PN compared to ORGANON-SMC or SWO.

An additional evaluation of the H/D_{L250} relationship is presented in Figure 19. Predicted H/D_{L250} values are compared with results from the Wind River (Reukema 1970, 1979) and Haney, B.C. (Reukema and Smith 1987) Douglas-fir spacing trials. Deviations of spacing trial results from the predicted curves for H/D_{L250} are not consistently negative or positive. Trends or points for most spacing trial densities fall remarkably close to the predicted curves for equivalent initial densities. The very high-density spacing trials (6,725 tph from Wind River and 12,350 tph from Haney) appear to have H/D_{L250} values well below the trends developed for lower densities. Unfortunately, there were no plantations in the combined data sets with Douglas-fir densities in this range.

3.5 DISCUSSION

A simple relationship developed with initial density of Douglas-fir and dominant height explains a substantial proportion of the variation in H/D_{L250} values (Table 6 and Figure 15). H/D_{L250} values fall to a low in the first 10 meters as an artifact of measuring diameter at breast height. Breast height represents a larger proportion of overall height in shorter trees. From a mechanistic perspective $(H-bh)/D$ is a more accurate description of tree stability. The variable D_x in Equation 7 is equivalent to the distance from the top of a tree to where diameter has been measured (i.e., $H-bh$). The use of H/D rather than $(H-bh)/D$ results in increasing overestimates of instability for shorter trees. The unadjusted H/D measure dominates the wind and snow stability literature. For ease of comparison $(H-bh)/D$ values have been converted to H/D for most presentations in this and subsequent chapters.

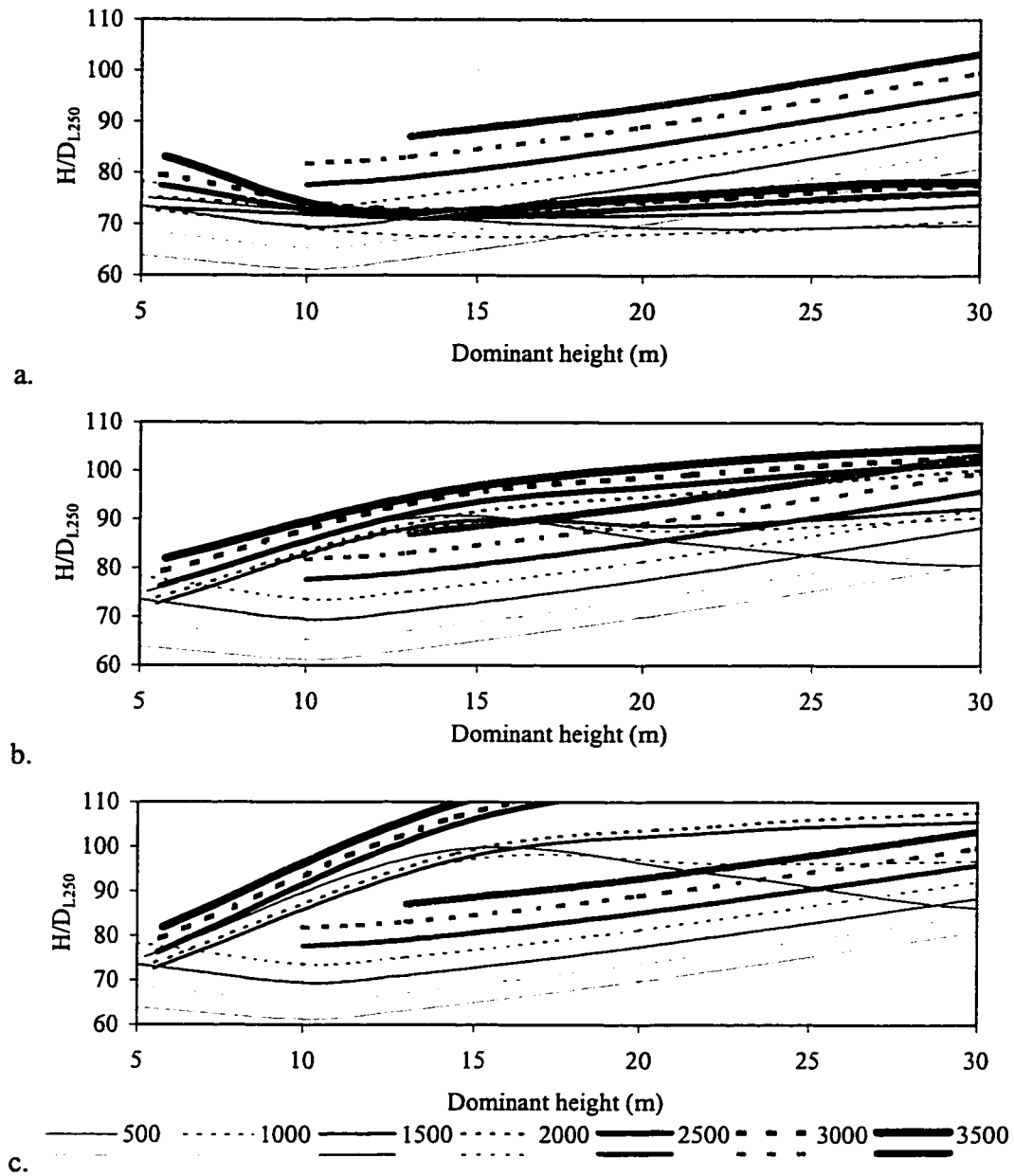


Figure 18: Comparison of predicted H/D_{L250} values (gray lines) to results from (a) FVS-PN variant, (b) ORGANON-SWO variant and (c) ORGANON-SMC variant (black lines). Legend specifies initial Douglas-fir density (trees/hectare).

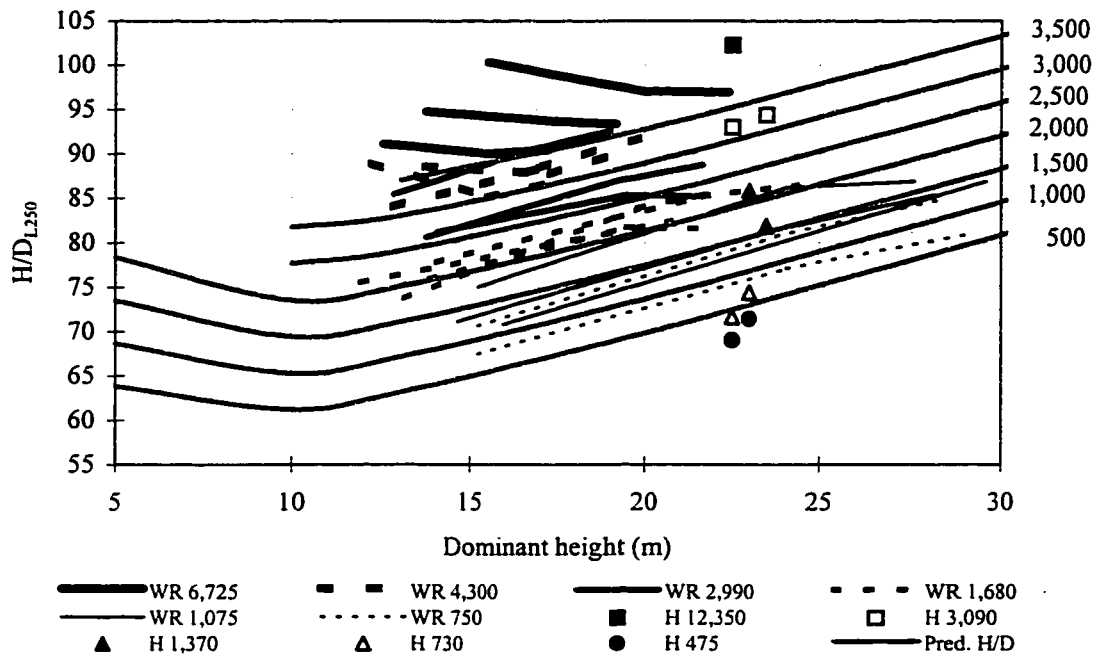


Figure 19: Comparison of predicted H/D_{L250} for plantations and results from the Wind River (WR) and Haney, B.C. (H) spacing trials. Initial Douglas-fir densities (tph) in the spacing trials are numbers to the right in the legend. Grayed trend lines display predicted H/D_{L250} at initial densities specified by line labels. (Data for Wind River (Reukema 1970, 1979), Haney, B.C. (Reukema and Smith 1987)).

Beyond stand heights of approximately 10 meters, H/D_{L250} values consistently and dramatically increase at all initial Douglas-fir densities. This finding closely matches H/D_{L250} trends found in Australian (Cremer et al. 1982) and French (Bequey and Riou-Nivert 1987) studies and provides more evidence to support the theoretical explanation of this phenomena detailed in Figure 14. Plantations in the data sets were not tall enough to have expressed the leveling and eventual decline in H/D_{L250} values beyond 25-30 meters predicted in Figure 14 and found with natural stands in Chapter 2 as well as in the Australian and French plantation studies.

The strong upward trend in H/D_{L250} values within the 10 to 30 meter height range has important implications for the effectiveness of late thinnings to promote stand stability. A

second H/D_{L250} relationship includes stands thinned by a proportion of basal area when stand heights ranged from 12 and 15 meters. Thinning stands in this height range lowers future H/D_{L250} values slightly (2 point declines for 20 % basal area removal); however, the strong upward trend in values is not curtailed (Figure 17). Even the most dominant trees in stands will have rising H/D values between heights of 10 and 30 meters (Figure 20). Once a stand has passed approximately 10 meters in height, thinning may help to keep H/D_{L250} values from getting quite as high; however, the general upward trend will continue until the stand height reaches 25 to 30 meters.

The 10-meter cutoff is approximate and this value declines substantially as initial density increases, reflecting timing of crown closure and onset of intense competition. Figure 21 shows early H/D trends from a Douglas-fir spacing trial in Haney, B.C. that employed a Nelder plot design (Smith 1983, Reukema and Smith 1987). This magnified evaluation of early H/D trends provides details missed with the coarse data used in this analysis. The higher the initial Douglas-fir density, the more unstable the resulting stand and the more restricted the “thinning window” for improving the situation. Thinning windows describe restricted periods during which thinning can effectively improve future stand stability. Trees less than 10 meters tall are in a critical stage of growth with strong implications for future stability.

There is an early and dramatic divergence of H/D values for trees growing in different competitive environments (Figure 21). In order to emerge from this stage of growth with moderately stable H/D values (e.g., < 80), in anticipation of rising values in all stands between 10 and 30 meters, thinning windows become quite restrictive at higher densities. According to this criteria approximate thinning window cutoffs are 11 meters for initial Douglas-densities of 1,000 tph, 7 meters for initial densities of 2,000 tph, and < 5 meters for stands with initial densities $> 3,000$ tph. These windows are likely to be somewhat conservative because the Nelder plot data H/D values are calculated for all trees in the distribution, not just the dominants.

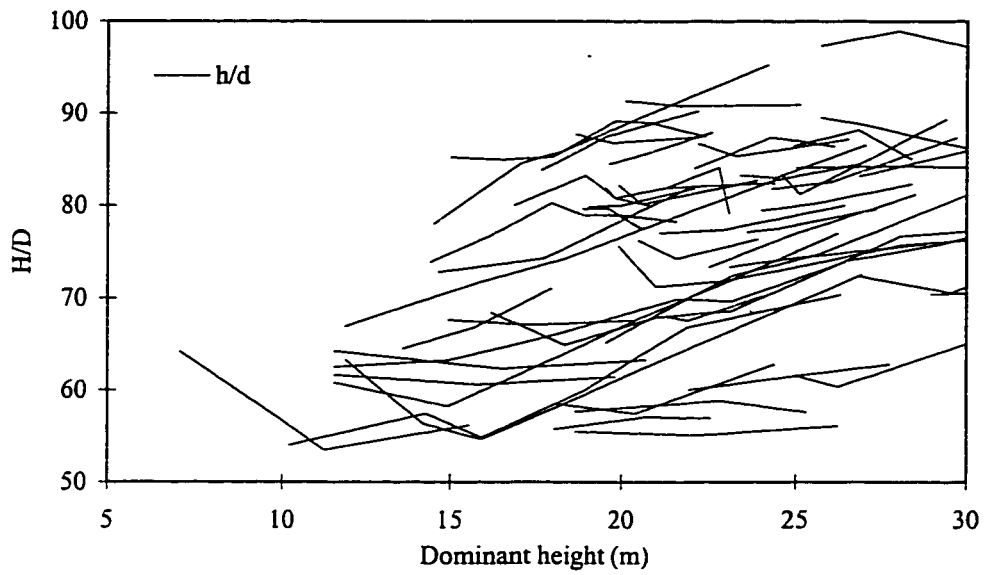


Figure 20: H/D trends for the 2 largest (dbh) individual trees per plot when they had heights measured over several periods.

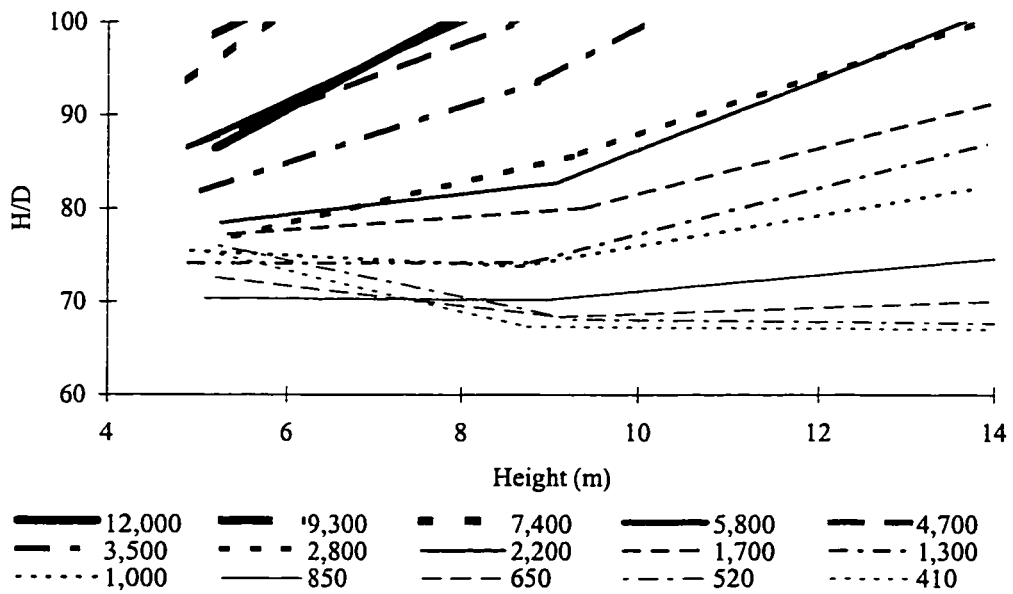


Figure 21: Early H/D trends from Haney, B.C. nelder plot data. Numbers to the right of legend lines represent initial Douglas-fir density (tph) in particular arcs. (Data from Smith 1983, Reukema and Smith 1987).

The relationships developed in this analysis suggest thinning stands that already have high H/D_{L250} values provide minimal future stability benefits. Conversely, thinning stands with high H/D_{L250} values may cause more damage by reducing dampening from neighbors in the stand and exposing leave trees to greater wind loads and turbulence (A discussion of thinning impacts on wind damage susceptibility is given in Chapter 4). Thinning Douglas-fir stands between 10 and 30 meters tall cannot lower H/D_{L250} levels; it can only reduce the rate of increase. This means H/D_{L250} values can only be effectively controlled by adjusting initial planting densities or through very early thinnings.

The H/D_{L250} statistic is remarkably sensitive to small changes in either height or diameter. In addition, it only evaluates the top portion of a tree distribution, the largest 250 tph. These characteristics make H/D_{L250} values an illuminating test of growth model performance. The equation developed in this analysis provided predictions lying between FVS-PN and ORGANON-SWO/SMC results. FVS-PN predicted consistently higher mortality and diameter growth than ORGANON-SMC or SWO. High mortality rates may result from using highly differentiated naturally regenerated stand data for model development rather than plantation data. The rapid diameter growth predicted by FVS-PN resulted in substantially lower H/D_{L250} values than from ORGANON-SWO and SMC variants. The growth models used in this analysis utilize a distance independent “tree list” approach (Vanclay 1994). The tree list approach may be more useful for predicting future stand-average values (e.g., quadratic mean diameter or volume per area) rather than a statistic measuring a portion of the distribution (e.g., H/D_{L250}). Users should critically evaluate growth model predictions of partial distribution statistics, such as H/D_{L250} , before they are employed.

Comparisons of H/D_{L250} predictions to Douglas-fir spacing trial results suggest the trends generated by the equation are quite reasonable for the range of development data. Plots with extremely high initial Douglas-fir densities (i.e., > 6,000 tph) have much lower H/D_{L250} values than might be expected from the trends for lower densities. These very

high-density spacing trials may have become so stagnant that height growth was substantially reduced. The heightened experimental control in spacing trials (e.g., planting on a rigid grid) might tend to reduce tree size variation below that typically found in plantations. Reduced differentiation in these plots could be expected to raise H/D_{L250} values above those normally found at specific densities; however, the comparison with predictions showed no clear trend in this direction.

3.6 CONCLUSION

Early Douglas-fir density in plantations is critical to future stability in the stand. Stands planted at high densities develop high H/D_{L250} values. In addition, high-density stands have a limited stand height window during which thinning can be used to improve future stand stability substantially. A stand planted at lower densities can be managed more flexibly because thinnings are not required to maintain stand stability. Thinnings can be optionally incorporated at any time during the rotation if specific timber markets are good or a certain stand structure is desired. If wider spacings raise weed competition or wood quality concerns (e.g., large branches, juvenile wood core, and low percentage latewood) species such as western hemlock and western red cedar, that appear to have a minimal impact on future dominant Douglas-fir stability, can be interplanted with Douglas-firs to augment overall stand density. Stands planted above 1,000 tph require thinning or thinnings to keep H/D_{L250} values in a moderate range (< 85) before they reach heights of 30 meters. Increasing planting densities to 2,000 tph and above reduces management flexibility further by restricting the time period during which thinning is effective.

In this analysis, height has been used as a surrogate for time, making comparisons possible across data from many sources without accurate age information. Site quality will interact with management flexibility by reducing or expanding the translation from height to time. The more productive the site, the more time restricted thinning windows become. More restrictive thinning windows for improving future stand stability reduce

management flexibility further. A “density effect,” where early height and diameter growth is increased in trees growing under higher densities, has been reported in Douglas-fir plantations (Ritchie 1997, Scott et al. 1988). This ephemeral growth increase mimics a site quality boost and should further restrict thinning windows in dense plantations.

There is no one H/D_{L250} value that guarantees stand stability; rather, increasingly severe storms will damage increasingly more stable stands. The goal for forest managers and landowners should be to strike a balance between developing greater stand stability and the myriad of other objectives that have been identified for a forest.

CHAPTER 4: DEVELOPING A RATING SYSTEM FOR LANDSCAPE-SCALE WIND RISK

An equation predicting height to diameter ratios for dominant plantation trees was developed and evaluated in Chapter 3. This chapter scales up from stability measures for trees and stands to evaluate landscape wind risk. A landscape wind risk ranking system is developed and used to evaluate the potential for reducing future wind risk through adjusting harvest schedules and modifying stand conditions.

4.1 INTRODUCTION

Wind damage is an important consideration in forest management throughout the world, including the coastal Pacific Northwest. Wind damage can occur as catastrophic stand-destroying events or chronic tree and stand damage. Hurricane force storms hit the coasts of Oregon and Washington on a twenty-year frequency. A single powerful storm in 1962 blew down an estimated 38 million cubic meters of timber in western Oregon and Washington (Wiley 1965, Lynette and Cramer 1966, Henderson et al. 1989). A recent survey of wind damage in British Columbia found that endemic wind damage averaged 2 million cubic meters of timber each year (Mitchell 1995a). Damage may represent a monetary loss, a salvage and coordination nightmare, or loss of important habitat. To evaluate and reduce current and future wind risk for landscapes, a generalized rating system is developed in this chapter from the literature. The system uses spatial information as well as current and projected inventories to evaluate landscape wind risk. Ratings for individual stands are developed from soil, topographic exposure, and stand conditions. This chapter reviews the wind damage literature and describes the wind risk rating system. Variation in topographic exposure models is evaluated and discussed. A case study landscape is used to explore the potential for reducing landscape wind risk

ratings through adjustments to timing and placement of harvesting operations and by modification of future stand characteristics.

4.2 BACKGROUND

4.2.1 WIND RISK MODELING

A variety of wind risk classification systems have been developed. These classification systems have followed two general trends: 1) Mapping climatic, soil, and topographic conditions to delimit areas at different levels of wind risk (Kennedy 1974, Quine 1995, Quine et al. 1995, Tang et al. 1997); and 2) Evaluating which site, stand, and tree characteristics are correlated with windthrow and windsnap after a substantial windthrow event or events (Kennedy 1974, Cremer et al 1977, Cremer et al. 1982, Becquey and Riou-Nivert 1987, Carter 1988, Lohmander and Helles 1987). Most of the risk mapping projects do not differentiate risk between stands with different characteristics. Analysis of tree and stand damage after major storm events provides useful insights, but the analysis of risk is scaled to specific wind characteristics (speed and behavior).

The most generally applicable of the wind risk models is the British Windthrow Hazard Classification (Savill 1983, Mason and Quine 1995, Quine et al. 1995), a system that assesses both where and when (during a rotation) windthrow is likely to occur (Quine 1995). The classification includes climatic and soil conditions as well as stand height and thinning history in the analysis of wind hazard (Quine et al. 1995). The analysis does not include some stand attributes, such as the height to diameter ratio (H/D), that are known to impact wind susceptibility. As a result the British Windthrow Hazard Classification output stresses progressively shorter rotations (to limit stand height) and reduced thinnings (to ensure canopy closure) as the site risk (i.e. climate, soils, topography) increases (Quine 1995, Mason and Quine 1995, Quine et al. 1995).

Quine (1995) suggested that the British Windthrow Hazard Classification evaluates the risk of stands to “endemic” rather than “catastrophic” wind events. In catastrophic events, the importance of site characteristics diminishes because extreme windspeed overwhelms any mitigating factors. This evaluation is applicable to soils, but topography will protect certain stands even under extreme conditions. Models that include topographical attributes of the landscape can be useful no matter what the windspeed. Increasingly severe wind events can be expected to damage an increasing number of moderate and, finally, even low risk stands.

Literature reporting wind damage in forests identifies four factors that appear highly correlated with the occurrence of wind damage. These factors are climate, soils, topography, and stand conditions (see Savill 1983, Bouchon 1987, Mitchell 1995b, Ruel 1995, and Everham and Brokaw 1996, Tang et al. 1997 for reviews)

4.2.1.1 Climate

Wind damage can occur in a catastrophic storm or endemically with small windthrow pockets growing slowly through time as new edges are exposed (Savill 1983, Miller et al. 1987, Greene et al. 1992). Although spectacular, infrequent catastrophic events may cause less damage within a region during a typical rotation than endemic damage (Rollinson 1987). Areas where strong winds are common may be less subject to catastrophic damage because of preconditioning of stands to wind. Similarly, storm winds not from the prevailing wind direction may cause increased damage (Ruel 1995, Kenworthy 1998). Storm winds that are preceded by heavy precipitation often result in greater amounts of wind damage (Cremer et al. 1977, Versfeld 1980, Ruel 1995). This association is attributed to reduced shear strength in waterlogged soils (Day 1950, Busby 1965).

4.2.1.2 Soils

The relationship between soil conditions and wind risk is straightforward and consistent in the literature. Soil conditions that restrict rooting depth/growth (e.g. hardpans, bedrock, water-table) or decrease soil shear strength (e.g. waterlogging) are more prone to wind damage (Day 1950, Ruth and Yoder 1953, Andersen 1954, Busby 1965, Fraser and Gardiner 1967, Neustein 1971, Bouchon 1987, Mitchell 1995b). In a review of 119 papers characterizing forest damage after windstorm events, Everham and Brokaw (1996) found consistent relationships reported between soil characteristics and wind damage. In papers that described damage by soil attributes, damage was: negatively related with soil depth in 13 of 15 papers; positively related to soil moisture in 18 of 19 papers; positively related to existence of a hardpan in 9 of 9 papers; and negatively related to root growth in 16 of 16 papers (Everham and Brokaw 1996).

Rebertus et al. (1997) conducted a landscape blowdown reconstruction for an area in the Andes of Tierra del Fuego. They found blowdown return intervals were more frequent in areas with deeper soils. This finding appears counter to most others; however, deeper soils mean better sites and faster tree height growth, so stands may become susceptible to windthrow more rapidly on these sites (Quine 1995, Rebertus et al. 1997).

The Windthrow Hazard Classification model developed for Great Britain rates soils by rooting depth. Soils receive low scores if rooting depth exceeds 45 cm and high scores if rooting is restricted to a depth of less than 25 cm (Miller 1985).

4.2.1.3 Topography

In contrast to soils, the relationship between topography and wind risk appears more complicated and is considerably less consistent. The effects of topography on wind risk may be confounded by biotic and soil interactions with slope position (Everham and Brokaw 1996).

In their review, Everham and Brokaw (1996) report a generally positive relationship between wind damage and forest stands on ridges, in parallel valleys, and on exposed slopes. Eighteen papers reviewed detail a lee slope relationship with wind damage. Of these, Everham and Brokaw (1996) report that 12 find a positive relationship while 6 find a negative one. In a subsequent review of these 18 papers for this analysis, 5 positive relationships reported by Everham and Brokaw (1996) are not supported by findings in the cited papers. Lee slope damage may reflect increased turbulence when winds flow over ridges or preconditioning of trees on the windward slopes to strong winds (Ruel 1995, Everham and Brokaw 1996)

Three papers provide a clear demonstration of inconsistent relationships between topography and wind damage. All three studies were done in moderately mountainous terrain, and all collected information through aerial surveys. Cremer et al. (1977) reviewing damage from a windthrow event near Canberra, Australia found that topographic features were unimportant with damage found on both lee and windward slopes. The authors believed more damage was found in valleys than on ridgetops because of differences in the stand and soil conditions rather than the topography (Cremer et al. 1977). Neustein (1971) analyzed wind damage to Scottish forests after a gale and found damage primarily influenced by topography. Most damage was restricted to windward and perpendicular slopes, ridges, and topographic funnels. Lee slopes were rarely impacted by the storm (Neustein 1971). Ruth and Yoder (1953) evaluated storm damage over several years in the Oregon Coast Range. They found that damage was primarily located on ridges and lee slopes. The authors report that damaging winds were from the southwest in all cases.

A further complication to understanding the impacts of topography on wind damage is multiple storms with different wind directions. Rebertus et al. (1997) found blowdown in the Andes of Tierra Del Fuego was concentrated in parallel valleys, windward slopes, and upper leeward slopes; however, individual storm directions changed enough that few

portions of the landscape were not impacted by wind. In 1997 a windstorm leveled 20,000 acres of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) in the Rocky Mountains. Winds came from the east rather than the prevailing westerly direction (Kenworthy 1998)

There have been several topographic wind risk models developed. The models reflect the inconsistencies found in the literature. The Topographic Exposure model (TOPEX) was developed for use with the Windthrow Hazard Classification system. Angles to the visible skyline at the eight major compass points are summed. TOPEX scores below 31 are exposed while those above 100 are sheltered (Miller 1985, Miller et al. 1987, Ruel 1995). A Topex-to-distance model has been proposed to differentiate between hilltops and flat areas and to discount sheltering topography that is far removed (Hannah et al. 1995). Ruel et al. (1997) compared output from two airflow behavior models and TOPEX-to-distance to results from a wind tunnel study. TOPEX-to-distance provided satisfactory estimates of wind exposure (Ruel et al. 1997).

The TOPEX model reflects general exposure related to surrounding topography but does not take account of valley funneling effects or prevailing wind direction. A revised Windthrow Hazard Classification has been developed to account for both an aspect and a funneling effect (Quine and White 1993). The aspect effect is calculated by multiplying each sector angle by a constant reflecting prevailing wind. Fitting a regression to flag tatter data generated the constants. The sum of converted sectors is divided by 1,000. The funneling effect (Equation 11) compares sector scores for adjacent sectors based on prevailing wind directions (Quine and White 1993). Aspect and funnel effect values are summed. Values in Great Britain have ranged between -0.3 and 6.3 (Quine and White 1993).

$$\text{funnelingeffect} = 0.1074 * \sqrt{(N - E + S - W)^2 + (NE - SE + SW - NW)^2} \quad (11)$$

where: N, E, etc. are angles to the visible skyline for the eight compass points (Quine and White 1993).

Mitchell (1995b) proposed a topographic exposure model based on prevailing wind direction and topographic forms. Areas are judged low, moderate, or high risk. Low risk areas are valley bottoms not parallel to prevailing wind and lee mid slopes. Moderate risk areas include valley bottoms parallel to prevailing winds, windward mid slopes and lee upper slopes. Mid and upper slopes parallel to prevailing wind, windward upper slopes and ridges fall into the high risk category (Mitchell 1995b).

Summarizing damage from a 1968 Scottish windstorm, Neustein (1971) developed a low, moderate, and high topographic risk model. Low ratings are assigned to very steep windward slopes and all lee slopes. Windward and perpendicular slopes as well as ridgetops are assigned moderate rankings. High-risk areas are funnel features parallel to prevailing winds and windward upper slopes (Neustein 1971).

Tang et al. (1997) developed a wind damage potential ranking for a watershed on the Olympic Peninsula of Washington that includes rankings for topographic exposure, soil drainage, and a combination of primary species and soil drainage. The topographic exposure factors included in the rankings were aspect, elevation, and slope. Potential damage rankings based on topographic exposure were highest on steep windward slopes at higher elevations (Tang et al. 1997).

In an evaluation of damage from the 1938 New England hurricane, Foster and Boose (1992) used an exposure model based on reported studies and empirical results. The exposure model ranks areas as exposed, intermediate, or protected. Protected areas are moderate to steep lee slopes (slope > 10°). Intermediate exposures are assigned to areas

with mild lee slopes ($5^\circ \leq \text{slope} \leq 10^\circ$) or perpendicular slopes ($\text{slope} \geq 5^\circ$). Level sites ($\text{slope} < 5^\circ$) and windward slopes are considered exposed.

Boose et al. (1994) produced a topographic exposure model (EXPOS) for a comparison of hurricane damage in tropical and temperate forests. EXPOS evaluates a landscape based on wind direction and a digital elevation model and rates areas as protected or exposed. Wind is assumed not to bend downwards more than a fixed inflection angle from horizontal as it passes over topographic features. Protected areas are those that fall in the wind shadow of upwind features. Increasing the fixed inflection angle decreases the proportion of the landscape that is protected. The authors found inflection angles between 5 and 10° provided good results (Boose et al. 1994).

The Foster and Boose (1992), EXPOS (Boose et al. 1994), and TOPEX (Miller 1985) exposure models rank flat areas or gentle slopes as risky. This finding is supported by Busby (1965), who suggests that regions with steeper sloped topography suffer less wind damage than flat or gently undulating topography. Neustein (1971) found a similar pattern with wind damage after a Scottish gale.

4.2.1.4 Stand conditions

The wind risk literature identifies seven stand attributes that have been associated with wind damage. These are: height to diameter ratio (H/D—both measurements in the same units), stand height, inter-tree spacing, species, prevalence of root and stem diseases, recent thinning, and recently exposed edges caused by harvest, burning, or other removals of adjacent stands (see Savill 1983 for review). As stand height and H/D values increase, trees become increasingly unstable (Petty and Worrell 1981, Cremer et al. 1982, Becquey and Riou-Nivert 1987, Laiho 1987, Lohmander and Helles 1987, Smith et al. 1987, Peltola and Kellomaki 1993, Nykanen et al. 1997; Chapter 3).

Spacing of trees in a stand has contradictory effects on susceptibility to wind damage. More widely spaced stands develop lower H/D ratios, making individual trees more

stable. Conversely, more closely spaced stands tend to have smoother canopies that allow less wind penetration and create less turbulence (Savill 1983, Blackburn and Petty 1988, Gardiner et al. 1997). The increased turbulence at wider spacing appears to be compensated by the reduced sway periods of lower H/D trees (Blackburn and Petty 1988).

There are differences between the impacts of wind on different species. Evergreen gymnosperms tend to be much more susceptible to windsnap and windthrow than deciduous angiosperms (Carter 1988, Foster 1988, Boucher et al. 1990, Putz and Sharitz 1991, Foster and Boose 1992, Peltola et al. 1997). The reduced susceptibility to windthrow found in deciduous trees may reflect the timing of windstorms relative to leaf-fall (Peltola et al. 1997). Putz and Sharitz (1991) found species common to better-drained sites but growing in sloughs were disproportionately damaged by Hurricane Hugo. The species common to better-drained sites could not develop adequate roots in the waterlogged soils or had become established on unstable sites such as fallen logs.

The wood of Monterey pine (*Pinus radiata* D. Don) and Norway spruce (*Picea abies* [L.] Karst.) has lower bending strength and stiffness than Douglas-fir; however, an Irish study by Kennedy (1974) found little difference between the percentage of Norway spruce and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) plots with wind damage. In that same study, Douglas-fir was found to have the shallowest average rooting depth of all plantation species evaluated (Kennedy 1974). Lohmander and Helles (1987) found spruces (*Picea abies* and *Picea sitchensis* [Bong.] Carr.) to be more windfirm than true firs (*Abies alba* and *Abies nordmanniana*) and Douglas-firs. Examining a drainage of the Olympic National Forest, Baker (1915) found more windthrow in western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and true firs (*Abies* sp.) than western red cedar (*Thuja plicata* D. Don ex Lambert) or Douglas-fir. Ruth and Yoder (1953) reported similar findings when evaluating windthrow in the Oregon Coast Range. They found Douglas-fir and Sitka spruce were less prone to wind damage than western hemlock. Conversely,

Wiley (1965) found damage equally distributed between Douglas-fir and western hemlock in a survey of Washington plots after a 1962 windstorm.

The presence of root and stem rots appears to increase the susceptibility of trees to windthrow and windsnap (Ruth and Yoder 1953, Matlack et al. 1993, Ruel 1995). Thomasius et al. (1991 [cited in Bouchon 1987]) suggested that for stability, mean H/D must be 70 when root or stem rots are present compared to 100 when trees are clear of infection. Wiley (1965) found 40% of mortality caused by a windstorm was in trees with root and stem rots. Wind damage that does not cause mortality leaves wounded trees that are at a high risk for developing root and/or stem rots in the future (Wiley 1965, Putz and Sharitz 1991, Nykanen et al. 1997). Zumrawi et al. (1995) found site association and stand origin (naturally regenerated or planted) to be the most important factors determining the presence and impact of root rot diseases. Root and stem rot diseases were more common and caused greater mortality in planted stands.

Stands that have been thinned recently are more susceptible to wind damage (Smith and Weitknecht 1915, Weidman 1920a and 1920b, Alexander 1964, Chandler 1968, Cremer et al. 1977, Cremer et al. 1982, Laiho 1987, Lohmander and Helles 1987, Carter 1988, Valinger and Lundquist 1992, Valinger et al. 1994, Milne 1995, Gardiner et al. 1997). Thinning exposes remaining trees to more wind and increases turbulence within a stand. Increased turbulence and less dampening of sway by neighboring trees may expose thinned stands to more dynamic wind loads (Blackburn and Petty 1988, Milne 1995). The heavier the thinning, the more susceptible a stand becomes. Thinnings that remove dominants and co-dominants leave stands more susceptible to wind damage (Ruth and Yoder 1953, Valinger et al. 1994). Increased wind risk associated with thinned stands declines after 2 years in some stands but persists for 10 years in others (Carter 1988). Cremer et al. (1977) found increased wind risk associated with stands that had been thinned in the last 5 years. Thinned stands are more susceptible to damage during 2-5 years immediately after a thinning (Savill 1983). The length of the stabilization time after

thinning will depend on tree growth and health (Ruel 1995). In wind tunnel experiments Gardiner et al. (1997) found the thinning pattern less important than the resulting stand density in determining wind loads on residual trees; however, the creation of moderate gaps (gap diameter > 1 tree ht) increased wind load on exposed trees dramatically (Gardiner et al. 1997).

Harvesting an adjacent upwind stand creates an edge exposed to the full force of the wind and increases a stand's susceptibility to wind damage (Alexander 1964, Alexander 1967, Cremer et al. 1977, Lohmander and Hells 1987, Peltola and Kellomaki 1993). Heightened risk associated with the creation of edges diminishes with time as the edge trees become acclimated to the new wind conditions (Ruel 1995). The smaller the clearcut opening, the greater the proportions of edge to interior forest (Ruel 1995, Tang et al. 1997). Buffer strips between adjacent clearcuts and in riparian areas increases the amount of exposed edge (Moore 1977 cited in Ruel 1995).

4.3 METHODS

4.3.1 RATING STAND AND LANDSCAPE WIND RISK

A wind risk model is designed and calibrated in this chapter based on information from the wind risk literature. Mitchell (1995b) proposed a relatively simple method for combining site and stand risk ratings into a wind risk rating system. Soil conditions and exposure determine site risk. This rating is then evaluated in combination with stand characteristics to provide an overall wind risk rating. Mitchell (1995b) suggested that a moderate rating in one factor, matched with a low rating in another factor, generated a moderate rating for the matrix. These rating rules produce very few stands (none in tests) with a low ranking. The modified risk rating system used in the development of the model is shown in Figure 22.

The wind risk model was developed in Microsoft Access, a database management program, using output from the Landscape Management System (LMS; McCarter et al. 1996, McCarter 1997, McCarter et al. *in press*), a computerized system that integrates landscape-level data, stand-level information, and growth models to project changes through time across forested landscapes (McCarter et al. *in press*, Wilson and Baker *in press*, Wilson et al. *in press*). The flow of information to the wind risk model is detailed in Figure 23. LMS facilitates the projection of stand characteristics into the future. Projected stand characteristics allow landscape wind risk rankings to be compared under a variety of management scenarios, including no harvesting (McCarter et al. *in press*).

A.

		SITE RISK EXPOSURE		
		LOW	MODERATE	SEVERE
SOIL RISK	LOW	1	1	2
	MODERATE	1	2	3
	SEVERE	2	3	3

B.

		WIND RISK SITE RISK		
		1	2	3
STAND RISK	1	LOW	LOW	MODERATE
	2	LOW	MODERATE	SEVERE
	3	MODERATE	SEVERE	SEVERE

Figure 22. Matrices describing how risk rankings for soil, exposure, and stand characteristics are combined into an overall wind risk value. Values for Site Risk from the first matrix (A.) are used for Site Risk in the second matrix (B.) The values 1, 2, and 3 reflect low, moderate, and severe risk ratings for risk associated with site and stand conditions (modified from Mitchell 1995b).

The wind risk associated with a stand is determined by two classes of factors: site and stand characteristics (Shaw 1983, Alexander 1987, Mitchell 1995b). Site characteristics describe environmental conditions such as rooting depth, soil moisture, topographic exposure, and slope. Site characteristics are not generally altered by forest management

(Kennedy 1974, Cremer et al., 1982, Mitchell 1995b, Quine 1995). Stand characteristics such as heights, ratio of height to diameter, species, trees per area, crown sizes, and conditions of upwind neighbors are determined by the individual trees in the stand and landscape (Cremer et al., 1982, Ruel 1995, King 1986, Becquey and Riou-Nivert 1987, Lohmander and Helles 1987, Foster 1988). Stand characteristics can be responsive to manipulation.

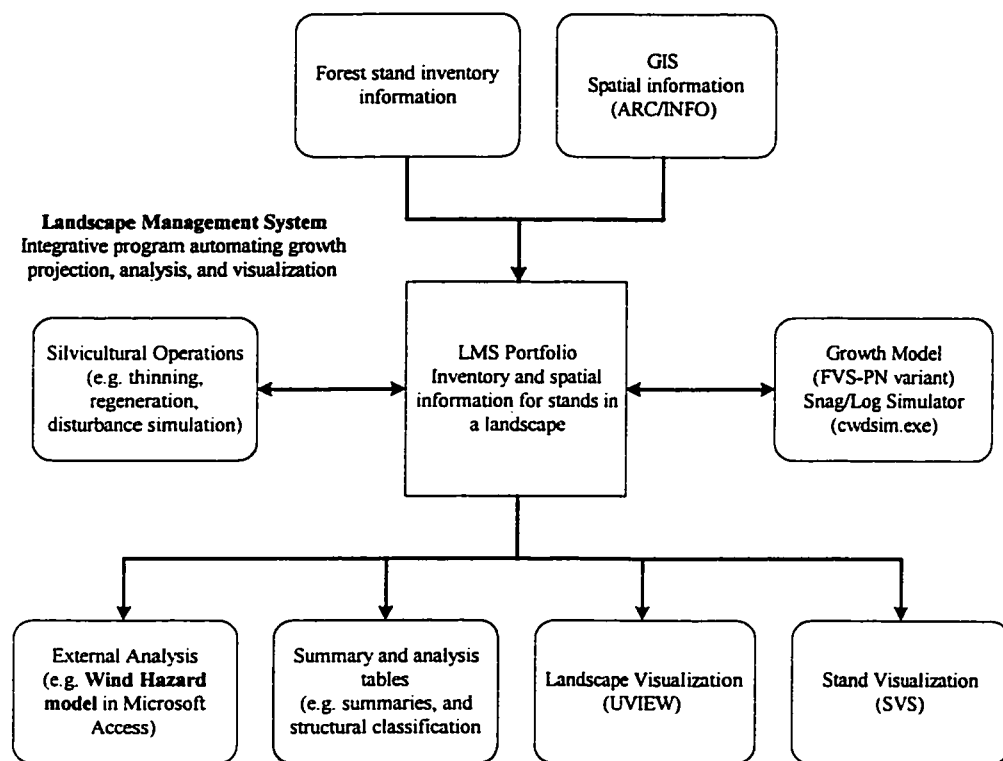


Figure 23. Flow of information to the wind risk rating system. Grayed area in the diagram represents limits of LMS. Modified from McCarter et al. (in press).

4.3.1.1 Spatial relationships between neighboring polygons

The determination of exposure rankings and conditions of downwind neighbors require an ability to evaluate spatial relationships between neighboring stands on the landscape.

A neighborhood file format created from GIS (ARC/INFO) output provides these spatial relationships (Table 8). Stands immediately outside of the landscape being considered are included in the neighbor table to avoid border issues in the exposure rankings. Downwind neighbor analysis does not take account of stand conditions outside the landscape being considered. While it is likely that an upwind hill adjacent to the landscape will be there in fifty years, future stand conditions outside of the landscape are less predictable.

Table 8: Column formats for the neighborhood table. The relationship between a focus stand and all adjacent stands is reported. Degree represents the direction of a line perpendicular to the average border direction.

Focus stand	Adjacent stand	Degree	Shared border (m)
2059	5493	172	2613
5493	2257	129	420
2257	5493	309	420
5493	2434	15	1519
2434	5493	195	1519
5493	5489	263	463
5489	5493	83	463
5493	5495	233	914
Etc.....			

ARC/INFO outputs required for developing the neighbor table are polygon, arc, and node attribute files for the landscape. Shared arc distances between adjacent polygons are summed to produce the shared border column. Border directions of each arc are calculated by comparing locations of beginning and ending node coordinates from individual arcs (Equation 12).

$$angle = a \tan \left(\frac{|y_i - y_j|}{|x_i - x_j|} \right) * 57.29578 \quad (12)$$

where: atan = arc tangent;

y = y-coordinates of *from* (i) and *to* (j) nodes;

x = x-coordinates of *from* (i) and *to* (j) nodes; and

57.2957795 = conversion of radians to degrees.

The angle value represents deviations from the horizontal and needs to be converted to a 360° scale based on which quadrant contains the *to* node. Many neighboring stands share more than one arc. Degree values have no starting point (i.e. 360° and 0° are equivalent) and no magnitude (e.g. 120° is no larger than 40°); therefore, calculations designed for circular distributions must be employed to calculate statistics such as a mean angle weighted by arc length (Zar 1984). Polar coordinates from circular distributions are converted through trigonometric functions to rectangular (i.e. Cartesian coordinates). Equation 13 details the calculations to derive mean arc angle weighted by arc length. Specific sine and cosine pairs, produced in Equations 14 and 15, describe specific angles. When both or just the sine is positive, the average angle is equal to $\text{acos}(\cos \bar{a}) * 57.2957795$. If both or just the sine is negative, the average angle equals $360 - \text{acos}(\cos \bar{a}) * 57.2957795$.

$$\bar{X} = \frac{\sum_{i=1}^n l_i \cos a_i}{\sum_{i=1}^n l_i}, \quad \bar{Y} = \frac{\sum_{i=1}^n l_i \sin a_i}{\sum_{i=1}^n l_i} \quad (13)$$

where: l_i = length of arc *i* and
 a_i = angle of arc *i* in radians.

$$r = \sqrt{\bar{X}^2 + \bar{Y}^2} \quad (14)$$

$$\cos \bar{a} = \frac{\bar{X}}{r}, \quad \sin \bar{a} = \frac{\bar{Y}}{r} \quad (15)$$

A program written in Python, an interpreted programming language with high-level built-in data structures (Watters et al. 1996, Lutz 1996), creates neighbor tables. The neighbor table program and other Python programs developed for this project are included in Appendix B.

4.3.1.2 Exposure risk rating

Three simple exposure models with published criteria are provided in the landscape wind risk model. Results from any available exposure model can be substituted for the internally available exposure options. The exposure models use mean elevation, slope, and aspect values for stands in combination with adjacency information from the neighbor table (described in the previous section) to evaluate stand exposure based on a user-defined direction from which storm winds are expected (8 compass points). The three exposure models included in the analysis are Neustein (1971), Foster and Boose (1992), and Mitchell (1995b). Descriptions of decision criteria for each of the models are presented in section 4.2.1.3 Topography. The exposure models included in the wind risk model are intended to be both simple to understand and general in scope. Although accurate exposure assessment is important to evaluating wind risk, it is not the focus of this project. Exposure rating results from more detailed or more site-specific models should be substituted for the internal choices where they are available.

4.3.1.3 Soil risk rating

Soil risk ranking is an external process from the wind risk model. Results are provided to the wind risk model via a soil risk table that details a ranking for each stand in the landscape under consideration. For this analysis, a soil windthrow risk classification developed by the Washington State Department of Natural Resources has been used. The classification is based on minimal soil depth and soil drainage criteria. The soil risk table for a landscape should be based on detailed and site specific models where they are available.

4.3.1.4 Stand characteristic risk rating

Seven stand characteristics have been widely identified as having important ramifications for stand stability (see section 4.2.1.4 Stand conditions). Four of them, H/D, height, recent thinning, and upwind neighbor harvesting, are included in the stand risk ranking. Stand spacing was excluded because this factor has opposing impacts on stand stability,

making its overall contribution unclear. Species were excluded because the model was developed specifically to evaluate wind risk in stands dominated by a single species, Douglas-fir. Exclusion of an explicit species variable has the advantage of making the model a general, rather than regionally specific, risk evaluation tool. In addition, studies evaluating species susceptibility to wind damage are often contradictory. The impact of root and stem rots on wind stability is consistent and substantial; however, including this factor in the model requires predictions of future rot conditions in projected stands. Current models that predict future stem and root disease conditions cover limited geographic ranges and stand conditions (Stage et al. 1990). Where root and stem rot development models are available, the impact of these pathogens should be included in any wind risk model. In the absence of applicable models wind risk rankings for landscapes with widespread root-rot disease pockets should be considered conservative.

Rating criteria for height, H/D, recent thinning, and upwind neighbor harvesting are user-defined variables. For the analysis reported in this chapter, these variables have been equated to general results from empirical studies of wind damage and mechanistic model results (see section 4.2 Background). Stand height and H/D values are based on the largest (dbh) 250 trees per hectare (H/D_{L250}) in each stand. Generating means for all trees in a stand allows height and H/D values to be strongly influenced by suppressed and intermediate trees that are sheltered by more vigorous trees, making them poor predictors of stand stability. In addition, the largest trees tend to have the highest timber, aesthetic and habitat values, making their stability the critical factor (see Chapter 3 for detailed justification of this measure).

Recent thinning in a stand is evaluated by dividing the current number of trees per hectare by values from the previous projection period (10 years in this analysis). Harvesting in upwind neighbor stands is detected by comparing dominant height of upwind neighboring stands with the current focus stand. Upwind neighbors are determined by a user-defined direction from which storm winds are expected (8 compass points) and stand adjacency

provided in the neighbor table (see section 4.3.1.1 Spatial relationships between neighboring polygons, for details). A minimum-shared border variable can be used to eliminate impacts of upwind neighbors that share a small proportion of the total border of the focus stand. For this analysis, the minimum-shared border was set to 15 percent. Neighboring stands in which a few green trees have been retained after a harvest could have mean heights that appear protective of the focus stand. To avoid this complication, a minimum tree per hectare variable provides a way to discount shelter from a sparse upwind stand. The minimum tree variable was set to 50 tph for this analysis. Critical values used for the stand risk ratings are detailed in Table 9.

Table 9: Rating criteria used in this analysis for stand risk ratings.

	Low (1)	Moderate (2)	Severe (3)
Mean height largest 250 tph	≤ 15.00	≤ 30.00	> 30.00
Mean H/D of largest 250 tph	≤ 80.00	≤ 90.00	> 90.00
Current tph/previous tph	$> .80$	$\leq .80$	$\leq .60$
Upwind neighbor ht./stand ht.	$> .75$	$\leq .75$	$\leq .50$

Low, moderate, and severe ratings for each of the four stand factors have numerical values of 1, 2, and 3 respectively. Summing the four individual stand factor ratings creates a single stand risk ranking. The stand risk rankings are translated to codes (i.e. low < 7 , moderate ≥ 7 , severe ≥ 9). If the height factor rating for a stand is low ($H_{L250} \leq 15$ m), it is assigned a low stand risk ranking no matter what ratings are for the other factors.

4.3.2 EVALUATING THE WIND RISK RATING SYSTEM

The wind risk model produced considerably different ratings in a comparison of three alternative management approaches on the same landscape. (McCarter et al. *in press*). A logical extension of that analysis is evaluating whether small adjustments to individual scenarios can reduce wind risk ratings. For example, can modifying the timing of harvest

for particular stands or changing planting density result in wind risk rating reductions for the landscape? If small changes in scenarios produce wind reductions, scenarios can be fine-tuned to meet acceptable risk levels using an iterative approach. The potential for reducing wind risk is evaluated in two parts in this chapter. First, exposure ratings between different models are compared. Second, a base scenario is projected using LMS and the Pacific Northwest variant of the Forest Vegetation Simulator (FVS-PN [Donnelly 1996, Teck et al. 1996]) and evaluated using the wind risk rating system. Three adjustments to the base scenario are made to evaluate the potential for reducing landscape wind risk ratings.

4.3.2.1 Comparing exposure model ratings

Models that evaluate the wind exposure of different landscape positions provide important input to the overall landscape wind risk ranking. The importance of exposure models is heightened when the analysis goes beyond a general evaluation of landscape risk to risk reduction through fine-tuning of a potential management alternative. In more applied analyses, timing and placement of harvesting operations are adjusted based on results from the site portion of the wind risk rating system in Figure 22. To evaluate the amount of discrepancy between exposure predictions, rankings produced by the three exposure models included in the wind risk rating system were compared. Variability between soil risk models is not considered in this analysis. The reported impacts of soil conditions on wind-throw risk are considerably more consistent than topographic influences.

4.3.2.2 Adjusting scenarios to reduce wind risk

Spatial data from a 1,000 ha landscape on the Olympic Peninsula was used in combination with inventory information synthesized from the experimental plot measurements of naturally regenerated stands described in Chapter 2. Initial conditions on the landscape simulate a relatively even-aged group of naturally regenerated stands with ages ranging from 60 to 70 years. A base scenario was projected from 1970 until

2050. During the first five decades, all stands were clear-cut and replanted to Douglas-fir at densities ranging from 1,000-2,000 tph. Stands cut in any particular decade were chosen randomly. Fifty percent of the plantations were thinned by 20% of their basal areas from below in the second decade after planting. Harvesting of the planted stands began in the year 2030. Stands were cut in the same order as the initial harvest. The projected landscape information was evaluated using the landscape wind risk model. The Mitchell (1995b) exposure model was used for determining a topographic exposure rating. Height to diameter ratio of the largest 250 tph for each stand was calculated from equations developed in Chapters 2 and 3. Equations for natural and planted stands are presented in Equations 16 and 17. These equations generate more reasonable H/D_{L250} values than available growth models for the region. See Chapter 3 for a comparison of H/D estimates. The effects of using growth model H/D predictions on wind risk rating are evaluated in Chapter 5.

$$H / D_{L250}(\text{nat. reg. stnds.}) = \left(\frac{ht}{ht - bh} \right) * 6957575 + .91613(mht) - .02245((mht)^2) + .00469(iddf) - 5.18967(mgini * mht) \quad (16)$$

where: ht = height L_{250} ;
 mht = ht - breast height - 23.06;
 $iddf$ = initial density of Douglas-fir (tph); and
 $mgini$ = gini coefficient - .089.

$$H / D_{L250}(\text{plant stnds.}) = \left(\frac{ht}{ht - bh} \right) * 61.33741 + 1.15262(mht) + .0075(iddf) - .10961(thinc) \quad (17)$$

where: mht = ht - breast height - 19.34 and
 $thinc$ = thinning proportion as a percent of basal area.

Three alternatives to the base scenario, designed to reduce wind risk ratings, were developed and projected to evaluate the potential for improving landscape wind risk. The first alternative simply reduced the number of Douglas-fir being planted after harvesting

stands from 1,000-2,000 tph to 500-1,000 tph. Order of harvesting was unchanged from the base scenario. The second alternative altered the order in which stands were harvested but left planting densities unchanged. Stands were favored for earlier harvesting if their exposure rating was high. Stands immediately upwind of recently harvested stands were the next priority. The establishment of this cutting pattern reduces future potential for exposing windward edges of stands that are topographically exposed. Stands that had low exposure ratings had the lowest priority. Planting densities were unchanged from the base scenario. The third alternative combined the harvesting order and planting density changes from the first and second alternative.

4.4 RESULTS

4.4.1 COMPARISON OF EXPOSURE MODELS

The comparison between exposure model rankings in Table 10 and Figure 24 highlights some inconsistencies in the understanding of how topography influences wind damage to forests. Figure 24 compares the number of stands in each exposure hazard class based on model used. The Foster and Boose (1992) model provides considerably different rankings for individual stands and more extreme rankings over the landscape than the others. This exposure model was developed for the gently sloping topography of central Massachusetts and only considers stand slope and aspect in the rating. The greater number of extreme ranks produced by the Foster/Boose model result from the omission of spatial relationships between neighboring polygons. Extreme ranks for individual stands, low or severe, are often moderated in the other models by evaluating relative position on the landscape. The minimal information required for the Foster/Boose model make it easy to employ; however, the lack of adjacent topography considerations in the analysis may make it less applicable to more mountainous terrain. The Neustein (1971) and Mitchell (1995b) models produce relatively similar ratings. Stand ratings are either equal or only one class different between the two models (Table 10).

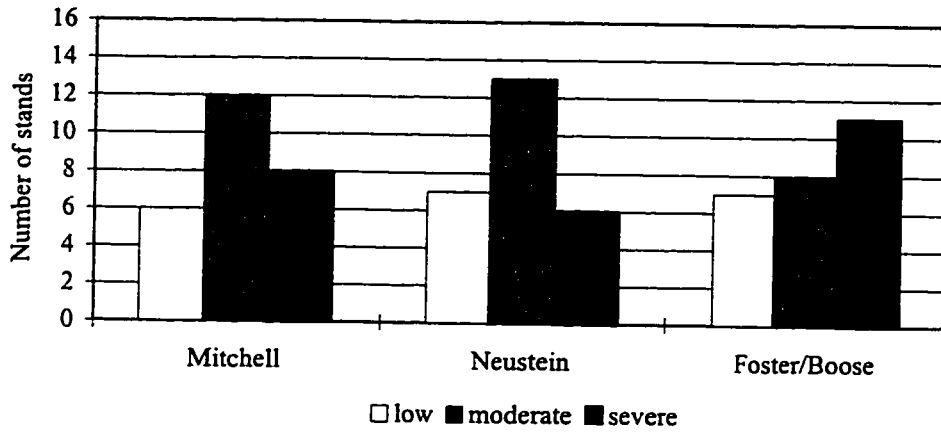


Figure 24: Count of stands in each exposure rating under the different exposure models. Ratings are for winds from the southwest.

Table 10: Comparison of exposure model ratings for stands in the Olympic Peninsula landscape. Ratings are for winds from the southwest.

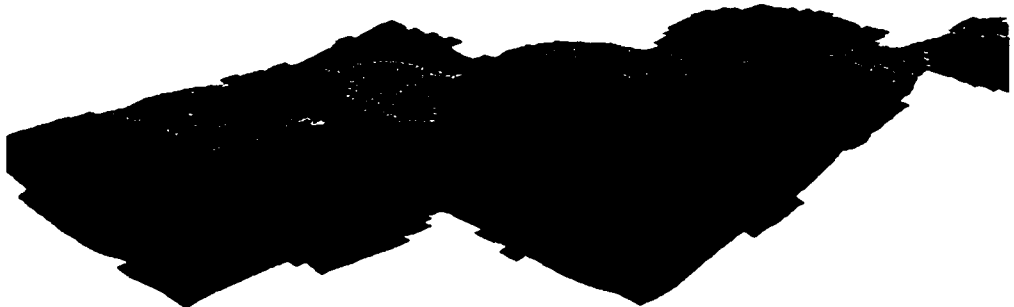
Stand	Mitchell (1995b)	Neustein (1971)	Foster/Boose (1992)
2266	Moderate	Moderate	Severe
5362	Severe	Moderate	Moderate
5363	Moderate	Low	Severe
5364	Moderate	Moderate	Severe
5470	Moderate	Moderate	Severe
2430	Low	Moderate	Severe
5471	Low	Low	Low
5472	Low	Low	Low
5476	Severe	Severe	Severe
5477	Low	Low	Low
2432	Severe	Moderate	Moderate
5481	Moderate	Severe	Moderate
5482	Severe	Severe	Severe
5483	Low	Low	Low
2434	Moderate	Moderate	Low
5486	Moderate	Severe	Moderate
2056	Severe	Moderate	Moderate
2057	Low	Low	Low
2059	Severe	Moderate	Moderate
5487	Moderate	Moderate	Severe
2065	Severe	Moderate	Moderate
5488	Moderate	Severe	Moderate
2073	Sever	Severe	Severe
2258	Moderate	Moderate	Low
5495	Moderate	Low	Severe
5497	Moderate	Moderate	Severe



a. Mitchell (1995b)



b. Neustein (1971)



c. Foster/Boose (1992)

Figure 25: View of the case-study landscape from the southwest comparing exposure model ratings. Severe ratings = black, moderate ratings = dark gray, and low ratings = light gray. Ratings are for winds out of the southwest.

Exposure model ratings are compared in Figure 25 using terrain maps with polygon overlays shaded according to exposure rating. The landscape image based on the Foster/Boose exposure ratings (Figure 25c) shows the ratings are primarily determined by aspect while the other models produce patterns of exposure risk that are more complicated.

4.4.2 WIND RISK RATINGS

4.4.2.1 Base scenario

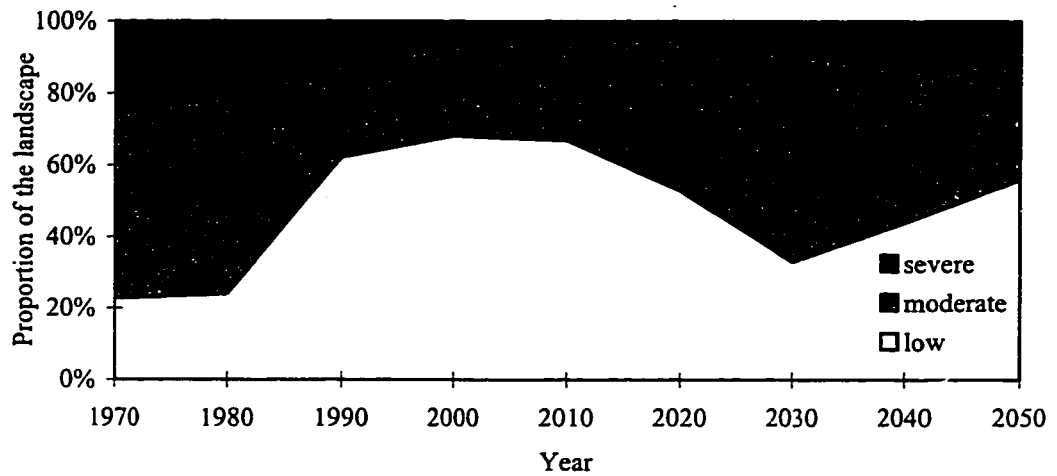
Proportions of the landscape in each wind-risk class under the base scenario and three revised alternatives are shown in Figure 26 and Figure 27. In the base scenario (Figure 26a) the landscape starts out with almost 80 percent in the severe or moderate wind-risk class. By the year 2000 this proportion has been reduced to less than 40 percent. Risk drops as the 60 to 70 year-old naturally regenerated stands are replaced with young plantations. As the plantations grow in height, wind risk on the landscape increases until 2030, when final harvesting begins again.

4.4.2.2 Reduced planting density alternative

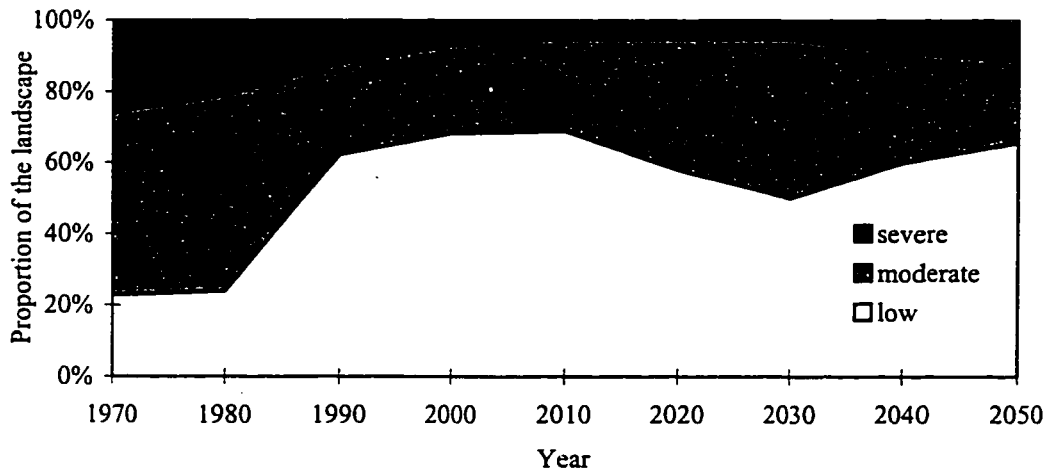
The first alternative scenario has little impact on early risk ratings. In this scenario only planting densities were modified so reductions in wind risk should not be expected until the first planted stands develop wind susceptible heights. Figure 26b shows a very similar pattern of landscape wind risk compared to the base scenario; however, the rise in wind risk after 2020 is lessened when planting densities are reduced. In the year 2030, 50 percent of the landscape is in the severe or moderate risk classes compared to over 65 percent in the base scenario. The proportions of the landscape in both the severe and moderate risk classes are reduced similarly in this revised scenario.

4.4.2.3 Revised harvest schedule alternative

In the second alternative scenario, the order of stand harvesting is altered so landscape wind risk ratings are altered from the first decade on (Figure 27a). In this scenario the proportion of the landscape in the severe class is almost eliminated in the early and late decades. Between the years 2020 and 2030 over 10 percent of the landscape is assigned to the severe wind hazard class. The rise in severe wind hazard occurs because all of the most topographically exposed stands were harvested in 1970 or 1980. By 2020 the trees planted in these exposed stands have gotten tall and developed high H/D_{L250} values.



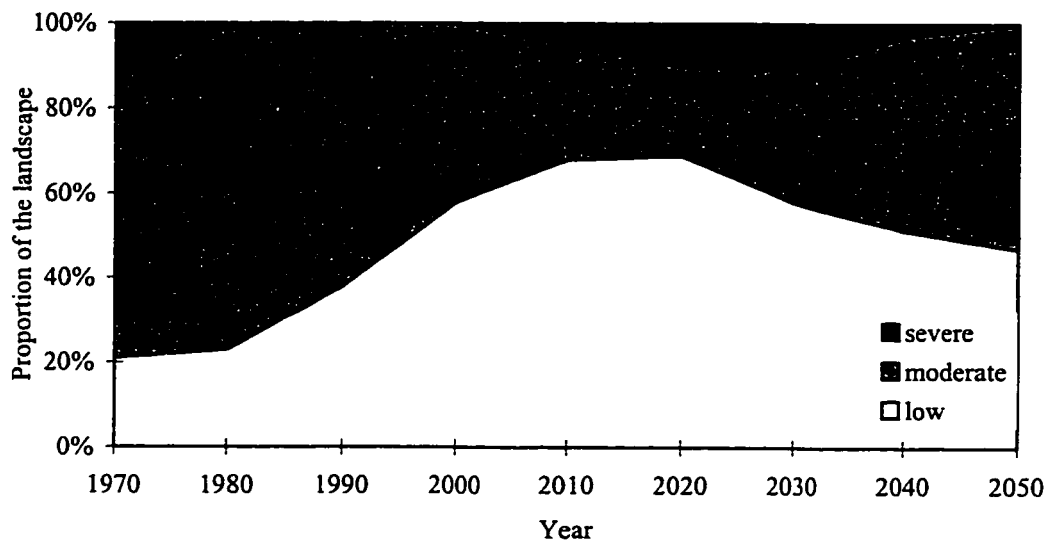
a.



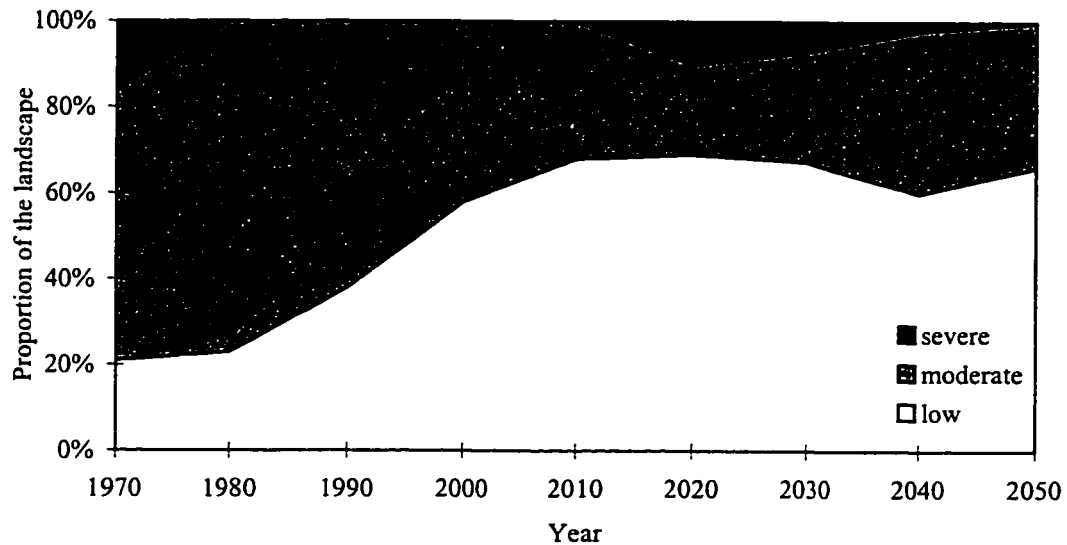
b.

Figure 26: Landscape proportions assigned to each wind hazard class in (a) the base scenario and (b) the first alternative scenario with reduced Douglas-fir densities in planted stands. Plantation densities are 500-1,000 tph as opposed to 1,000-2,000 tph in the base scenario. Winds are from the southwest.

The rise occurs because all of the exposed stands are reaching these high values around the same time. In the base scenario, harvest of the exposed sites was spread over several decades rather than two. The proportion of the landscape assigned to moderate and low risk classes changes little from the base scenario. The harvesting order changes focused on the high-risk stands.



a.



b.

Figure 27: Landscape proportions assigned to each wind hazard class in (a) an alternative harvesting schedule designed to reduce topographic exposure and (b) an alternative combining reduced topographic exposure and reduced Douglas-fir densities in planted stands. Plantation densities are 500-1,000 tph as opposed to 1,000-2,000 tph in the base scenario. Winds are from the southwest.

A comparison of windward edges being exposed by harvesting neighboring stands in the base scenario and the alternative harvest schedule scenario is provided in Figure 28. The

numbers are only for stands that have a moderate or severe exposure ranking. The alternative scenario successfully reduced the overall number of windward edges exposed in high-risk stands; however, the revised harvesting schedule concentrates exposure of high-risk windward edges in the fifth decade.

4.4.2.3 Combined planting density and harvest schedule alternative

The third alternative scenario combines the planting density and harvesting schedule changes of the first two revisions. Figure 27b shows the resulting landscape wind risk rating patterns. The proportion of the landscape in the severe risk class is reduced from the base scenario. There is still a rise in the severe risk class during the years 2020 to 2030; however, the class is always assigned to less than 10 percent of the landscape. Landscape proportions in the severe and moderate classes are reduced over the base scenario in the years 2040 to 2050.

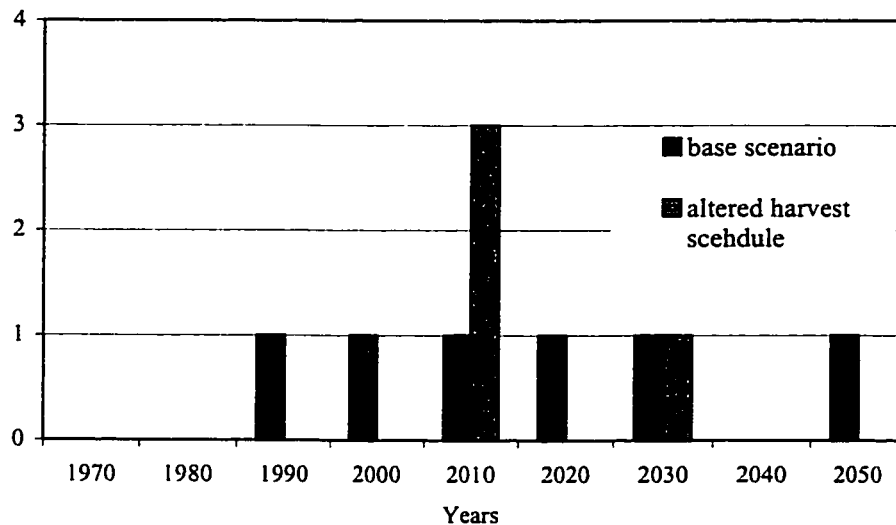


Figure 28: Number of times a windward edge was exposed in stands with moderate or severe exposure ratings in the base scenario (Figure 26a) and the alternative harvest schedule (Figure 27a).

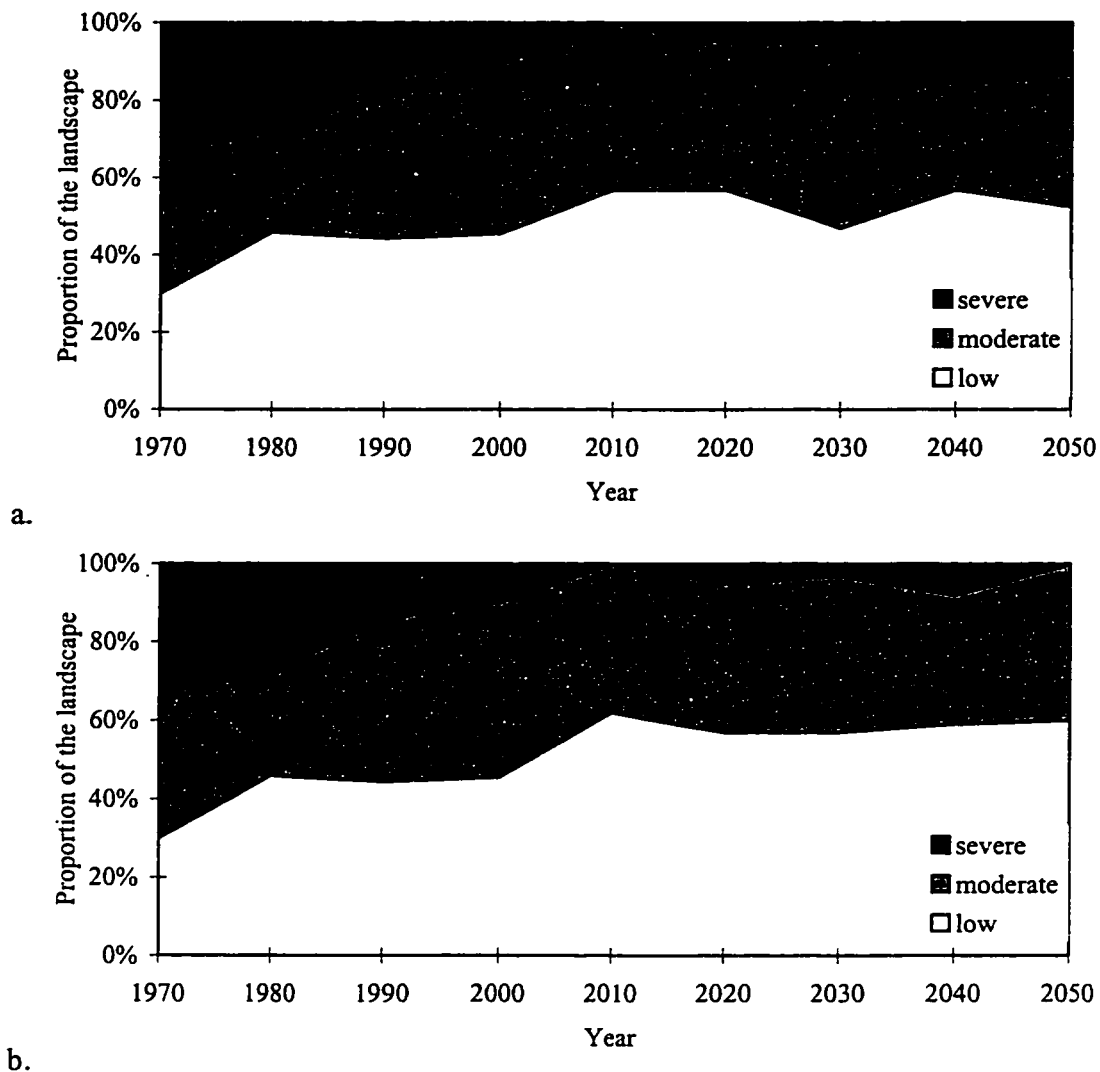


Figure 29: Landscape proportions assigned to each wind hazard class in (a) an alternative harvest schedule designed to reduce topographic exposure and (b) an alternative combining reduced topographic exposure with reduced Douglas-fir densities in planted stands. Plantation densities are 500-1,000 tph as opposed to 1,000-2,000 tph in the base scenario. Winds are out of the north.

Landscape wind risk ratings for winds from the north rather than the southwest are shown in Figure 29. Wind risk ratings are for the second (Figure 27a) and third (Figure 27b) alternatives to the base scenario. A wind direction change leads the rating system to

assign over 30 percent of the landscape into the severe wind risk class in the early decades and 20 percent in the late decades. Reducing planting densities in addition to modified timing (Figure 29b) does not change risk ratings in early decades; however, proportions of the landscape assigned to the severe class are lowered in the later ones.

4.5 DISCUSSION

The three exposure ratings evaluated show moderate variability in the number of stands assigned to each class; however, variations between individual stand ratings are more pronounced. For a general comparison of wind risk ratings between management approaches, the exposure model variability is relatively unimportant. All three of the exposure models put stands in each of the classes. As long as a single exposure model is used, general trends in landscape risk are comparable between alternative scenarios. When the objectives of wind risk analysis become more applied (e.g. fine-tuning a management scenario in a particular landscape) the exposure model used becomes critical. Adjusted harvested orders based on exposure rankings would be acutely different between the three exposure rankings tested. This difference makes having an exposure model that is applicable to the specific landscape being evaluated very important for more applied analysis. The importance of the exposure model is heightened in the example landscape since there was little variation in soil risk ratings for the landscape. Two stands in the landscape were assigned severe soil risk ratings, the rest had moderate ratings; therefore, variation in topography was primarily responsible for variation in site risk ratings.

All three attempts to reduce landscape wind risk through modifications of a base scenario were relatively successful. Modifying the order in which stands were harvested provided reductions in the severe risk class during most of the projection. An unanticipated side effect of the modifications was a rise in the severe risk class during the middle decades of the projection. This increase occurred because the plantations on topographically exposed

sites all reached critical heights and H/D_{L250} values within a two-decade period. If desired, further modifications to the scenario could reduce the severity of the concentrated risk by spreading out the harvesting on exposed sites. If harvest of exposed sites were delayed, landscape scale wind risk would rise during the early and late decades of the projection. Lowering planting densities provides a general decline in future wind risk in contrast to concentration of risk in specific periods. Combining the two types of modifications lowers early risk substantially and provides moderate improvements to future conditions.

Options for reducing wind risk in topographically exposed stands are limited. To keep from developing very high-risk situations, these stands should be harvested earlier than their upwind neighbors. This early harvest ensures a protected windward edge. In addition, thinning should be avoided in these stands. To reduce risk in future rotations these exposed sites could be limited to shorter rotations, planted at relatively low densities, or a combination of the two. In all three cases, the need for thinning is reduced and the development of high H/D_{L250} values is avoided. Stands situated in topographically protected sites can be managed more flexibly. These sites are the most logical areas to extend rotations through thinning or develop and maintain older forest habitat.

Moderately exposed areas provide the greatest opportunity to reduce landscape scale risk through planting stands at wider spacings.

Changing the direction from which winds are modeled may modify a stands exposure ranking. Scheduling harvesting to reduce wind risk in exposed stands may be ineffective or possibly detrimental if storm winds come from an unexpected direction. Reducing planting densities has the attractive outcome of lowering general landscape wind risk to winds from any direction.

4.6 CONCLUSION

Tailoring management decisions around exposure rankings is necessary and important for reducing short-term landscape wind risk ratings. For exposure ratings to be useful, they must be applicable to the landscape being evaluated. In addition, adjustments made to a management scenario based on exposure to winds from one direction may lead to high risks of forest damage if storms come from an unexpected direction. As management scenarios are developed and modified, tradeoffs between risk from expected and unexpected storm directions should be considered.

Reducing planting densities in Douglas-fir plantations helps lessen future landscape wind risk no matter what exposure model or wind direction is selected. Densities reduced through planting at wider spacings or very early thinning lowers future H/D_{L250} values and requirements for future thinnings. Landscapes made up of stands that developed at lower densities will have generally reduced wind risk from any wind direction. For maximum benefit, the two approaches should be combined. In this approach, short-term risk is reduced through timing and placement of operations and long-term risk is reduced through developing more stable stands.

Landscape wind risk is only one of many considerations that have to be weighed in the determination of appropriate management for a forest. The development of tools such as LMS and the wind risk rating system described in this analysis are steps toward making the consideration of tradeoffs between multiple goals in landscape management possible.

CHAPTER 5: COMPARING PAST AND FUTURE LANDSCAPE-SCALE WIND RISK IN MANAGED LANDSCAPES OF THE COASTAL PACIFIC NORTHWEST

A landscape-scale wind risk rating system was developed in Chapter 4. This chapter uses the system to compare trends in wind risk for managed landscapes of the Pacific Northwest.

5.1 INTRODUCTION

Managed landscapes in the coastal Pacific Northwest have or will generally pass through three characteristic developmental periods. The first period was dominated by naturally regenerated second-growth stands established after an initial harvest and/or fire in a landscape. Initial harvest areas tended to be large; creating landscapes dominated by similarly aged stands. When the second growth stands reach 60 to 80 years old they are typically harvested and replaced with planted stands. The second period is the transition from a landscape dominated by second growth to one dominated by plantations. Most landscapes in the region are in this period. The third period occurs when the second growth stands have all been harvested and replaced with plantations. There are, of course, many variations and exceptions to this development pattern.

These shifts in landscape pattern should have dramatic implications on region-wide landscape values. Impacted landscape attributes may include aesthetics, habitat, harvest volume, species mix, wood quality, and susceptibility to wind damage. Susceptibility to wind damage is an important consideration in forest management throughout the world, including the coastal Pacific Northwest. Storms generating hurricane-level windspeeds hit the coasts of Oregon and Washington on a twenty-year frequency. A single powerful storm in 1962 blew down an estimated 38 million cubic meters of timber in western Oregon and Washington (Wiley 1965, Lynott and Cramer 1966, Henderson et al. 1989).

Wind damage can occur as catastrophic stand-destroying events or chronic tree and stand damage. Damage may represent a monetary loss, a salvage and coordination problem, or loss of important habitat. The analysis described in this paper integrates inventory and spatial information, growth models, and a rating system for wind risk to evaluate how the shifting patterns in managed landscapes have and will impact landscape wind risk.

5.2 BACKGROUND

5.2.1 FOREST STAND ATTRIBUTES THAT DETERMINE SUSCEPTIBILITY TO WIND DAMAGE

The wind risk literature identifies seven stand attributes that determine susceptibility to wind damage. These are: height to diameter ratio (H/D same units), stand height, inter-tree spacing, species, prevalence of root/stem rot diseases, recent thinning, and recently exposed edges created by harvest or other disturbance in adjacent stands (see Savill 1983 for review). The seven stand attributes are described in Chapter 4. H/D values, tree species, and the prevalence of root or stem rot diseases determine the resistance of trees to windsnap or windthrow. The other four factors determine wind exposure or the forces trees must resist.

5.2.2 EFFECTS OF CHANGING LANDSCAPE PATTERNS ON STAND RISK FACTORS

Understanding how the shifting patterns in managed landscapes of the Pacific Northwest might impact wind damage susceptibility requires evaluating how shifting patterns might interact with each of the seven factors introduced above. Interactions between the natural regeneration, transition, and plantation periods and stand risk factors are summarized in Table 11.

The analysis in Chapter 2 showed that plantations were more susceptible to developing higher H/D_{L250} values because of reduced variation in tree size compared to natural

stands. During the transition period, the landscape is divided between plantations and naturally regenerated stands so the impact of this period on H/D values is neutral.

Table 11: Impacts of the three managed landscape periods on the seven factors impacting wind damage susceptibility. Impacts are + = increases susceptibility, - = decreases susceptibility, 0 = neutral, or ? = unknown.

	Natural regen. Period	Transition Period	Plantations Period
H/D	-	0	+
Height	+	+	-
Spacing	?	?	?
Species	?	?	?
Root/stem rot disease	-	0	+
Thinning	-	+	+
Exposed windward edges	-	+	+

Naturally regenerated stands were/are generally allowed to grow taller before harvesting than the shorter rotations for plantations allow. Some of these tall naturally regenerated stands persist during the transition period. In two studies comparing matched naturally regenerated and planted Douglas-fir stands, age to achieve breast height was reduced by 3 to 4 years and site index (50 year) was increased by 4 to 8 meters in the planted stands (Miller et al. 1993, Miller and Anderson 1995). More rapid height growth in plantations may offset some portion of the shorter heights expected in shorter rotations.

The impact of landscape period on spacing is unclear since it is so dependent on the particular planting densities used in an area. In any case, stand spacing is excluded from the analysis because this factor has opposing impacts on stand stability, making its overall contribution unclear.

Naturally regenerated stands may have greater species diversity in dominant canopy trees than plantations; however, this analysis is concentrating on wind stability of naturally regenerated and planted stands dominated by Douglas-fir. In addition, species

composition is not evaluated in the wind risk rating system because there are conflicting reports about the wind damage susceptibility of specific species in this region (Chapter 4).

There is some evidence that planted stands are more susceptible to root and stem rot diseases (Zumrawi et al. 1995). The transition and plantation periods are assigned neutral and positive impacts on root and stem rot diseases. Although important, the presence of these diseases is not considered in the wind risk rating system.

Naturally regenerated stands were rarely thinned during their development. The reduced tree size variability in planted stands makes thinning to promote growth in leave trees more common in both young and old plantations.

The naturally regenerated second growth stands developed in large, similarly-aged landscapes; consequently, there were few exposed windward edges until harvesting began during the transition phase. The naturally regenerated stands generally were or are being harvested over several decades. The resulting heterogeneity of planted stand ages will likely be increased in turn with their harvest.

The transition and plantation periods are assigned many more increasing impacts on stand risk factors than the natural regeneration period in Table 11. The increase in stand risk factors raises concern that susceptibility to wind damage may increase dramatically as managed landscapes move into the transition and plantation periods.

5.3 METHODS

5.3.1 THE WIND RISK RATING SYSTEM

Mitchell (1995b) has proposed a simple model for combining site and stand hazard ratings into a wind hazard assessment. Site hazards describe environmental conditions, such as rooting depth, soil moisture, and topographic exposure, and are not generally

altered by forest management (Cremer et al. 1982, Mitchell 1995b, Quine 1995). Stand characteristics, such as tree height and diameter, crown size, species, trees per area, and the condition of neighboring upwind stands, are determined by the individual trees in the stand and landscape and are responsive to changing stand conditions (Cremer et al. 1982, Becquey and Riou-Nivert 1987, Lohmander and Helles 1987). Site and stand ratings are combined to provide a wind hazard rating. Instead of explicitly predicting and simulating disturbance events, this approach rates the susceptibility of each stand to wind. Managers can decide how much risk they are willing to tolerate in their management. A modification of Mitchell's wind hazard assessment procedure is used for the wind risk rating system and is described in Figure 22. Chapter 4 provides a more detailed description of the wind risk rating system.

The wind risk rating system was developed in Microsoft Access, a database management program, using output from the Landscape Management System (LMS; McCarter et al. 1996, McCarter 1997, McCarter et al. *in press*), a computerized system that integrates landscape-level data, stand-level information, and growth models to project changes through time across forested landscapes (McCarter et al. *in press*, Wilson and Baker *in press*, Wilson et al. *in press*). Figure 23 details the flow of information to the wind risk rating system. LMS facilitates the projection of stand characteristics into the future. Projected stand characteristics allow landscape wind risk rankings to be compared under a variety of management scenarios (McCarter et al. *in press*). Previously, the wind risk rating system has been used to compare wind risk rankings for three alternative management approaches (McCarter et al. *in press*) and to evaluate potential reductions of landscape wind risk through adjusting harvest timing and modifying future stand conditions (Chapter 4).

The Mitchell (1995b) exposure model was used for determining a topographic exposure rating (see Chapter 4 for a comparison of exposure model ratings). A soil windthrow risk classification developed by the Washington State Department of Natural Resources has

been used for the soil ratings. The classification is based on minimal soil depth and soil drainage criteria. Critical values used for variables used in the wind risk analysis are detailed in Table 9. Low, moderate, and severe ratings have numerical values of one, two, and three respectively. Summing the four individual stand factor ratings creates a single stand risk rating. The stand risk ratings are translated to codes (i.e. low < 7 , moderate $7 \leq 9$, and severe ≥ 9). If the height factor rating for a stand is low ($H_{L250} \leq 15$ m) it is assigned a low stand risk ranking no matter what ratings are for the other factors.

H/D_{L250} values for each stand in every projection period were calculated from equations developed in Chapters 2 and 3. Equations for natural and planted stands are presented in Equations 16 and 17 (Chapter 4). These equations generate more reasonable H/D_{L250} values than available growth models for the region. (See Chapter 3 for a detailed comparison of H/D_{L250} predictions.) Stand heights used in the calculation of H/D ratios are from LMS output and are generated by the Pacific Northwest variant of the Forest Vegetation Simulator FVS-PN growth model (Donnelly 1996, Teck et al. 1996). Wind risk ratings will also be calculated using H/D_{L250} values derived from FVS-PN and the Southwest Oregon variant of ORGANON-SWO (Hester et al. 1989) growth model projections to evaluate the impacts of different predictors.

5.3.2 EVALUATING WIND RISK UNDER CHANGING LANDSCAPE PATTERNS

Spatial data from a 1,000 ha landscape on the Olympic Peninsula was used in combination with inventory information synthesized from experimental plot measurements of naturally regenerated Douglas-fir stands. Initial conditions on the landscape simulate a relatively even-aged group of naturally regenerated stands with ages ranging between 10 and 20 years. Fifty-year site index values range from 25 to 40 meters for stands in the landscape.

Two scenarios were developed to evaluate changing landscape patterns in the coastal Pacific Northwest. The two scenarios are designed to reflect common management

approaches that may have dramatic impacts on a landscape's progression through the natural regeneration, transition, and planted periods. The first, a long-transition scenario, harvests the naturally regenerated stands over five decades beginning in 1970 (Table 12). Harvested stands are replanted to Douglas-fir at densities ranging from 1,000 to 2,000 trees per hectare. Half of the planted stands are thinned at age 20 and 40. Planted stands are harvested in the order they were planted beginning in 1930. The second, a short-transition scenario, removes all naturally regenerated stands from the landscape in two decades beginning in 1970. Planting and thinning in the second scenario are identical to the first.

Table 12: Years in each landscape period for the long- and short-transition scenarios.

	Long-transition scenario	Short-transition scenario
Natural regeneration period	1920-1969	1920-1969
Transition period	1970-2019	1970-1989
Plantation period	2020-2050	1990-2050

In the long-transition scenario the plantations are harvested over five decades rather than two. This harvest pattern is designed to simulate a transition to more diverse age classes in the landscape after the initial plantation rotation. Differences between the two approaches during the transition period are depicted in Figure 30. The long-transition scenario (Figure 30a) develops heterogeneity in stand ages across the landscape. The short-transition scenario (Figure 30b) maintains the even-aged nature of the natural-regeneration period landscape.

5.3.3 COMPARING WIND RISK RATINGS USING DIFFERENT H/D_{L250} PREDICTORS

Wind risks in the long-transitions scenario are also evaluated using H/D_{L250} values derived from FVS-PN and ORGANON-SWO growth model projections. Landscape risk rankings

are compared between estimates from growth models and the H/D_{L250} equations developed in Chapters 2 and 3. This comparison provides an evaluation of how sensitive the wind risk ratings are to changing H/D_{L250} values.



Figure 30: Landscape visualization of the case study landscape depicting the transition period in the (a) long- and (b) short-transition scenarios. Scenarios are pictured halfway through the transition period (long-transition scenario 1990, short-transition scenario 1970). The landscape is viewed from the southwest using UVIEW (Ager and McGaughey 1997).

5.4 RESULTS

5.4.1 COMPARISON OF WIND RISK BETWEEN LANDSCAPE PERIODS

Proportions of the landscape assigned to wind risk classes are displayed in Figure 31, for the long- and short-transition scenario. The two management scenarios are identical until 1970 and generate the same wind risk patterns up to that year. Landscape risk is very low in the first three decades when the naturally regenerated stands are young. In the fourth and fifth decades, there is a dramatic increase in both the moderate and severe risk classes. This rise occurs prior to any harvesting. The rise is precipitated by the similarly

aged, naturally regenerated stands all developing moderate stand risk ratings within two decades. A moderate rating is assigned because the stands are tall and have moderate H/D_{L250} values.

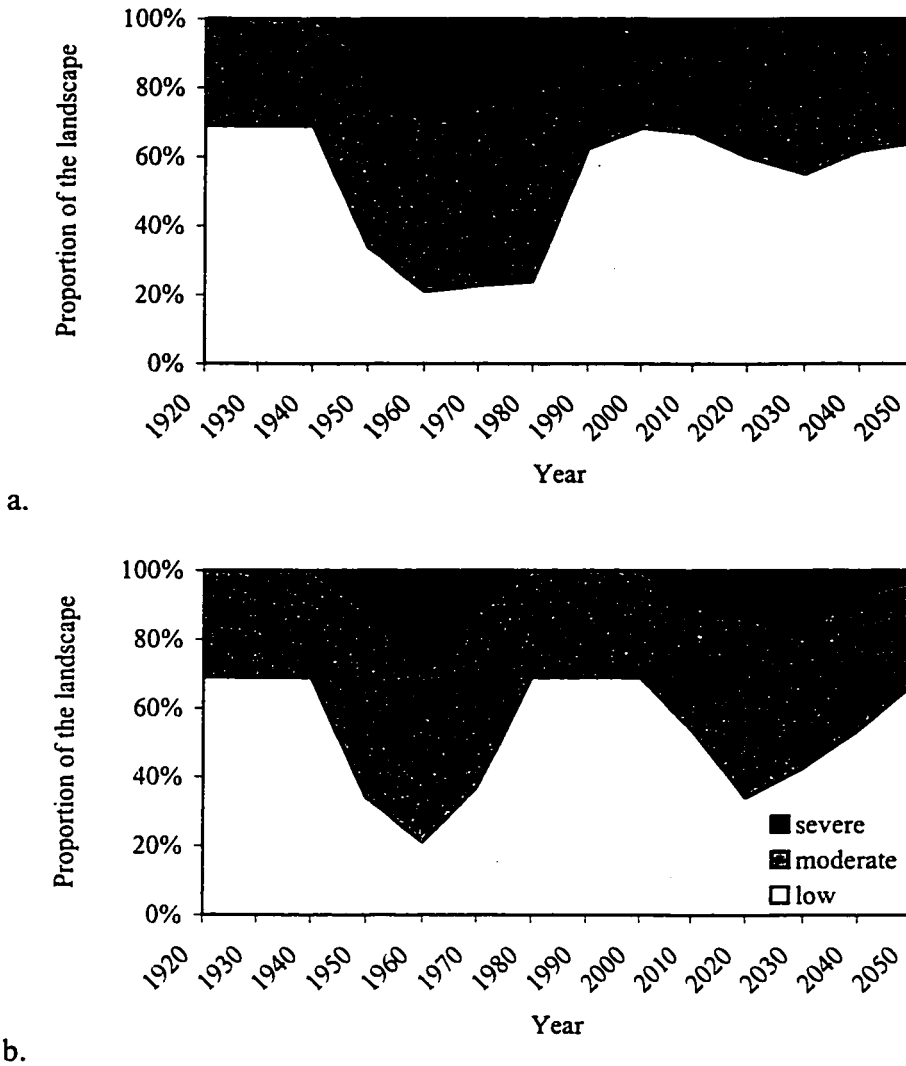


Figure 31: Proportions of the landscape assigned to different wind risk rankings for the (a) long- and (b) short-transition scenarios.

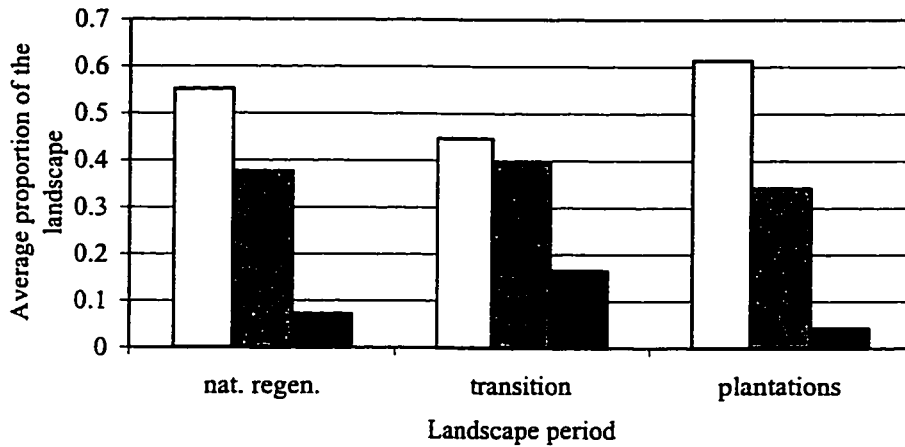
As harvesting of the naturally regenerated stands is initiated in 1970, risk begins to decline on the landscape. The decline is more rapid in the short-transition simulation

(Figure 31b) because the moderately risky naturally regenerated stands are harvested in two rather than five decades. Stands assigned to the severe wind risk class disappear from the short-transition scenario when young plantations dominate the landscape between 1980 and 2000. As the plantations age, landscape wind risk in both scenarios increases. The increase happens sooner in the short-transition simulation because the average age of planted stands is greater and the range of ages is limited in this scenario.

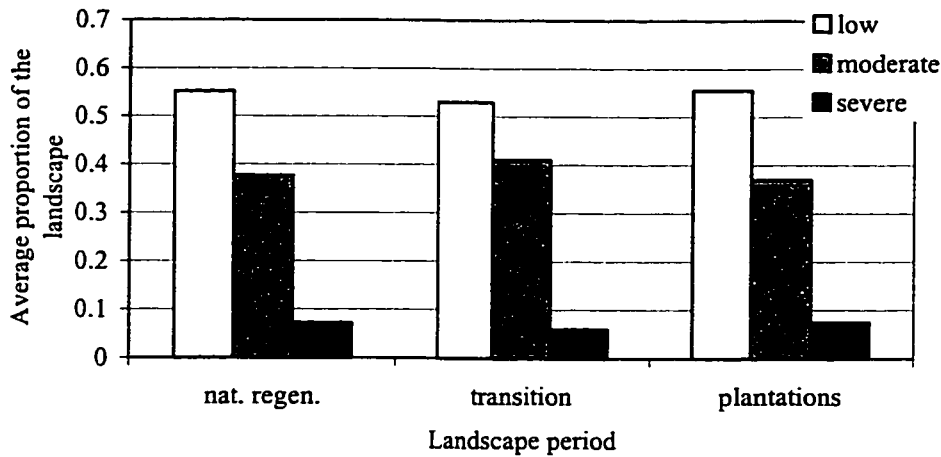
In the short-transition scenario, the average proportions of the landscape assigned to specific wind hazard classes during landscape periods are similar (Figure 32b.). In the long-transition scenario (Figure 32a.), the transition period has a higher proportion of the landscape in the severe class (16.5 %). Heightened risk in the transition period reflects the five-decade period during which moderately susceptible, naturally regenerated stands persist in the landscape. In the plantation period of the long-transition scenario, average proportions of the landscape assigned to the low risk class exceed 60 percent. In the long-transition scenario wind risk is low during the plantation period because all plantations are harvested when they reached 50 years. In the short-transition scenario, the transition from the first to second plantation rotation is extended to simulate the development of more heterogeneity of ages on the landscape; therefore, some plantations are harvested at ages over 50 years, generating higher risks.

5.4.2 COMPARISON OF STAND RISK FACTORS

The three-class rating scheme for wind risk provides broad hazard classes; however, it is easy to break down overall ratings by examining stand, soil, and exposure ratings individually. Soil and exposure ratings do not vary between the landscape periods or scenarios, so they will not be considered in this analysis. Stand ratings vary considerably between scenarios and landscape periods (Figure 33).



a.



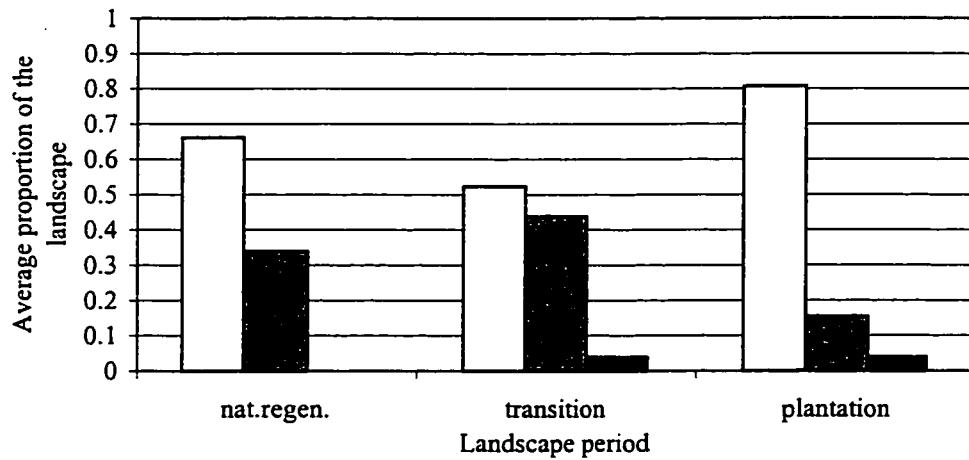
b.

Figure 32: Average portion of the landscape assigned to each wind risk class during the three landscape periods in the (a) long- and (b) short-transition scenarios.

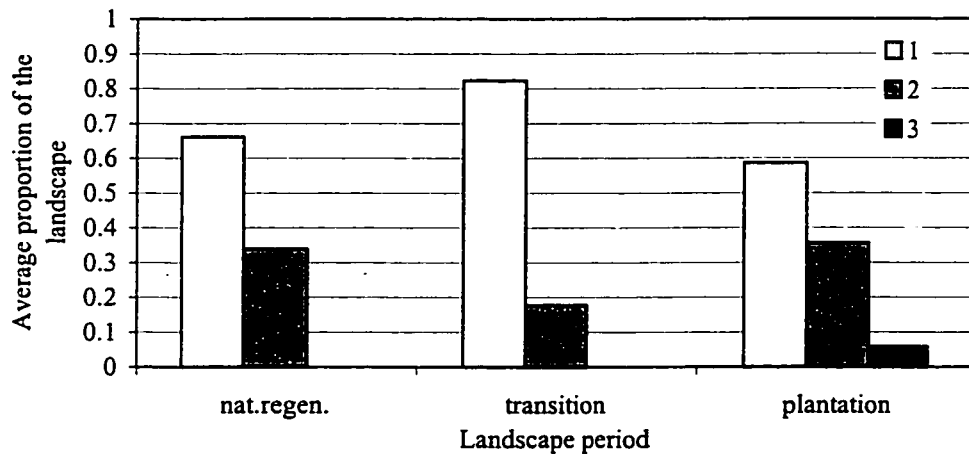
During the natural regeneration period in the long-transition scenario (Figure 33a.) the landscape is split between the low and moderate stand wind risk, 65 and 35 percent respectively. The landscape proportion assigned low ratings drops to 51 percent during the transition period and a small proportion of the landscape is assigned to the severe risk class. During the plantation period, 80 percent of the landscape is assigned a low stand

risk rating. The rest of the landscape is split 35 and 10 percent between the moderate and severe stand risk ratings respectively.

Stand risk patterns for the short-transition scenario are displayed in Figure 33b. In this scenario, the transition period averages low levels of stand risk while the plantation period has the highest proportions in the moderate and severe risk classes.



a.



b.

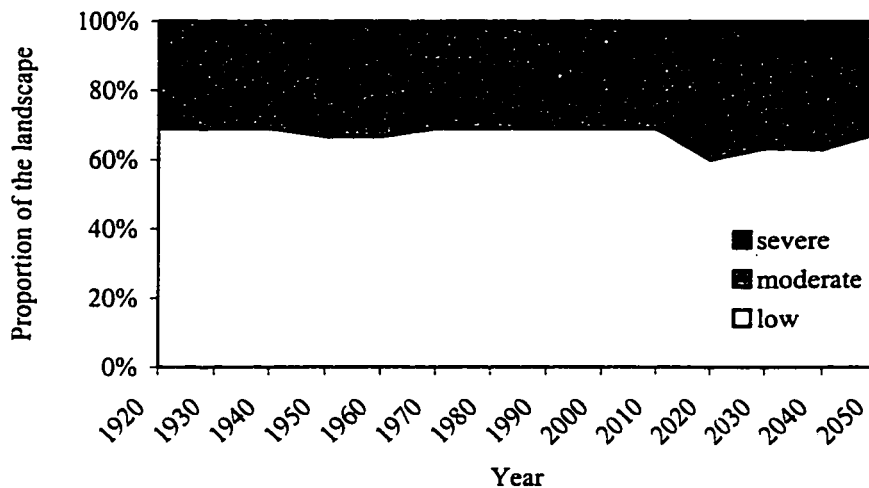
Figure 33: Average proportions of the landscape assigned to each stand hazard class for the different landscape periods under (a) long- and (b) short-transition scenarios.

5.4.3 RANGE IN WIND RISK RATINGS PRODUCED BY DIFFERENT ESTIMATES OF H/D_{L250}

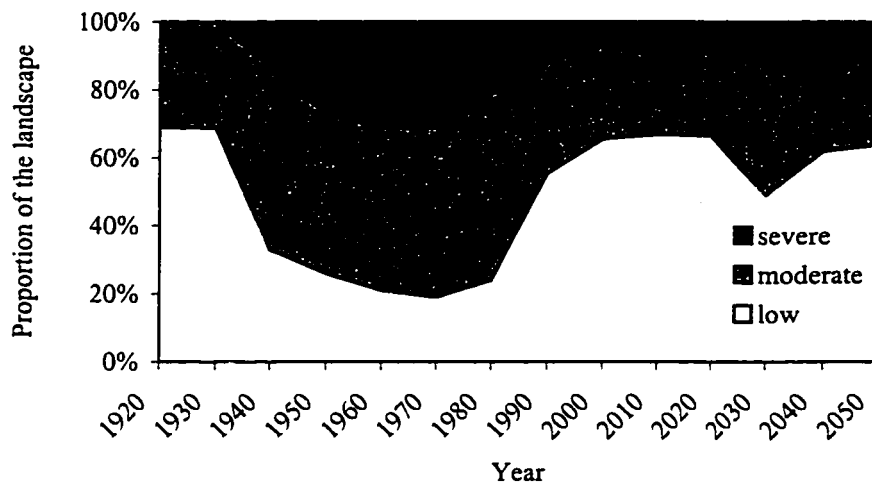
Landscape wind risk trends for the long-transition scenario are very different when H/D_{L250} values are derived from growth model estimates rather than the equations developed in Chapters 2 and 3 (Figure 34). Rankings derived from ORGANON-SWO projections (Figure 34b.) show higher proportions of the landscape in the moderate and severe risk classes; nevertheless, the overall pattern through time is very similar to the estimates using H/D_{L250} equations. The rankings associated with FVS-PN projections (Figure 34a.) show both lower risks and a considerably different pattern to the trend through time. H/D_{L250} values derived from FVS-PN projections rarely get above 80, meaning that naturally regenerated stands never achieve moderate ratings for H/D_{L250} values or for stand risk ratings. A series of small (< 5 percent) increases in the severe risk class occur during the transition and plantation period. Thinning and exposed windward edges created during these periods cause some stands to be assigned the higher risk levels in the absence of high H/D_{L250} values.

5.5 DISCUSSION

The highest landscape risk in both scenarios occurred at the end of the natural regeneration period rather than during the transition or plantation periods. Almost all stands in a homogeneously aged landscape (i.e. the naturally regenerated period) develop moderate stand risk ratings within a couple of decades. When all stands have moderate stand ratings, site ratings (i.e. exposure and soils) determine wind risk rankings. Even-aged landscapes experience periods of low risk when they are young and increasingly higher risk as they mature. This type of landscape development concentrates wind risk in particular periods. In the short-transition period scenario, the relatively even-aged nature of the landscape has been preserved during the first plantation rotation. Figure 31b. shows how this has maintained the cyclic and concentrated nature of wind risk. The second rise in the severe wind risk class is not as substantial as the first because the plantations are



a.



b.

Figure 34: Landscape wind risk rankings for the long-transition scenario when H/D_{L250} values are derived from growth models (a) FVS-PN and (b) ORGANON-SWO.

harvested after 50 years vs. 70 years for the naturally regenerated stands. When the naturally regenerated stands are harvested over five decades in the long-transition scenario (Figure 31a.) landscape wind risk patterns are considerably different. Landscape risk declines more slowly in the transition period because the replacement of moderately risky naturally regenerated stands with young, low-risk plantations takes longer. The

second rise in landscape wind hazard is much reduced in this scenario as the plantations obtain moderate stand risk rankings over an extended period. Heterogeneously aged landscapes will have more subdued periods of high and low landscape risk; however, some portion of the landscape will be susceptible to damage at most times.

The transformation from homogeneously to heterogeneously aged landscapes generally results in a period of increased wind risk. Heightened risk occurs because rotation lengths must be extended in some of the stands to generate more age diversity. When rotation lengths are increased, stands grow taller and spend more time at heights susceptible to wind damage. In addition, the patchwork harvesting of stands is likely to expose some windward edges, increasing hazard further. Wind damage can be an agent that promotes the transformation to more heterogeneously aged landscapes by creating exposed edges that increase wind risk during future storm events.

The end of the naturally regenerated period may represent the highest period of landscape risk; however, when the percentage of the landscape in each risk class throughout a landscape period is evaluated, the difference is less substantial. High risk will be concentrated during specific periods in even-aged landscapes. Similar levels of overall risk will be increasingly spread out in landscapes with greater age diversity. By incorporating thinning, higher H/D_{L250} levels, and exposed windward edges, plantation management generates stands in the severe stand risk class. At moderate plantation densities, the increased risk is mostly nullified by shorter rotation lengths reducing stand heights and the amounts of time stands are in susceptible conditions. High initial densities increase H/D_{L250} levels further and eliminate some of the risk reductions associated with reduced rotation lengths (Figure 35).

A closer examination of the stand risk ratings shows that the naturally regenerated stands only develop moderate risk ratings as they mature. Moderate ratings are generated when the stands develop heights above 30 meters and H/D_{L250} values over 80. Severe stand

ratings do occur in the transition and plantation periods because high H/D_{L250} values are combined with exposed windward edges and thinning in half of the plantations.

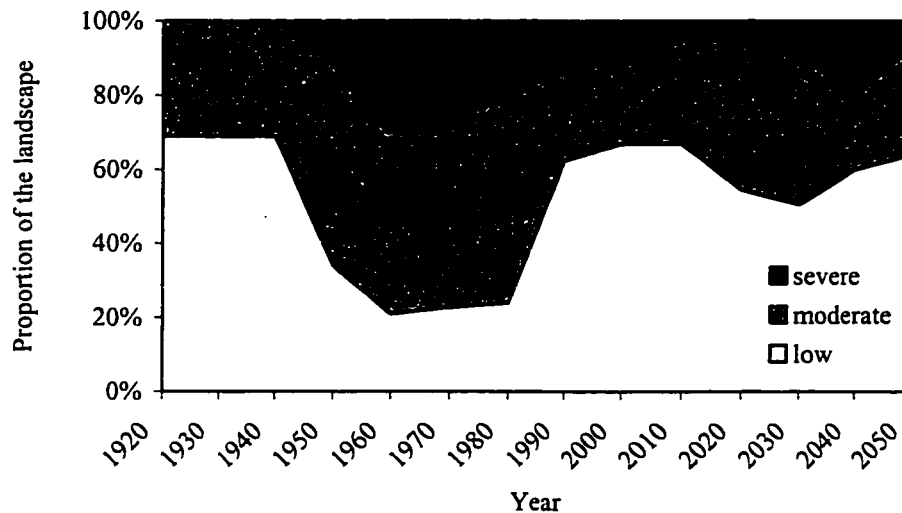


Figure 35: Landscape wind risk rankings for the long-transition scenario. In this scenario plantation densities range from 2,000 – 3,500 tph rather than 1,000 – 2,000 tph used in Figure 31a.

5.6 CONCLUSION

Disturbance history and management approaches have considerable impact on landscape-scale, wind-risk trends through time. Landscapes containing similarly aged stands have concentrated periods of low and then high wind risk. Increasing age diversity moderates wind hazard fluctuations. When an intense storm coincides with a susceptible even-aged landscape, damage may be widespread. Wind damage should occur more regularly but be less widespread in landscapes with diverse ages, because some portion of the area is in a susceptible condition at most times. The risk of stands in susceptible conditions is heightened by the creation of exposed edges, thinning, and high H/D_{L250} levels in plantation management.

The different wind risk patterns have substantial implications for the management of landscapes where consistent forest attributes or outputs are important. An example is watershed management where high water quality is promoted by having few stands in the open condition, with associated sedimentation and turbidity. An even-aged landscape provides this desirable condition over most of the landscape for most of the time; however, when that landscape becomes susceptible to wind damage, a major storm may leave an unacceptable proportion of the watershed in the open condition. A landscape with more age diversity may provide slightly lower water quality in most years, but may be less prone to widespread damage and unsatisfactory water quality levels after a major storm event. The value of age diversity for landscape management is not limited to water quality. Other examples include maintenance of a particular habitat, aesthetics, forest product flows, and avalanche/landslide control.

More concentrated periods of wind risk may be a desired attribute in the management of some forested landscapes. Road closures could be scheduled to coincide with periods of low wind risk for a more even-aged landscape. When the landscape develops moderate wind risk levels roads could be re-opened to make salvage of wind damaged-timber possible.

The tradeoff between consistent forest attributes or outputs and potential high rewards is only one of many considerations that have to be weighed in the determination of an appropriate management plan for a forest. The development of tools such as LMS and the wind risk model described in this analysis are steps toward making the consideration of tradeoffs within and between multiple goals in landscape management possible.

CHAPTER 6: THE IMPACT OF WIND STABILITY ON FLEXIBILITY OF FOREST MANAGEMENT

Past, present, and future wind risk in managed landscapes of the coastal Pacific Northwest were compared in Chapter 4. In this concluding chapter, the implications of stand- and landscape-scale wind stability on flexibility of management are discussed. Flexibility of management reflects the rigidity of intervention requirements and/or potential range of development pathways possible for a stand.

6.1 INTRODUCTION

Managing forest stands and landscapes are tasks made complex by long planning horizons. Long time horizons generate substantial uncertainty surrounding future markets, objectives, regulations, labor availability, and natural disturbance events. The uncertainty inherent in forest management may make stands and landscapes that can be flexibly managed desirable. There are two closely related dimensions to the flexibility of stand management: operational and developmental. Operational flexibility reflects the rigidity of intervention requirements, such as thinning to promote stability or reduce stagnation during particular developmental windows. The need for, and therefore intensity of, management declines as operational flexibility increases. Thinnings or other interventions are not excluded in stands that can be managed with operational flexibility. If timing for markets or labor availability are good, thinning can be pursued aggressively; however, if timing is poor, thinning can be postponed or eliminated without dramatic implications for the future stand. Developmental flexibility describes the range of potential future stand conditions that are possible for a particular stand. Stands and landscapes with developmental flexibility are not limited to a single path or end-point. For example, stands that contain wind-stable trees are developmentally flexible. The

stable trees can be expected to survive late thinnings and extended rotations designed to create high quality wood, or used to develop and maintain older forest structure.

Typically, the cost of greater management flexibility is less efficient use of growing space by the desired species. To generate large future biomass yields, a single species of tree is planted at close spacings so as to usurp the available growing space quickly; however, the intense competition between trees in dense plantations necessitates early thinning to promote stand development beyond a narrow range of possibilities. Forest managers and owners must seek a comfortable balance between flexibility of management and efficient use of growing space. A graphical representation of this tradeoff is depicted in Figure 36. High-density plantations efficiently capture available growing space for the desired species; however, operational requirements and developmental restrictions make them inflexible to manage. Flexibility peaks at moderate growing space efficiency because the range of potential developmental pathways is also reduced at low initial densities.

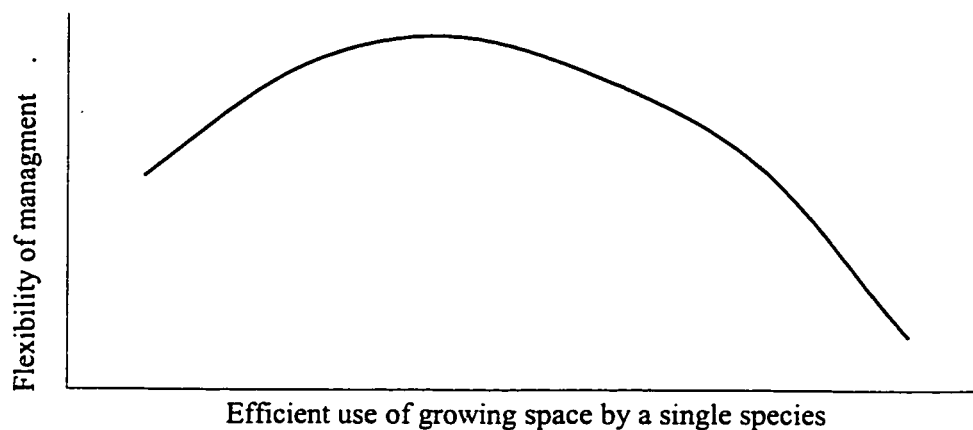


Figure 36: Schematic diagram depicting tradeoffs between management flexibility and efficient use of growing space by a single tree species. Forest owners and managers must find an appropriate balance between how intensively they are willing to manage and how efficiently they wish growing space to be utilized by the planted species.

This chapter proposes that forest managers and owners should consider flexibility of management in the development of stand and landscape plans. The implications of wind stability for coastal Pacific Northwest Douglas-fir plantations provide an example evaluation of the tradeoffs between management flexibility and efficient use of growing space.

6.2 WIND STABILITY AND MANAGEMENT FLEXIBILITY

The impacts of stand stability on flexibility of management are related to the current and projected wind risk in a stand. Stands at high risk of wind damage are developmentally inflexible because they are unlikely to persist after thinnings or through long rotations. The range of possible future conditions in stands is limited when they do not contain windfirm trees. The risk of wind damage in a stand is determined by three classes of factors: regional climate, site, and stand characteristics (Alexander 1987, Mitchell 1995b). Regional climate determines the potential for windstorms of sufficient intensity to damage forest stands. If damaging windstorms are rare, the wind risk of a stand or landscape may have minor implications for flexibility of management; however, when rare storms impact trees and stands that are not preconditioned to high winds or to winds from particular directions, damage may be considerable (Kenworthy 1998). Site characteristics describe environmental conditions such as rooting depth, soil moisture, topographic exposure, site quality, and slope. These characteristics are not generally altered by forest management (Kennedy 1974, Cremer et al., 1982, Mitchell 1995b, Quine 1995). Stand characteristics such as average height, tree taper, species composition, trees per area, average crown size, and characteristics of upwind neighbors are determined by the individual trees in the stand (Cremer et al. 1982, Ruel 1995, King 1986, Becquey and Riou-Nivert 1987, Lohmander and Helles 1987, Foster 1988). Stand characteristics are responsive to manipulation. The implications of stand and site characteristics on wind risk and flexibility of managing Pacific Northwest Douglas-fir plantations are considered separately in the next sections.

6.2.1 STAND-SCALE CONSIDERATIONS

The wind risk literature identifies seven stand attributes that are associated with wind damage susceptibility. These attributes are stand height, height to diameter ratio (H/D—both measurements in the same units), inter-tree spacing, species, prevalence of root and stem rot diseases, recent thinning, and recently exposed stand edges due to harvest of adjacent stands (see Savill 1983, Chapter 3 for a review). All of these attributes may be altered by management to reduce wind damage susceptibility. For simplicity, this section concentrates on evaluating the implications of a single attribute, H/D values, on wind risk and management flexibility. The impact of H/D values on wind risk is consistent and well documented. In addition, H/D values can be easily manipulated and reflect management flexibility more directly than the other attributes. For example, wind risk can be lowered by harvesting stands early, in effect limiting stand height; however, such short rotations accept restricted stand developmental options and timber outputs rather than promote greater flexibility of management.

The most widespread management regime in coastal Oregon, Washington and British Columbia is to plant Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) following a clearcut harvest. Planting densities vary widely by ownership but typically range between 1,000 and 3,500 trees per hectare (tph). Planted stands generally develop less variation in tree sizes than the naturally regenerated stands they replace (Chapter 2). Greater variation of tree sizes within a stand lowers the height to diameter ratio of dominant trees. H/D is a simple yet effective measure of tree stability under wind and snow loads (Chapter 3 for review). The value of H/D as a stability measure is supported by both mechanistic models of tree stability and empirical evidence (Petty and Worrell 1981, Cremer et al., 1982, Becquey and Riou-Nivert 1987, Lohmander and Helles 1987, Peltola and Kellomaki 1993, Slodicak 1995).

Averaging the H/D for dominant trees (H/D for the largest 250 tph [H/D_{L250}]) reflects stand-scale wind stability (Cremer et al. 1982, Chapter 3). The trend of H/D_{L250} values for

a stand through time typically follows a steep rise between 10 - 30 meters of height and a slow decline after that (Cremer et al. 1982, Becquey and Riou-Nivert 1987, Chapter 2). H/D_{L250} curves and peaks are higher for stands with greater initial tree densities. Only very early thinning provides substantial reductions in H/D values (Cremer et al. 1982, Slodicak 1995, Chapter 3).

A theoretical comparison of allometric relationships in an individual Douglas-fir (Figure 14) helps explain both the requirement for very early thinnings to reduce H/D ratios and the peaking of H/D ratios at 25-30 meters (Chapter 3). To maintain relatively stable H/D values between stand heights of 10 to 30 meters requires substantial basal area increments (double and triple what they were at 5 meters). Rapid height growth and basal area increments being a function of diameter squared combine to assure rising H/D ratios between 10 and 30 meters in all but open grown trees. Tree height-growth increments decline beyond 25-30 m of stand height. The resulting reductions in basal area increment requirements help explain why studies have found H/D values peak in this height range.

A family of H/D_{L250} curves for a range of initial Douglas-fir densities developed from Pacific Northwest experimental plot data is presented in Figure 15 (Chapter 3). Plantation data did not contain old enough stands to show slow declines in H/D_{L250} values beyond 25-30 meters of height found in previous studies. Plot data from older naturally regenerated stands shows the peak and decline more clearly (Figure 7). Thinnings stands after they reach 10 meters of height produce only very moderate declines in H/D_{L250} levels. Thinning plantations by 20 percent of their basal area from below at an average height of 15 meters produced only 2.5 point reductions in predicted H/D_{L250} levels at heights of 30 meters (Figure 17). The range of H/D values for dominant Douglas-fir tree ranges from 55 to 100.

There is an early and dramatic divergence of H/D values for trees growing in different competitive environments (Figure 21). To emerge from this period of growth with modest H/D values (e.g. < 80), in anticipation of rising H/D values in all stands between 10 and

30 meters, thinning must be accomplished before H/D values reach moderate levels. According to this criterion, approximate thinning window cutoffs are: 11 meters for initial Douglas-fir densities of 1,000 tph; 7 meters for initial densities of 2,000 tph; and < 5 meters for stands with initial densities > 3,000 tph (Chapter 3). These windows are likely to be somewhat conservative because the Nelder plot data H/D values used in this study are calculated for all trees in the distribution not just the dominants.

Two options for maintaining relatively low H/D_{L250} values are available. One, initial densities of Douglas-fir can be reduced, either through planting at wide spacings (< 1,000 tph) or early thinning. The higher the initial density the earlier stands must be thinned to remain stable. Two, plantations or thinnings could be designed to generate greater variation in tree sizes to mimic naturally regenerated stands more closely. This could be achieved by planting seedlings of different ages or using irregular planting patterns. If H/D_{L250} values continue to rise throughout a stand's development, the second approach provides the more flexible option for long rotations. Strong differentiation of tree sizes reflects a hierarchy that persists through the life of stands. Fortunately, H/D_{L250} values in Douglas-fir stands tend to decline beyond 25-30 meters as the height growth increments decrease relative to diameter growth increments; consequently, controlling initial densities can promote stability throughout the development of a stand. An approximate maximum H/D_{L250} value can be anticipated through planting design or early thinning. The advantage of controlling early densities rather than developing greater tree size variation is the ease of implementation. Generating greater tree size variation requires planting seedlings with a range of ages or developing complex planting patterns.

The two options discussed above could be combined by developing mixed species stands. Relatively low initial Douglas-fir densities could be augmented by planting more shade tolerant species that Douglas-fir generally overtops (Wierman and Oliver 1979). Western hemlock and western red cedar are two species that appear to have minimal impacts on future Douglas-fir H/D_{L250} values (Chapters 2 and 3). In this approach, mixed-species

crown and size stratification replace size variation within a single species caused by age differences or spatial aggregation. One advantage of the mixed-species alternative is that it addresses concerns that wider spacings reduce wood quality (e.g. large branches, juvenile wood core, and weed competition). In addition, this approach increases species diversity. Diversity of tree species enhances habitat value and provides a greater range of timber products from a stand. A range of products provides some insurance against downturns in specific markets. In addition, a stand with multiple tree species is less likely to be completely decimated by insects or pathogens.

The management of Douglas-fir stands planted at high densities is less flexible from both an operational and a developmental perspective. Higher initial densities will increasingly restrict the thinning window which can effectively lower H/D_{L250} values. If thinning has not been accomplished during the narrow window, potential developmental pathways and endpoints for the stand are curtailed. Stands that develop high H/D_{L250} values do not have suitable trees to leave after late thinnings or for extended rotations. Options for the stand are primarily restricted to harvesting after a short rotation. If the objectives and expectations for a stand focus on high volume production during a short rotation, efficient use of growing space represents a high priority -- making planting Douglas-fir at high densities a reasonable management approach. When objectives are less clearly defined or future markets are somewhat uncertain, the value of stands that can be managed flexibly increases. Stands that cannot be managed flexibly lock the owner/manager into a strict treatment schedule or a limited product mix that may be costly if conditions change. Flexibility in management may be most critical for forestland controlled by public agencies. Even basic objectives for public agency forestland may swing widely with conflicting political pressures. Developing stands that, with minimal intervention, can provide outputs ranging from timber production to older forest habitat seems critical when future goals and management options are uncertain.

6.2.2 LANDSCAPE-SCALE CONSIDERATIONS

Exposure, soils, and site quality all interact with stand conditions to determine the risk of wind damage. Risk in turn has important implications for how flexibly a stand can be managed. Stands in topographically protected areas can be managed more flexibly since risk of wind damage is reduced by the site. Topographically protected sites may be exposed if wind come from unexpected directions (Rebertus et al. 1997). As landscape-scale silvicultural approaches are developed and modified, tradeoffs between risk from expected and unexpected storm directions should be considered (Chapter 4). Deeper well-drained soils that are less prone to windthrow increase management flexibility in much the same way as exposure. The interaction with site quality is slightly more complicated. Stands developing on sites that are more productive grow more quickly in height, achieving high heights and H/D_{L250} values sooner. More rapid height growth also results in temporally narrowed thinning windows for effective reduction of H/D values. In some cases site quality, soils, and exposure may have confounding impacts on wind risk and management flexibility. For example, stands on deep soils may be relatively productive, narrowing potential thinning windows and generating risk sooner (Rebertus et al. 1997).

The risk of wind damage changes dramatically across a landscape. Exposure ratings in Figure 25 depict this variation within a landscape. A management approach that is not modified according to landscape position does not account for these inherent differences in risk of wind damage. The balance between efficiency and flexibility changes when a single management approach is implemented on different landscape positions (Figure 37a). Wind risk in the graph is composed of equal contributions from site and stand risks (Chapter 4). On exposed sites with shallow soils, wind risk is heightened and management flexibility is reduced under all stand conditions. The importance of efficiency increases relative to flexibility if sites with high risk are managed in the same manner as those with low risk.

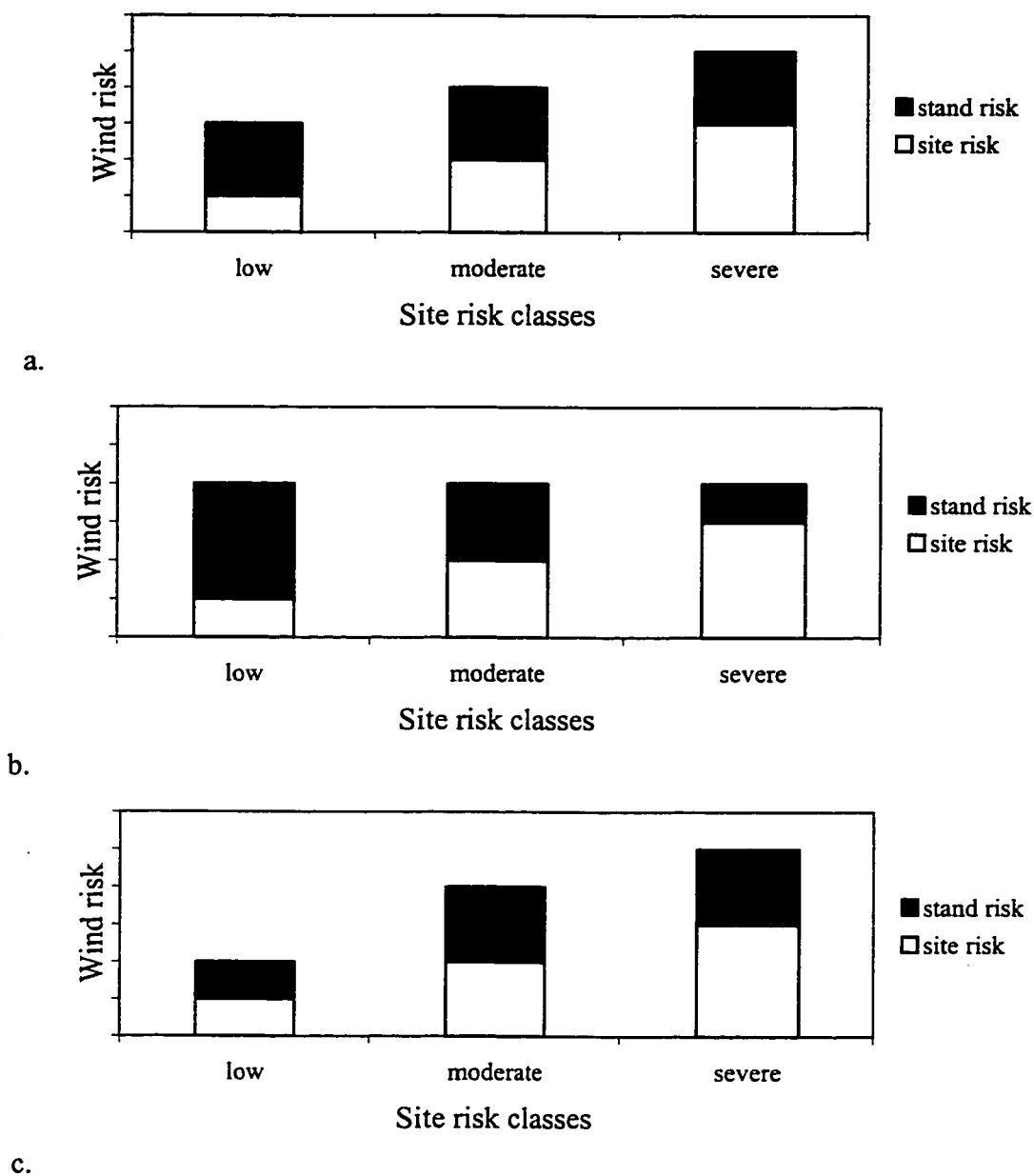


Figure 37: Conceptual comparison of wind risk rankings: (a) when a single silvicultural approach is used across a landscape; (b) when prescriptions are altered to account for inherent site risk; and (c) low site and stand risk are combined to provide very low risk stands that are more suitable for long rotations. Overall wind risk is composed of equal parts site and stand risk.

An alternative approach is to adapt management to site conditions so that the balance between efficiency and flexibility is applied more consistently across the landscape. In a simplified example that does not consider productivity differences between sites, planting density could be increased in stands with decreasing inherent site risk levels. Protected sites are planted at high densities; exposed sites are planted at lower densities or thinned earlier. The increased risk associated with stand attributes would be balanced by low site risk (Figure 37b). Conversely, if some proportion of the landscape needs to be in older forest structure flexibility could be weighted more heavily in stands with low inherent wind risk (Figure 37c). Low-density plantations on low-risk sites are capable of producing older forest structure that is likely to persist on the landscape. If older forest structure needs to be created rapidly, low risk, high quality sites could be preferentially chosen.

These simplified examples reveal the complexities associated with forest management when relatively subtle tradeoffs such as management flexibility and efficient use of growing space are considered. Tools that facilitate evaluations of complex management tradeoffs, such as a landscape wind risk rating system based on inventory information and growth model projections, have been proposed and developed (Mitchell 1995b, Chapter 4, Chapter 5, McCarter et al. *in press*).

6.3 CONCLUSION

The range of owner objectives and landscape conditions in the coastal Pacific Northwest suggests that no one silvicultural approach can achieve the appropriate balance between efficiency and flexibility. The intensive management required for high-density plantations may be acceptable for some owners, managers, and sites. For others, narrow thinning windows and restricted developmental pathways may be a burden that overwhelms any resulting gains in efficiency. Within an ownership, the range of site conditions over a landscape makes the balance between efficient use of growing space and management

flexibility variable and generally inconsistent if a single silvicultural approach is employed uniformly across the landscape. Sites with low wind risk provide opportunities for increasing efficiency or for providing older forest structure and high-quality forest products. Where operational constraints exist, such as limited access, the importance of management flexibility increases. The more difficult it is to access or conduct operations in a stand, the more burdensome timely treatment requirements or windthrow salvage become.

The increased emphasis on partial harvests, riparian buffer zones, and older forest habitat throughout the coastal Pacific Northwest and other regions heightens the value of stands that are developmentally flexible. Stands containing stable trees can provide residual trees, riparian buffers, and older forest structures with a high probability of surviving future windstorms.

Wind hazard is only one of many factors impacting flexibility of management; however, it provides a clear example how tradeoffs need to be evaluated. Other factors include fire and insect hazards, growth stagnation, wood quality, and stand structural constraints. Interestingly, extreme silvicultural approaches typically generate the most inflexible stands. Planting single-cohort stands at high densities for high volume production requires timely interventions to maintain stand stability. Similarly, establishing or maintaining multi-cohort stands of desirable shade-intolerant species requires multiple interventions to prevent mortality and maintain wood quality in the younger cohorts. A middle-ground approach, where operational and developmental flexibility are factored in decision making, may provide a more sensible combination of timber outputs, habitat, risk, management requirements, and future possibilities for many forest ownerships.

REFERENCES

- Ager, A.A., and R. J. McGaughey. 1997. UTOOLS: microcomputer software for spatial analysis and landscape visualization. USDA Forest Service, PNW Res. Sta. Gen. Tech. Rep. PNW-GTR-397.
- Alexander, R.R. 1964. Minimizing windfall around clear cuttings in spruce-fir forests. *For. Sci.* 10:131-142.
- Alexander, R.R. 1967. Windfall after clearcutting on Fool Creek. U.S.D.A. Forest Service Research Note. RM-92. 11 p.
- Alexander, R.R. 1987. Ecology, silviculture, and management of Engelmann spruce and subalpine fir type in central and southern Rocky Mountains. U.S.D.A. Forest Service Agric. Handbook No. 659.
- Andersen, K.F. 1954. Gales and gale damage to forests, with special reference to the effects of the storm of 31st January 1953, in the northeast of Scotland. *Forestry (Oxford)* 27:97-121.
- Assmann, E. 1970. *The Principles of Forest Yield Study*. Pergamon Press, Oxford and New York, 606 p.
- Baker, G.T. 1915. A windfall problem. *Forestry Quart.* 13:317-324.
- Batista, J.L.F. 1994. Spatial dynamics of trees in a Brazilian Atlantic tropical forest under natural and managed conditions. Dissertation. University of Washington. 327 p.
- Becquey, J. and P. Riou-Nivert. 1987. L'existence de zones de stabilite des peuplements. Consequences sur la gestion. *Revue Forstiere Francaise* 39:323-334.
- Bella, I.E. 1971. A new competition model for individual trees. *For. Sci.* 17:364-372.
- Bence, J.R. 1995. Analysis of short time series: correcting for autocorrelation. *Ecol.* 76:628-639
- Benjamin L.R. and R.C. Hardwick. 1986. Sources of variation and measures of variability in even-aged stands of plants. *Ann. Bot.* 58:757-778.

- Blackburn, P. and J.A. Petty. 1988. Theoretical calculations of the influence of spacing on stand stability. *Forestry* 61:235-244.
- Blackburn, P. J.A. Petty, and K.F. Miller. 1988. An assessment of the static and dynamic factors involved in windthrow. *Forestry* 61:29-43.
- Boose, E.R., D.R. Foster and M. Fluet. 1994. Hurricane impacts to tropical and temperate forest landscapes. *Ecol. Monogr.* 64:369-400.
- Boucher, D.H., J.H. Vandermeer, K. Yih, and N. Zamora. 1990. Contrasting hurricane damage in tropical rain forest and pine forest. *Ecol.* 71:2022-2024.
- Bouchon, J. 1987. Etat de la recherche relative aux degats forestiers dus aux tempetes. *Revue Forstiere Francaise* 39:301-312.
- Burrows, F.M. 1991. Biomass production, structural deformation, self-thinning and thinning mechanisms in monocultures. *Philosophical Transactions of the Royal Society of London B*, 333:119-245.
- Busby, J.A. 1965. Studies on the stability of conifer stands. *Scott. For.* 19:86-102.
- Cannell, M.G.R., P. Rothery, and E.D. Ford. 1984. Competition within stands of *Picea sitchensis* and *Pinus contorta*. *Ann. Bot.* 53:349-362.
- Carter, P.C.S. 1988. Wind damage in Kinleith forest- effects of Cyclone Bola. in *Proceedings of Workshop on Wind Damage in New Zealand Exotic Forests*. New Zealand Forestry Institute Bulletin 146. p.17-19.
- Chandler, K.C. 1968. Climatic damage to the forests of the Tapanui district. *N. Z. J. For.* 13:98-110.
- Collier, R. and J. Haukaas. 1996. Stand Management Cooperative: Database Report. Stand Management Cooperative, College of Forest Resources, University of Washington. 25 p.
- Clatterbuck, W.K. and J.D. Hodges. 1988. Development of cherrybark oak and sweet gum in mixed, even-aged bottomland stands in central Mississippi, U.S.A. *Can. J. For. Res.* 18:12-18.
- Clutter, J.L., J.C. Fortson, L.V. Pinearr, G.H. Brister, and R.L. Bailey. 1983. *Timber Management: A Quantitative Approach*. John Wiley and Sons, New York. 333 p.

- Cremer, K.W., B.J. Myers, F. Van Der Duys, and I.E. Craig. 1977. Silvicultural lessons from the 1974 windthrow in radiata pine plantations near Canberra. *Austral. For.* 40:274-292.
- Cremer, K.W., C.J. Borough, F.H. McKinnell, and P.R. Carter. 1982. Effects of stocking and thinning on wind damage in plantations. *N. Z. J. For. Sci.* 12:244-268.
- Crowder, M.J. and D.J. Hand. 1990. *Analysis of Repeated Measures*. Chapman and Hall. New York. 257 p.
- Coutts, M.P. 1986. Components of tree stability in Sitka spruce on peaty gley soil. *Forestry* 59:173-197.
- Curtis, R.O. and D.D. Marshall. 1986. Levels-of-growing-stock cooperative study in Douglas-fir: Report no. 8-The LOGS Study: Twenty-year results. USDA Forest Service Research Paper. PNW-356. 113 p.
- Curtis, R.O., D.D. Marshall, and J.F. Bell. 1997. LOGS a pioneering example of silvicultural research in coast Douglas-fir. *J. For.* 95(5):19-25.
- Daniels, R.F. 1976. Simple competition indices and their correlation with annual loblolly pine tree growth. *For. Sci.* 22:454-456.
- Deen, J.L. 1933. Some aspects of an early expression of dominance in white pine. *Yale University School of Forestry Bulletin No. 36*. 34 p.
- Day, W.R. 1950. The soil conditions which determine windthrow in forests. *Forestry* 23:90-95.
- Donnelly, D.M. 1996. Pacific Northwest Coast Variant of the Forest Vegetation Simulator. WO-Forest Management Service Center. USDA-Forest Service. Fort Collins, Colorado. 38 p.
- Drew, T.J. and J.W. Flewelling. 1977. Some recent Japanese theories of yield-density relationships and their application to Monterey pine plantations. *For. Sci.* 23:517-534.
- Drew, T.J. and J.W. Flewelling. 1979. Stand density management: an alternative approach and its application to Douglas-fir plantations. *For. Sci.* 25:518-532.
- Everham, E.E. and N.V.L. Brokaw. 1996. Forest damage and recovery from catastrophic wind. *The Bot. Rev.* 62:114-185.

- Farnden, C. 1996. Coastal Douglas-fir stand density management diagram, B.C. Ministry of Forests, Silviculture Practices Branch.
- Fight, R.D., J.M. Cahill, T.A. Snellgrove, and T.D. Fahey. 1987. Prune-Sim Users Guide. USDA Forest Service, General Technical Report PNW-209.
- Firbank, L.G. and A.R. Watkinson. 1987. On the analysis of competition at the level of the individual plant. *Oecologia* 71:308-317.
- Ford, E.D. 1975. Competition and stand structure in some even-aged plant monocultures. *J. Ecol.* 63:311-333.
- Ford, E.D. 1982. High productivity in a polestage Sitka spruce stand and its relation to canopy structure. *Forestry* 55:1-17.
- Ford, E.D. and P.J. Diggle. 1981. Competition for light in a plant monoculture modelled as a spatial stochastic process. *Ann. Bot.* 48:481-500.
- Foster, D.R. 1988. Species and stand response to catastrophic wind in central New England, U.S.A. *J. Ecol.* 76:135-151.
- Foster, D.R. and E.R. Boose. 1992. Patterns of forest damage resulting from catastrophic wind in central New England, USA. *J. Ecol.* 80:79-98.
- Fowler, N.L. 1984. The role of germination date, spatial arrangement, and neighbourhood effects in competitive interactions in *Linum*. *J. Ecol.* 72:307-318.
- Franco, M. 1986. The influence of neighbours on the growth of modular organisms with an example from trees. *Phil. Trans. R. Soc. Lond.*, 313:209-225.
- Franco, M. and J.L. Harper. 1988. Competition and the formation of spatial pattern in spacing gradients: An example using *Kochia scoparia*. *J. Ecol.* 76:959-974.
- Fraser, A.I. and J.B.H. Gardiner. 1967. Rooting and stability in Sitka spruce. *Forestry Commission Bulletin No. 40*. 28 p.
- Galinski, W. 1989. A windthrow-risk estimation for coniferous trees. *Forestry* 62:139-146.
- Gardiner, B.A., G.R. Stacey, R.E. Belcher, and C.J. Wood. 1997. Field and wind tunnel assessments of the implications of respacing and thinning for tree stability. *Forestry* 70:233-252.

- Getis, A. and J. Franklin. 1987. Second-order neighborhood analysis of mapped point patterns. *Ecol.* 68:473-477.
- Gibson, D.J. and R.E. Good. 1986. Population structure and thinning in natural stands of Atlantic white cedar (*Chamaecyparis thyoides* (L.) BSP). *Oecologia* 69:348-353.
- Green, S.E., P.A. Harcombe, M.E. Harmon, and G. Spycher. 1992. Patterns of growth, mortality and biomass change in a coastal *Picea sitchensis* - *Tsuga heterophylla* forest. *J. Veg. Sci.* 3:697-706.
- Hannah, P., J.P. Palutikof, and C.P. Quine. 1995. Predicting windspeeds for forest areas in complex terrain. in *Wind and Trees*. ed. M.P. Coutts and J. Grace. Cambridge University Press, Cambridge, 485 p.
- Hara, T. 1988. Dynamics of size structure in plant populations. *Trends Ecol. Evol.* 3:129-132.
- Hara T., M. Kimura, and K. Kikuzawa. 1991. Growth patterns of tree height and stem diameter in populations of *Abies veitchii*, *A. mariesii* and *Betula ermanii*. *J. Ecol.* 79:1085-1098.
- Hara, T. and T. Wyszomirski. 1994. Competitive asymmetry reduces spatial effects on size-structure dynamics in plant populations. *Ann. Bot.* 73:285-297.
- Harrington, T.B., J.C. Tappeiner II, and T.F. Hughes. 1991. Predicting average growth and size distributions of Douglas-fir saplings competing with sprout clumps of tanoak or Pacific madrone. *New Forests* 5:109-130.
- Harper, J.L. 1977. *The Population Biology of Plants*. Academic Press, London, 892 p.
- Henderson, J.A., D.H. Peter, R.D. Leshner, and D.C. Shaw. 1989. Forested plant associations of the Olympic National Forest. USDA Forest Service, Regional Ecology Technical Paper 001-88.
- Hester, A.S., D.W. Hann and D.R. Larsen. 1989. ORGANON: Southwest Oregon growth and yield model user manual, Version 2.0. Oregon State University, Forest Research Laboratory, Corvallis, Oregon. 59p.
- Holbrook, N.M. and F.E. Putz. 1989. Influence of neighbors on tree form: Effects of lateral shade and prevention of sway on the allometry of *Liquidambar styraciflua* (sweet gum). *Amer. J. Bot.* 76:1740-1749.

- Hoyer, G.E. 1991. Growing Douglas-fir standards: a two-aged alternative to evenaged forests. Forest Land Management Center Contribution No. 346. State of Washington, Department of Natural Resources. 27 p.
- Huston, M.A. and D.L. DeAngelis. 1987. Size bimodality in monospecific populations: a critical review of potential mechanisms. *The Amer. Nat.* 129:678-707.
- Hutchings, M.J., and C.S.J. Budd. 1981. Plant competition and its course through time. *Biosci.* 31:640-645.
- Kenkel, N.C. 1988. Pattern of self-thinning in jack pine: Testing the random mortality hypothesis. *Ecol.* 69:1017-1024.
- Kennedy, M.J. 1974. *Windthrow and Windsnap in Forest Plantations, Northern Ireland*. Michigan Geographical Publication No. 11, University of Michigan, Ann Arbor. 164 p.
- Kenworthy, T. 1998. Gone with the wind; Forest Service mulls over miles of toppled trees in the Rockies. *The Wash. Post*. Feb. 2.
- Kikuzawa, K. 1988. Intraspecific competition in a natural stand of *Betula ermanii*. *Ann. Bot.* 61:727-734.
- Kimmins, J.P. 1987. *Forest Ecology*. Macmillan Publishing Company, New York. 531 p.
- King, D.A. 1986. Tree form, height growth, and susceptibility to wind damage in *Acer saccharum*. *Ecol.* 67:980-990.
- Kohyama T., T. Hara, and Y. Yadaki. 1990. Patterns of trunk diameter, tree height and crown depth in crowded *Abies* stands. *Ann. Bot.* 65:567-574.
- Kozlowski, T.T., P.J. Kramer, and S.G. Pallardy. 1991. *The physiological ecology of woody plants*. Academic Press, San Diego, 657 p.
- Knowe, S.A. 1991. Simultaneous prediction of the development of loblolly pine and woody competitors in young plantations. *New Forests* 5:175-193.
- Knowe, S.A. 1992. Basal area and diameter distribution models for loblolly pine plantations with hardwood competition in the Piedmont and upper Coastal Plain. *South. J. App. For.* 16:93-98.

- Knowe, S.A. 1994. Effect of competition control treatments on height-age and height-diameter relationships in young Douglas-fir plantations. *For. Ecol. Manage.* 67:101-111.
- Knowe, S.A., T.B. Harrington, and R.G. Shula. 1992. Incorporating the effects of interspecific competition and vegetation management treatments in diameter distribution models for Douglas-fir saplings. *Can. J. For. Res.* 22:1255-1262.
- Knowe, S.A., B.D. Carrier, and A. Dobkowski. 1995. Effects of bigleaf maple sprout clumps on diameter and height growth of Douglas-fir. *W. J. App. For.* 10(1):5-11.
- Knox, R.G., R.K. Peet, and N.L. Christensen. 1989. Population dynamics in loblolly pine stands: Changes in skewness and size inequality. *Ecol.* 70:1153-1166.
- Laiho, O. 1987. Susceptibility of forest stands to windthrow in southern Finland. *Folia Forestalia.* 706:3-24
- Lohmander, P. and Helles, F. 1987. Windthrow probability as a function of stand characteristics and shelter. *Scand. J. For. Res.* 2:227-238.
- Long, J.N. and F.W. Smith. 1983. Relation between size and density in developing stands: a description and possible mechanisms. *For. Ecol. Man.* 7:191-206.
- Lonsdale, W.M. 1990. The self-thinning rule: dead or alive? *Ecol.* 71: 1373-1388.
- Lutz, M. 1996. *Programming Python.* O'Reilly and Associates. Sebastopol, CA USA.
- Lynott, R.E. and O.P. Cramer. 1966. Detailed analysis of the 1962 Columbus Day windstorm in Oregon and Washington. *Monthly Weather Review* 94:105-117.
- Mack, R.N. and J.L. Harper. 1977. Interference in dune annuals: Spatial pattern and neighbourhood effects. *J. Ecol.* 65:345-363.
- Maccurrach, R.S. 1991. Spacing: an option for reducing storm damage. *Scott. For.* 45:285-297.
- Martin, G.L. and A.R. Ek. 1984. A comparison of competition measures and growth models for predicting plantation red pine diameter and height growth. *For. Sci.* 30:731-743.
- Mason, W.L. and C.P. Quine. 1995. Silvicultural possibilities for increasing structural diversity in British spruce forests: the case of Kielder Forest. *For. Ecol. Man.* 79:13-28.

- Matlack, G.R., S.K. Gleeson, and R.E. Good. 1993. Treefall in a mixed oak-pine coastal plain forest: immediate and historical causation. *Ecol.* 74:1559-1566.
- Mattheck, C., K. Bethge, and W. Albrecht. 1995. Failure modes of trees and related failure criteria. in *Wind and Trees*. ed. M.P. Coutts and J. Grace. Cambridge University Press, Cambridge, 485 p.
- McCarter, J.B. 1997. Integrating forest inventory, growth and yield, and computer visualization into a landscape management system. In: Teck, R., M. Moeur, and J. Adams (*comps.*), Proceedings of the Forest Vegetation Simulator conference. Gen. Tech. Rep. INT-GTR-373. Ogden, UT. USDA Forest Service, Intermountain Research Station. p.159-167.
- McCarter, J.B., J.S. Wilson, P.J. Baker. 1996. Landscape Management User's Manual, Version 1.5. Landscape Management Project, College of Forest Resources, University of Washington. 97 pp.
- McCarter, J.M., J.S. Wilson, P.J. Baker, J.L. Moffett, and C.D. Oliver. *in press*. Landscape management through integration of existing tools and emerging technologies. *J. For.*
- McMahon, T.A. 1973. Size and shape in biology. *Science* 505:1201-1204.
- McMahon, T.A. 1975. The mechanical design of trees. *Sci. Amer.* 233:92-102.
- McMahon, T.A. and R.E. Kronauer. 1976. Tree structures: Deducing the principle of mechanical design. *J. Theor. Bio.* 59:443-466.
- Mergen, F. 1954. Mechanical aspects of wind-breakage and windfirmness. *J. For.* 52:119-125
- Meredith M.P. and S.V. Stehman. 1991. Repeated measures experiments in forestry: focus on analysis of response curves. *Can. J. For. Res.* 21:957-965.
- Miller, K.F. 1985. Winthrow hazard classification. Forestry Commission Leaflet 85. 14 p.
- Miller, K.F., C.P. Quine, and J. Hunt. 1987. The assessment of wind exposure for forestry in upland Britain. *Forestry* 60:180-192.
- Miller, R.E., R.E. Bigley, and S. Webster. 1993. Early development of matched planted and naturally regenerated Douglas-fir stands after slash burning in the Cascade Range. *W. J. App. For.* 8:5-10.

- Miller, R.E. and H.W. Anderson. 1995. Stand characteristics of 65-year-old planted and naturally regenerated stands near Sequim, Washington.. USDA Forest Service Research Paper, PNW-482, 11 p.
- Miller, T.E. and J. Weiner. 1989. Local density variation may mimic effects of asymmetric competition on plant size variability. *Ecol.* 70(4):1188-1191.
- Milne, R. 1995. Modelling mechanical stresses in living Sitka spruce stems. in *Wind and Trees*. ed. M.P. Coutts and J. Grace. Cambridge University Press, Cambridge, 485 p.
- Mitchell, K.J. and I.R. Cameron. 1985. Managed stand yield tables for coastal Douglas-fir: Initial density and precommercial thinning. B.C. Ministry of Forests, Land Management Report 31, 69 p.
- Mitchell, K.J. 1975. Dynamics and simulated yield of Douglas-fir. *For. Sci. Monogr.* 17. 39 p.
- Mitchell, K.J. 1986. Comparison of McArdle, DFSIM and TASS growth and yield models. in *Douglas-fir: Stand Management for the Future*. ed. C.D. Oliver, D. Hanley, and J. Johnson. University of Washington, College of Forest Resources, Seattle. 388 p.
- Mitchell, K.J. and K.R. Polsson. 1988. Site index curves and tables for British Columbia: Coastal species. B. C. Ministry of Forests, FRDA Report 037, 29 p.
- Mitchell, S.J. 1995a. A synopsis of windthrow in British Columbia: occurrence, implications, assessment and management. in *Wind and Trees*. ed. M.P. Coutts and J. Grace. Cambridge University Press, Cambridge, 485 p.
- Mitchell, S.J. 1995b. The windthrow triangle: A relative windthrow hazard assessment procedure for forest managers. *The For. Chron.* 71:446-450.
- Mitchell-Olds, T., 1987. Analysis of local variation in plant size. *Ecol.* 68:82-87.
- Moeur, M. 1993. Characterizing spatial patterns of trees using stem-mapped data. *For. Sci.* 39:756-775.
- Moeur, M. 1997. Spatial models of competition and gap dynamics in old-growth *Tsuga heterophylla/Thuja plicata* forests. *For. Ecol. Man.* 94:175-186.

- Mohler, C.L., P.L. Marks, and D.G. Sprugel. 1978. Stand structure and allometry of trees during self-thinning of pure stands. *J. Ecol.* 66:599-614.
- Moser, E.B., A.M. Saxton, and S.R. Pezeshki. 1990. Repeated measures analysis of variance: application to tree research. *Can. J. For. Res.* 20:524-535.
- Neter J., Wasserman, W. and M.H. Kutner. 1989. *Applied Linear Regression Models*. Irwin, Inc. Boston.
- Neustein, S.A. 1971. Damage to forests in relation to topography soil and crops. p.42-48 in *Windblow of Scottish Forests in January 1968*. ed. B.W. Holtam. Forestry Commission Bulletin 45.
- Niklas, K.J. 1994. *Plant allometry: The scaling of form and process*. The University of Chicago Press, Chicago. 394 p.
- Nilsson, U. and A. Albrektson. 1994. Growth and self-thinning of two young Scots pine stands planted at different initial densities. *For. Ecol. Man.* 68:209-215.
- Nykanen, M.L., H. Peltola, C.P. Quine, S. Kellomaki, and M. Broadgate. 1997. Factors affecting snow damage of trees with particular reference to European conditions. *Silva Fennica* 31:193-213.
- O'Hara, K.L. 1988. Stand structure and growing space efficiency following thinning in an even-aged Douglas-fir stand. *Can. J. For. Res.* 18:859-866.
- O'Hara, K.L. 1995. Early height development and species stratification across five climax series in the eastern Washington Cascade range. *New Forests* 9:53-60.
- Oliver, C.D. 1995. A Portfolio approach to landscape management: an economically, ecologically, and socially sustainable approach to forestry. *Inn. Silv. Sys. in Boreal For.* 66-76.
- Oliver, C.D., W.K. Clatterbuck, and E.C. Burkhardt. 1990. Spacing and stratification patterns of cherrybark oak and American sycamore in mixed, even-aged stands in the southeastern United States. *For. Ecol. Manage.* 31:67-79.
- Oliver, C.D. and B.C. Larson. 1996 *Forest Stand Dynamics*. Wiley and Son, New York.

- Oliver, C.D., Michalec, W., Duvall, L., Wierman, C.A. and H. Oswald. 1986a. Silvicultural costs of growing Douglas-fir of various spacings, sites, and wood qualities. in *Douglas-fir: Stand Management for the Future*. ed. C.D. Oliver, D. Hanley, and J. Johnson. University of Washington, College of Forest Resources, Seattle. 388 p.
- Oliver, C.D. and M.D. Murray. 1983. Stand structure, thinning prescriptions, and density indexes in a Douglas-fir thinning study, western Washington, U.S.A. *Can. J. For. Res.* 13:126-135.
- Oliver, C.D., O'Hara, K.L., McFadden, G. and I. Nagame, 1986b. Concepts of thinning regimes. in *Douglas-fir: Stand Management for the Future*. ed. C.D. Oliver, D. Hanley, and J. Johnson. University of Washington, College of Forest Resources, Seattle. 388 p.
- Omule, S.A.Y. 1985. Response of coastal Douglas-fir to pre-commercial thinning on a medium site in British Columbia. B.C. Ministry of Forests Research Note 100, 56 p.
- Osher J. and D. Stoyan. 1981. On the second-order and orientation analysis of planar stationary point processes. *Biometrical J.* 23:523-533.
- Palik, B.J. and K.S. Pretzinger. 1991. The relative influence of establishment time and height-growth rates on species vertical stratification during secondary forest succession. *Can. J. For. Res.* 21:1481-1490.
- Papesch A.J.G. 1974. A simplified theoretical analysis of the factors that influence windthrow of trees. Fifth Australasian Conference on Hydraulics and Fluid Mechanics. Christchurch. 235-242.
- Peltola, H. and S. Kellomaki. 1993. A mechanistic model for calculating windthrow and stem breakage of Scots pines at stand edge. *Sylva Fennica.* 27:99-111.
- Peltola, H., M.L. Nykanen, and S. Kellomaki. 1997. Model computations on the critical combination of snow loading and windspeed for snow damage of Scots pine, Norway spruce, and birch sp. at stand edge. *For. Ecol. Manage.* 95:229-241.
- Petersen, T.D. 1988. Effects of interference from *Calamagrostis rubescens* on size distributions in stands of *Pinus ponderosa*. *J. App. Ecol.* 25:265-272.
- Petty, J.A. and C. Swain. 1985. Factors influencing stem breakage of conifers in high winds. *Forestry* 58:75-84.

- Petty, J.A. and R. Worrell. 1981. Stability of coniferous tree stems in relation to damage by snow. *Forestry* 54:115-128.
- Putz, F.E. and R.R. Sharitz. 1991. Hurricane damage to old-growth forest in Congaree Swamp National Monument, South Carolina, U.S.A. *Can. J. For. Res.* 21:1765-1770.
- Quine, C.P. 1995. Assessing the risk of wind damage to forests: practice and pitfalls. in *Wind and Trees*. ed. M.P. Coutts and J. Grace. Cambridge University Press, Cambridge, 485 p.
- Quine, C.P. and I.M.S. White. 1993. Revised windiness scores for the windthrow hazard classification: the revised scoring method. *Forestry Commission Research Information Note* 230. 5 p.
- Quine, C.P. Coutts, B. Gardiner, and G. Pyatt. 1995. Forests and wind: Management to minimise damage. *Forestry Commission Bulletin* 114, 24 p.
- Rebertus, A.J., T. Kitzberger, T.T. Veblen, and L.M. Roovers. 1997. Blowdown history and landscape patterns in the Andes of Tierra Del Fuego, Argentina. *Ecol.* 78:678-692.
- Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. *Journal of Agricultural Research* 46:627-638.
- Reukema, D.L. 1970. Forty-year development of Douglas-fir stands planted at various spacings. *USDA Forest Service Research Paper*, PNW-100, 21 p.
- Reukema, D.L. 1979. Fifty-year development of Douglas-fir stands planted at various spacings. *USDA Forest Service Research Paper*, PNW-253, 21 p.
- Reukema, D.L. and D. Bruce. 1977. Effects of thinning on yield of Douglas-fir: Concepts and some estimates obtained by simulation. *USDA Forest Service General Technical Report*, PNW-58, 38 p.
- Reukema, D.L. and J.H.G. Smith. 1987. Development over 25 years of Douglas-fir, western hemlock, and western redcedar planted at various spacings on a very good site in British Columbia. *USDA Forest Service Research Paper*, PNW-381, 46 p.
- Reynolds, J.H. 1997. Multi-criteria assessment of ecological process models using pareto optimization. *Dissertation*. University of Washington.

- Ritchie, G.A. 1997. Evidence for red:far red signaling and photomorphogenic growth response in Douglas-fir (*Pseudotsuga menziesii*) seedlings. *Tree Phys.* 17:161-168.
- Rollinson, T.J.D. 1987. Thinning control of conifer plantations in Great Britain. *Ann. Sci. For.* 44:25-34.
- Ross, M.A. and J.L. Harper. 1972. Occupation of biological space during seedling establishment. *J. Ecol.* 60:77-88.
- Ruel, J. 1995. Understanding windthrow: silvicultural implications. *The For. Chron.* 71:434-445.
- Ruel, J.C., D. Pin, L. Spacek, K. Cooper, and R. Benoit. 1997. The estimation of wind exposure for winthrow hazard rating: comparison between Strongblow, MC2, Topex and a wind tunnel study. *Forestry* 70:253-266.
- Ruth, R.H. and R.A. Yoder. 1953. Reducing wind damage in the forests of the Oregon Coast Range. U.S.D.A. Forest Service Research Paper. PNW-7. 30 p.
- Savill, P.S. 1983. Silviculture in windy climates. *For. Abs.* 44:473-487.
- Schwinning, S. and J. Weiner. 1998. Mechanisms determining the degree of size asymmetry in competition among plants. *Oecologia* 113:447-455.
- Scott, W., R. Meade, R. Leon, D. Hyink, and R. Miller. 1998. Planting density and tree-size relations in coast Douglas-fir. *Can. J. For. Res.* 28:74-78.
- Shaw, W.B. 1983. Tropical cyclones: determinants of pattern and structure in New Zealand's indigenous forests. *Pacific Sci.* 37:405-414.
- Shifley, S. and E. Lentz. 1985. Quick estimation of the three-parameter Weibull to describe tree size distributions. *For. Ecol. Man.* 13:195-203.
- Silvertown, J.W. and J.L. Doust. 1993. Introduction to plant population biology. Blackwell Scientific Publications, Oxford, 210 p.
- Slodicak, M. 1995. Thinning regime in stands of Norway spruce subjected to snow and wind damage. in *Wind and Trees*. ed. M.P. Coutts and J. Grace. Cambridge University Press, Cambridge, 485 p.
- Smith, D.M., B.C. Larson, M.J. Kelty, and P.M.S. Ashton. 1997. *The Practice of Silviculture: Applied Forest Ecology*. 9th ed., John Wiley & Sons, N.Y.C., 537 p.

- Smith, J.H.G. 1983. Graphical summaries and data on the U.B.C. Research Forest spacing trials (57-5) to age 26 and evaluations of results to date. Dept. of Forest Resource Management. Faculty of Forestry. 79 p.
- Smith, J.H.G. and D.L. Reukema. 1986. Effects of plantation and juvenile spacing on tree and stand development.in *Douglas-fir: Stand Management for the Future*. ed. C.D. Oliver, D. Hanley, and J. Johnson. University of Washington, College of Forest Resources, Seattle. 388 p.
- Smith, K. and R.H. Weitknecht. 1915. Windfall damage in selection cuttings in Oregon. Proc. Soc. Amer. Forest. 10:263-265.
- Smith, V.G., M. Watts, and D.F. James. 1987. Mechanical stability of black spruce in the clay belt region of northern Ontario. Can. J. For. Res. 17:1080-1091.
- Sokal, R.R. and F.J. Rohlf. 1981. *Biometry*. W.H. Freeman and Co. New York. 859 p.
- Stage, A.R., C.G. Shaw III, M.A. Marsden, J.W. Byler, D.L. Renner, B.B. Eav, P.J. McNamer, G.D. Sutherland, and T.M. Webb. 1990. User's manual for western root disease model. U.S.D.A. Forest Service. GTR-INT-267. 49 p.
- StatSoft, Inc. 1997. STATISTICA for Windows [Computer program manual]. Tulsa, OK: StatSoft, Inc., 2300 East 14th Street, Tulsa, OK 74104, phone: (918) 749-1119, fax: (918) 749-2217, email: info@statsoft.com, WEB: http://www.statsoft.com
- Stoll, P., Weiner, J., and B. Schmid. 1994. Growth variation in a naturally established population of *Pinus Sylvestris*. Ecol. 75(3):660-670.
- Stone, J.N. 1994. Extensive studies of fertilizing and thinning coastal Douglas-fir and western hemlock: An installation report. B.C. Ministry of Forests, FRDA Report 227. 116 p.
- Stubblefield, G.W. 1979. Reconstruction of a red alder/Douglas-fir/western, hemlock/western redcedar mixed stand and its biological and, silvicultural implications. Masters Thesis. College of Forest Resources, University of Washington.
- Tang, S.M., J.F. Franklin, and D.R. Montgomery. 1997. Forest harvest patterns and landscape disturbance processes. Landscape Ecol. 12:349-363.
- Teck, R., M. Moeur, and B. Eav. 1996. Forecasting Ecosystems with the Forest Vegetation Simulator. J. For. 94:7-10.

- Valinger, E. and J. Fridman. 1997. Modelling probability of snow and wind damage in Scots pine stands using tree characteristics. *For. Ecol. Man.* 97:215-222.
- Valinger, E. and L. Lundqvist. 1992. The influence of thinning and nitrogen fertilisation on the frequency of snow and wind induced stand damage in forests. *Scott. For.* 46:311-320.
- Valinger, E., L. Lundqvist, and L. Bondesson. 1993. Assessing the risk of snow and wind damage from tree physical characteristics. *Forestry* 66:249-260.
- Valinger, E., L. Lundqvist, and G. Brandel. 1994. Wind and snow damage in a thinning and fertilisation experiment in *Pinus sylvestris*. *Scand. J. For. Res.* 9:129-134.
- Vanclay, J.K. 1994. *Modeling Forest Growth and Yield: Applications to Mixed Tropical Forests*. CAB International. Wallingford, UK. 312 p.
- Versfeld, D.B. 1980. An assessment of windfall damage to *Pinus radiata* in the Bosboukloof Experimental Catchment. *South African For. J.* 112:15-19.
- Vonesh, E.F. and V.M. Chinchilli. 1997. *Linear and nonlinear models for the analysis of repeated measures*. Marcel Dekker Inc., N.Y.C. 560 p.
- Wampler, M. 1993. Growth of Douglas-fir under partial overstory retention. Masters Thesis. College of Forest Resources, University of Washington. 97 p.
- Wagner R.G. and S.R. Radosevich. 1991. Neighborhood predictors of interspecific competition in young Douglas-fir plantations. *Can. J. For. Res.* 21:821-835.
- Waller, D.M. 1981. Neighborhood competition in several violet populations. *Oecologia* 51:116-122.
- Ward, J.S., G.R. Parker, and F.J. Ferrandino. 1996. Long-term spatial dynamics in an old-growth deciduous forest. *For. Ecol. Man.* 83:189-202.
- Watkinson, A.R. 1985. Plant responses to crowding. in *Studies on Plant Demography A Festschrift for John L. Harper*. ed. J. White, Academic Press, New York, p. 275-289.
- Watters, A., van Rossum, G., and Ahlstrom, J.C. 1996. *Internet Programming with Python*. M&T Books. New York, USA.

- Weidman, R.H. 1920a. A study of windfall loss of western yellow pine in selection cuttings fifteen to thirty years old. *J. For.* 18:616-622.
- Weidman, R.H. 1920b. The windfall problem in the Klamath Region, Oregon. *J. For.* 18:837-843.
- Weiner, J. 1984. Neighbourhood interference amongst *Pinus rigida* individuals. *J. Ecol.* 72:183-195.
- Weiner, J. 1988. Variation in the performance of individuals in plant populations. in *Plant Population Ecology*, 28th Symposium of the British Ecological Society. ed. A.J. Davy, M.J. Hutchings, and A.R. Watkinson. Blackwell Scientific Publications, Oxford, p. 59-81.
- Weiner, J. 1995. Following the growth of individuals in crowded plant populations. *Trends Ecol. Evol.* 4:389-390.
- Weiner, J. and O.T. Solbrig. 1984. The meaning and measurement of size hierarchies in plant populations. *Oecologia* 61:334-336.
- Weiner, J. and S.C. Thomas. 1986. Size variability and competition in plant monocultures. *Oikos*. 47:211-222.
- West P.W. and C.J. Borough. 1983. Tree suppression and the self-thinning rule in a monoculture of *Pinus radiata* D. Don. *Ann. of Bot.* 52:149-158.
- Wheat, J. and R. Silen. 1985. Progress Report for IFA-PNW Cooperative Tree Improvement Program. Industrial Forestry Association, Portland, Oregon, 51 p.
- White J. 1985. The thinning rule and its application to mixtures of plant populations. in *Studies on Plant Demography*. ed. J. White. Academic Press, London. p. 291-309.
- White J. and J.L. Harper. 1970. Correlated changes in plant size and number in plant populations, *J. Ecol.* 58:467-485.
- Wierman, C.A. and W.H. Knapp. 1986. Douglas-fir thinning practices and their justification. in *Douglas-fir: Stand Management for the Future*. ed. C.D. Oliver, D. Hanley, and J. Johnson. University of Washington, College of Forest Resources, Seattle. 388 p.
- Wierman, C.A. and C.D. Oliver. 1979. Crown stratification by species in even-aged mixed stands of Douglas-fir - western hemlock. *Can. J. For. Res.* 9:1-9.

- Wiley, K.N. 1965. Effects of the October 12, 1962 windstorm on permanent growth plots in southwest Washington. Weyerhaeuser Forestry Paper No. 7, 13 p.
- Wilson, J.B. 1988. The effect of initial advantage on the course of plant competition. *Oikos* 51:19-24.
- Wilson, J.S. and P. J. Baker. *in press*. Mitigating fire risk to late-successional forest reserves on the east slope of the Washington Cascade Range, USA. *For. Ecol. Manage.*
- Wilson, J. S., E. S. Isaac, and R. I. Gara. *in press*. Impacts of mountain pine beetle (*Dendroctonus ponderosae*) infestation on future landscape susceptibility to the western spruce budworm (*Choristoneura occidentalis*) in north central Washington. *J. App. Ent.*
- Wimberly, M.C. and B.B. Bare. 1996. Distance-dependent and distance-independent models of Douglas-fir and western hemlock basal area growth following silvicultural treatment. *For. Ecol. Man.* 89:1-11.
- Yoda, K., T. Kira, H. Ogawa, and K. Hozumi. 1963. Self-thinning in overcrowded pure stands under cultivated and natural conditions. *J. of Biol., Osaka City University*, 14:107-129.
- Zar, J.H. 1984. *Biostatistical Analysis*. Prentice Hall, Engelwood Cliffs, N.J. 718 p.
- Zeide, B. 1987. Analysis of the $-3/2$ power law of self-thinning. *For. Sci.* 33:517-537.
- Zens, S. *in prep*. Structure and dynamics of Douglas-fir and western hemlock responses to reductions in density. Dissertation. Dartmouth University.
- Zumrawi, A.A., J. Beale, and L. de Montigny. 1995. Effects of site and treatment on root rot contribution to mortality in the EP703 standard installations. B.C. Ministry of Forests Research Branch. 54 p.

APPENDIX A: EXPERIMENTAL PLOT DATA USED IN THE ANALYSIS

Experimental Plot 703 (EP703): B.C. Ministry of Forests, Vancouver Island, BC (Stone 1994, *Zens in prep.*). In the early 1970's the British Columbia Ministry of Forests (BCMOF) established a large set of permanent forest plots in the southwest coast of British Columbia. Experimental Project 703 (EP703) was established to provide growth and yield data for Douglas-fir and western hemlock stands under intensive forest management (Stone 1994). The study has a two-factor design in which the effects of silvicultural thinning and fertilization are evaluated. It consists of 85 installations, each with multiple plots. Installations are primarily located in eastward-draining watersheds of Vancouver Island. This project principally uses data from the two control plots from 31 of the installations. Only installations that contain control plots and were dominated by Douglas-fir were chosen. Note: Installations with > 3 plots include those plots used for the evaluation of thinning in Chapter 3.

Installation	# of plots	# of measurements	50-year site index (m)	Plot size (ha)	Regeneration type
2	3	7	23.00	0.05	Natural
3	2	7	30.00	0.05	Natural
5	6	7	32.00	0.05	Planted
7	3	7	25.00	0.05	Natural
10	6	7	30.00	0.05	Planted
11	2	6	34.00	0.05	Planted
12	2	6	31.00	0.05	Planted
13	6	6	25.00	0.05	Planted
14	6	7	34.00	0.05	Planted
16	6	7	38.00	0.05	Planted
18	2	6	37.00	0.05	Natural
19	3	7	34.00	0.07	Natural
20	2	6	27.00	0.05	Natural
22	3	7	30.00	0.05	Natural
25	2	6	31.00	0.07	Natural
47	3	6	28.00	0.07	Natural
48	2	6	22.00	0.05	Natural
51	3	7	38.00	0.05	Natural
52	6	7	33.00	0.05	Planted
53	4	4	37.00	0.05	Planted
54	5	7	29.00	0.05	Planted
55	2	6	32.00	0.05	Planted
60	2	6	31.00	0.05	Natural

61	2	6	35.00	0.05	Planted
62	2	6	30.00	0.05	Natural
65	3	7	32.00	0.05	Natural
68	2	6	30.00	0.05	Natural
69	2	6	33.00	0.05	Natural
70	6	7	41.00	0.05	Planted
71	6	7	33.00	0.05	Planted
72	3	8	41.00	0.05	Natural

Levels of Growing Stock (LOGS): USFS, PNW, Oregon and Washington (Curtis and Marshall 1986). The LOGS study was established in the 1960's and consists of nine installations located in British Columbia, Oregon, and Washington. Each installation contains three replicates of a control and eight thinning regimes for a total of 27 plots. The objective of the study was to determine how repeated thinnings impact volume production, tree size, and growth (Curtis et al. 1997). Three LOGS installations containing 9 control plots from USFS land are used in the current analysis.

Installation	# of plots	# of measurements	50-year site index (m)	Plot size (ha)	Regeneration type
Iron Creek	3	8	36.58	0.08	Planted
Rocky Brook	3	7	24.39	0.08	Combination
Stampede Creek	3	6	30.48	0.08	Natural

Stand Management Cooperative (SMC): SMC, Oregon and Washington (Collier and Haukaas 1996). The Stand Management Cooperative (SMC) has a tree measurement database consisting of 400 installations in British Columbia, Oregon, and Washington. Each installation contains a single control and multiple treated plots (Collier and Haukaas 1996). Nineteen control plots from plantation installations dominated by Douglas-fir were selected. Installations were chosen with relatively low (<1,500 tph) initial Douglas-fir densities. The initial density criterion was designed to augment rare stand conditions in the EP703 database.

Installation	# of plots	# of measurements	50-year site index (m)	Plot size (ha)	Regeneration type
708	1	3	38.10	0.20	Planted
709	1	3	36.58	0.20	Planted
710	1	2	42.06	0.20	Planted
711	1	2	36.58	0.20	Planted
716	1	2	30.48	0.20	Planted
718	1	2	39.01	0.20	Planted

723	1	2	42.67	0.20	Planted
724	1	2	35.05	0.20	Planted
729	1	2	42.67	0.20	Planted
801	1	3	32.00	0.20	Planted
802	1	3	34.14	0.20	Planted
803	1	3	42.67	0.20	Planted
804	1	3	32.00	0.20	Planted
805	1	3	41.15	0.20	Planted
806	1	3	40.23	0.20	Planted
809	1	2	38.10	0.20	Planted
810	1	3	26.82	0.20	Planted
811	1	2	34.14	0.20	Planted
812	1	2	39.62	0.20	Planted

Miscellaneous data collected during the development of this analysis, Washington. Two plots were established during this analysis: a 55- year old planted stand on Champion International's Kapowsin Tree Farm; and a 60-year old naturally regenerated stand on the University of Washington's Pack Forest. Each plot combines information from 28 subject tree subplots. To locate subject trees a grid of points was randomly placed on a stand map. When a grid point was reached in the stand, random numbers were generated to determine the direction and distance from the point to locate a subject tree. Subject trees were chosen as the closest tree of a randomly selected crown class, ensuring an unbiased selection of subject trees. Measurements of each subject tree included height, dbh, a breast height core (for age), and crown information. In addition the distance, species, and dbh of live and dead competitors within a 5-meter radius are recorded. Combining subject tree sub-plot information produces a single plot representing .20 ha. To detect missing rings tree ages were cross-dated through a graphical analysis of growth increments.

Installation	# of plots	# of measurements	50-year site index (m)	Plot size (ha)	Regeneration type
Pack forest	1	1	28.00	0.20	Natural
Kapowsin	1	1	35.00	0.20	Planted

APPENDIX B: PROGRAMS DEVELOPED IN PYTHON FOR THE ANALYSIS

Ripley.py calculates Ripley's K statistic given x and y coordinates for trees in a plot. The program includes a correction for trees near the plot border. The Ripley's K statistic is used for the analysis in Chapter 2 to compare spacing in planted and naturally regenerated stands.

```
import sys, math, reesub, string
```

```
def RK():
```

```
    """ Return Ripley's K """
```

```
    n = 0
```

```
    xmax = 0
```

```
    xmin = 999999
```

```
    ymax = 0
```

```
    ymin = 999999
```

```
    m=[.5,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20]
```

```
    K = 0
```

```
    sumK = 0
```

```
    kdict = {}
```

```
    numb1 = xyone.keys()
```

```
    numb1.sort()
```

```
    for item1 in numb1:
```

```
        x = xyone[item1][0]
```

```
        y = xyone[item1][1]
```

```
        n = n + 1
```

```
        if x > xmax:
```

```
            xmax = x
```

```
        if x < xmin:
```

```
            xmin = x
```

```
        if y > ymax:
```

```
            ymax = y
```

```
        if y < ymin:
```

```
            ymin = y
```

```
    #print xmin, ymin, xmax, ymax
```

```
    a = xmax - xmin
```

```
    b = ymax - ymin
```

```
    area = a * b
```

```
    for radius in m:
```

```
        for item1 in numb1:
```

```
            xi = xyone[item1][0]
```

```
            yi = xyone[item1][1]
```

```
            numb2 = xyone.keys()
```

```
            numb2.sort()
```

```
            for item2 in numb2:
```

```
                xj = xyone[item2][0]
```

```

        yj = xyone[item2][1]
        dist = (abs(xi-xj)**2+abs(yi-yj)**2)**.5
        if (dist > 0) & (dist < radius):
            #print dist
            K = (1 / (area - (dist * ((2 * a) + (2 * b) - dist))/math.pi))
            sumK = sumK + K
        sumK2 = sumK / ((n / area)**2)
        L = math.sqrt(sumK2/((math.pi)))
        Lr = L - radius
        kdickt[radius] = Lr
        sumK = 0

    return kdickt

xyfile = 'cpxys.txt'
outfile = 'ripout2.txt'

f1 = open( xyfile, 'r' )
f2 = open( outfile, 'w' )

xyone = {}
rkdict = {}
cnt = 0

f2.write( 'install, plot, radius, K\n' )

line = f1.readline() #skip header

line = f1.readline()
field = string.splitfields( line, ',' )
laststand = field[0]
lastplot = field[1]
spp = field[2]
x = string.atof( field[6] )
y = string.atof( field[7] )
if spp == 'FD':
    cnt = cnt + 1
    xyone[cnt] = (x, y)

while 1:
    line = f1.readline()
    if not line: break
    field = string.splitfields( line, ',' )
    stand = field[0]
    plot = field[1]
    spp = field[2]
    x = string.atof( field[6] )
    y = string.atof( field[7] )
    if (stand != laststand) or (plot != lastplot):
        print 'working on:', laststand, lastplot
        rkdict = RK()
        rs = rkdict.keys()

```

```

rs.sort()
for rss in rs:
    #print laststand, lastplot, rss, rkdict[rss]
    f2.write ('%s, %s, %5.1f, %9.5f\n' % (laststand, lastplot, rss, rkdict[rss]))
laststand = stand
lastplot = plot
cnt = 0
rkdict = {}
xyone = {}
if spp == 'FD':
    cnt = cnt + 1
    xyone[cnt] = (x, y)
print 'working on:', stand, plot
rkdict = RK()
rs = rkdict.keys()
rs.sort()
for rss in rs:
    #print stand, plot, rss, rkdict[rss]
    f2.write ('%s, %s, %5.1f, %9.5f\n' % (stand, plot, rss, rkdict[rss]))

f1.close()
f2.close()
print 'done'

```

Quads.py calculates the degrees of the maximum pie of focus trees free from competing trees using x and y coordinates of trees in a plot. This statistic is used in Chapter 2 to compare spacing in planted and naturally regenerated stands.

```
import sys, math, reesub, string
```

```

def quad():
    """ Return quads """
    n = 0
    xmax = 0
    xmin = 999999
    ymax = 0
    ymin = 999999
    m = [1,2,3,4,5,6,7]
    qdict = {}
    cvs = {}
    numbl = xyone.keys()
    numbl.sort()
    for item1 in numbl:
        x = xyone[item1][0]
        y = xyone[item1][1]
        n = n + 1
        if x > xmax:
            xmax = x
        if x < xmin:
            xmin = x
        if y > ymax:

```

```

    ymax = y
    if y < ymin:
        ymin = y
#print xmin, ymin, xmax, ymax
a = xmax - xmin
b = ymax - ymin
area = a * b

for radius in m:
    qempty = 0
    qtot = 0
    qfull = 0
    max2sum = 0
    maxsum = 0
    meanmax = 0
    sdmax = 0
    numb=0
#print radius, qtot, qempty
for item1 in numb1:
    xi = xyone[item1][0]
    yi = xyone[item1][1]
    if (xi-radius >= xmin) and (xi+radius <= xmax) and (yi-radius >=ymin) and (yi+radius <= ymax):
        deg=[]
        qdict[1]=0
        qdict[2]=0
        qdict[3]=0
        qdict[4]=0
        numb2 = xyone.keys()
        numb2.sort()
        for item2 in numb2:
            xj = xyone[item2][0]
            yj = xyone[item2][1]
            dist = (abs(xi-xj)**2+abs(yi-yj)**2)**.5
            if (dist > 0) and (dist <= radius):
                #print dist
                if (xi <= xj) and (yi < yj): quad = 1
                elif (xi < xj) and (yi >= yj): quad = 2
                elif (xi >= xj) and (yi > yj): quad = 3
                else: quad = 4
                if abs(xi-xj) > 0:
                    qd = math.atan(abs(yi-yj)/abs(xi-xj))*57.29578
                else:
                    qd = 0
                if quad == 1: degree = 90 - qd
                elif quad == 2: degree = qd + 90
                elif quad == 3: degree = 270 - qd
                else: degree = qd + 270
                #if degree < 90: qdict[1] = qdict[1] + 1
                #elif degree < 180: qdict[2] = qdict[2] + 1
                #elif degree < 270: qdict[3] = qdict[3] + 1
                #else: qdict[4] = qdict[4] + 1
                #print degree, qdict

```

```

        deg.append(degree)
        #print deg
    #q = qdict.keys()
    #for sq in q:
    #    qtot = qtot + 1
    #    if qdict[sq] == 0: qempty = qempty + 1
    #    else: qfull = qfull + 1
    #    #print qdict, qtot, qfull, qempty
    deg.sort()
    i=0
    n=len(deg)
    if n>1:
        #print len(deg)
        diff=[]
        while i < (n-1):
            diff.append(abs(deg[i]-deg[i+1]))
            i = i + 1
        diff.append(deg[0]+(360-deg[n-1]))
        maxdeg = max(diff)
    else: maxdeg = 360
    #print maxdeg
    max2sum = max2sum + maxdeg**2
    maxsum = maxsum + maxdeg
    numb = numb + 1
    if numb > 0:
        meanmax = maxsum/numb
        sdmax = ((max2sum-(maxsum**2)/numb)/numb)**.5
    else:
        meanmax = 0
        sdmax = 0
    if meanmax > 0:
        cv = sdmax/meanmax
    else:
        cv = 0
    print meanmax, sdmax, cv
    #print radius, qempty, qtot
    #prop = 0
    #prop = (qempty/qtot)
    #print prop
    cvs[radius] = (meanmax, sdmax, cv)
    #print propempty
return cvs

```

```

xyfile = 'cpxys.txt'
outfile = 'cvsquad.txt'

```

```

f1 = open( xyfile, 'r' )
f2 = open( outfile, 'w' )

```

```

xyone = {}
propdict = {}

```

```

cnt = 0

f2.write( 'install, plot, radius, meanmax, sdmax, cv\n' )

line = f1.readline() #skip header

line = f1.readline()
field = string.splitfields( line, ',' )
laststand = field[0]
lastplot = field[1]
spp = field[2]
x = string.atof( field[6] )
y = string.atof( field[7] )
if spp == 'FD':
    cnt = cnt + 1
    xyone[cnt] = (x, y)

while 1:
    line = f1.readline()
    if not line: break
    field = string.splitfields( line, ',' )
    stand = field[0]
    plot = field[1]
    spp = field[2]
    x = string.atof( field[6] )
    y = string.atof( field[7] )
    if (stand != laststand) or (plot != lastplot):
        print 'working on:', laststand, lastplot
        cvsdict = quad()
        rs = cvsdict.keys()
        rs.sort()
        for rss in rs:
            #print laststand, lastplot, rss, propdict[rss]
            f2.write ( '%s, %s, %5.1f, %10.5f, %10.5f, %10.5f\n' % (laststand, lastplot, rss, cvsdict[rss][0],
cvsdict[rss][1], cvsdict[rss][2]))
            laststand = stand
            lastplot = plot
            cnt = 0
            xyone = {}
            propdict = {}
        if spp == 'FD':
            cnt = cnt + 1
            xyone[cnt] = (x, y)
    print 'working on:', stand, plot
    cvsdict = quad()
    rs = cvsdict.keys()
    rs.sort()
    for rss in rs:
        #print stand, plot, rss, propdict[rss]
        f2.write ( '%s, %s, %5.1f, %10.5f, %10.5f, %10.5f\n' % (stand, plot, rss, cvsdict[rss][0], cvsdict[rss][1],
cvsdict[rss][2]))

```

```
f1.close()
f2.close()
print 'done'
```

Degrees2.py creates a neighbor file from ARC/INFO exports (node, arc, and polygon attribute files) using circular statistics to calculate an average degree weighted by border length. The neighbor file is used to establish spatial relationships between polygons in the landscape wind risk rating system developed in Chapter 4.

```
import sys, math, re, string
```

```
def quad():
    """ Return quads """
    if (xy[fnode][0] <= xy[tmode][0]) and (xy[fnode][1] < xy[tmode][1]): quad = 1
    elif (xy[fnode][0] < xy[tmode][0]) and (xy[fnode][1] >= xy[tmode][1]): quad = 2
    elif (xy[fnode][0] >= xy[tmode][0]) and (xy[fnode][1] > xy[tmode][1]): quad = 3
    else: quad = 4
    if abs(xy[fnode][0] - xy[tmode][0]) > 0:
        qd = math.atan(abs(xy[fnode][1]-xy[tmode][1])/abs(xy[fnode][0]-xy[tmode][0]))*57.29578
    elif xy[fnode][0] >= xy[tmode][0]:
        qd = 180
    elif xy[fnode][0] < xy[tmode][0]:
        qd = 0
    if quad == 1: ndeg = 90 - qd
    elif quad == 2: ndeg = qd + 90
    elif quad == 3: ndeg = 270 - qd
    else: ndeg = qd + 270
    if ndeg >= 90:
        degree = ndeg - 90
    else:
        degree = 360 - (90 - ndeg)
    #print xy[fnode], xy[tmode], quad, qd, ndeg, degree
    return degree
```

```
nodefile = 'b3nat.txt'
arcfile = 'b3aat.txt'
polyfile = 'b3pat.txt'
outfile = 'b3neigh.txt'
f1 = open( outfile, 'w' )
```

```
f1.write('stand, adjacent, degree, distance\n')
```

```
f2 = open( polyfile, 'r' )
riu = {}
line = f2.readline() #skip header
line = f2.readline()
field = string.splitfields( line, ',' )
poly = field[2]
riuid = field[5]
riu[poly] = riuid
while 1:
```

```

line = f2.readline()
if not line: break
field = string.splitfields( line, ',' )
poly = field[2]
riuid = field[5]
riu[poly] = riuid
f2.close()

f3 = open( nodefile, 'r' )
xy = {}
line = f3.readline() #skip header
line = f3.readline()
field = string.splitfields( line, ',' )
node = field[1]
xcoord = string.atof( field[3] )
ycoord = string.atof( field[4] )
xy[node] = [xcoord, ycoord]
while 1:
    line = f3.readline()
    if not line: break
    field = string.splitfields( line, ',' )
    node = field[1]
    xcoord = string.atof( field[3] )
    ycoord = string.atof( field[4] )
    xy[node] = [xcoord, ycoord]
f3.close()

f4 = open( arcfile, 'r' )
poly = {}
n = 0
line = f4.readline() #skip header
line = f4.readline()
field = string.splitfields( line, ',' )
fnode = field[0]
mnode = field[1]
lpoly = field[2]
rpoly = field[3]
length = string.atof( field[4] )
poly[riu[rpoly]] = {}
poly[riu[rpoly]][riu[lpoly]] = {}
degree = quad()
#print degree
poly[riu[rpoly]][riu[lpoly]][0] = [length, degree]
#f1.write('%s, %s, %s, %s\n' % (riu[rpoly], riu[lpoly], length, degree))
while 1:
    line = f4.readline()
    if not line: break
    field = string.splitfields( line, ',' )
    fnode = field[0]
    mnode = field[1]
    lpoly = field[2]
    rpoly = field[3]

```

```

length = string.atof( field[4] )
degree = quad()
if (not poly.has_key(riu[rpoly])):
    poly[riu[rpoly]] = {}
if (not poly[riu[rpoly]].has_key(riu[lpoly])):
    poly[riu[rpoly]][riu[lpoly]] = {}
poly[riu[rpoly]][riu[lpoly]][len(poly[riu[rpoly]][riu[lpoly]])] = [length, degree]
#print riu[rpoly], riu[lpoly], poly[riu[rpoly]][riu[lpoly]][(len(poly[riu[rpoly]][riu[lpoly]])-1]
#f1.write('%s, %s, %s, %s\n' % (riu[rpoly], riu[lpoly], length, degree))
f4.close()

focus = poly.keys()
focus.sort()
for foc in focus:
    neigh = poly[foc].keys()
    neigh.sort()
    for ne in neigh:
        numb = poly[foc][ne].keys()
        numb.sort()
        for n in numb:
            if (poly[foc].has_key(ne)) and (poly.has_key(ne)):
                if (poly[ne].has_key(foc)):
                    numb2 = poly[ne][foc].keys()
                    numb2.sort()
                    for n2 in numb2:
                        if poly[ne][foc][n2][1] >= 180:
                            poly[foc][ne][len(poly[foc][ne])] = [poly[ne][foc][n2][0], poly[ne][foc][n2][1]-180]
                            del poly[ne][foc][n2]
                        else:
                            poly[foc][ne][len(poly[foc][ne])] = [poly[ne][foc][n2][0], 360 - (180 -
poly[ne][foc][n2][1])]
                            del poly[ne][foc][n2]
                            del poly[ne][foc]

focus = poly.keys()
focus.sort()
for foc in focus:
    neigh = poly[foc].keys()
    neigh.sort()
    for ne in neigh:
        sumlen = 0
        sumsin = 0
        sumcos = 0
        sumwdeg = 0
        cnt = 0
        if (poly[foc].has_key(ne)) and (poly.has_key(ne)):
            if (poly[ne].has_key(foc)):
                print 'uhoh', foc, ne
            numb = poly[foc][ne].keys()
            numb.sort()
            for n in numb:
                sumlen = sumlen + poly[foc][ne][n][0]

```

```

    cnt = cnt + 1
    sumcos = sumcos + (math.cos(poly[foc][ne][n][1]*.017453293)*poly[foc][ne][n][0])
    sumsin = sumsin + (math.sin(poly[foc][ne][n][1]*.017453293)*poly[foc][ne][n][0])
    x = sumcos/sumlen
    y = sumsin/sumlen
    r = (x**2 + y**2)**.5
    xr = x/r
    yr = y/r
    if xr >= 0 and yr >= 0:
        avgdeg = math.acos(xr)*57.2957795
    elif yr >= 0 and xr < 0:
        avgdeg = math.acos(xr)*57.2957795
    elif xr < 0 and yr < 0:
        avgdeg = 360 - math.acos(xr)*57.2957795
    else:
        avgdeg = 360 - math.acos(xr)*57.2957795
    #print foc, ne, sumwdeg, avgdeg
    fl.write('%s, %s, %4.0f, %8.0fn' % (foc, ne, avgdeg, sumlen))
    if avgdeg >= 180:
        fl.write('%s, %s, %4.0f, %8.0fn' % (ne, foc, avgdeg - 180, sumlen))
    else:
        fl.write('%s, %s, %4.0f, %8.0fn' % (ne, foc, 360 - (180 - avgdeg), sumlen))
    #print foc, ne, sumlen, avgdeg

fl.close()
print 'done'

```

VITAE

JEREMY STUART WILSON
University of Washington

Education:

University of Washington, College of Forest Resources, Seattle, WA. Ph.D. 1998. Dissertation title: Wind stability of naturally regenerated and planted Douglas-fir stands in coastal Washington, Oregon, and British.

Yale University School of Forestry and Environmental Studies, New Haven, CT. M.F. 1993.

Bowdoin College, Brunswick, ME. A.B. (magna cum laude). 1987. Economics, Environmental Studies.

Work Experience:

- 9/93 –present **University of Washington, Landscape Management Project, Seattle, WA (Research Analyst).** Develop methodology and computer programs to facilitate the management of forested landscapes. The Landscape Management System combines GIS technology, growth and yield models, stand and landscape visualization, and analysis tools to evaluate future landscape conditions under a variety of management scenarios.
- 1/96 - 3/96 **University of Washington, College of Forest Resources, Seattle, WA (Teaching Assistant).** Lectured, organized field trips, led laboratory and discussion sections, and graded for an undergraduate course in silviculture and graduate courses in ecosystem management and forest stand dynamics.
- 3/95 - 6/95
- 9/97 – 12/97
- 6/93 - 9/93 **Ecotrust, Portland, OR (Intern).** Conducted survey of alternative methods of silviculture being practiced in the Pacific Northwest. Wrote report describing general trends of forest management in the region and detailed activities of specific individuals and organizations.
- 5/92 - 8/92 **The Yale Forests, Union, CT and Swanzey, NH (Intern).** Assisted in the management of school forests. Work included timber sale marking and administration, timber stand improvement, and road repair.
- 4/91 - 8/91 **The Society for the Protection of New Hampshire Forests, Concord, NH (Intern).** Cruised Society land throughout New Hampshire for a timber inventory. Evaluated potential property acquisitions and helped develop a Christmas tree operation in the White Mountains.
- 5/88 - 4/91 **Abt Associates Inc., Cambridge, MA (Environmental Policy Analyst).** Researched; wrote; developed, managed, and analyzed economic databases; organized conferences; and managed multi-million dollar cost proposals to the U.S. EPA.
- 9/90 – 12/90 **The New Jersey Barn Company, Inc., Princeton, NJ, (Carpenter).** Historical restoration and reconstruction of 18th and 19th century English and Dutch barns and houses.
- 5/86 - 9/86 Dismantled, restored, moved and raised structures. Specialized in the repair and replacement of damaged timbers.

Awards and Honors:

James Bowdoin Scholar, Bowdoin
 Orren Chalmer Cup (Scholar-Athlete), Bowdoin
 Federated Garden Club Scholarship, Yale
 James L. Goodwin Memorial Scholarship, Yale
 Lockwood Fellow, University of Washington
 Nominated: Xi Sigma Pi, Forestry Honor Society

Publications:*Accepted:*

Wilson, J. S., E. S. Isaac, and R. I. Gara. *in press*. Impacts of mountain pine beetle (*Dendroctonus ponderosae*) infestation on future landscape susceptibility to the western spruce budworm (*Choristoneura occidentalis*) in north central Washington. *Journal of Applied Entomology*.

McCarter, J.M., J.S. Wilson, P.J. Baker, J.L. Moffett, and C.D. Oliver. *in press*. Landscape management through integration of existing tools and emerging technologies. *Journal of Forestry*.

Wilson, J.S. and P. J. Baker. *in press*. Mitigating fire risk to late-successional forest reserves on the east slope of the Washington Cascade Range, USA. *Forest Ecology and Management*.

Wilson, J.S. 1988. Wind stability of naturally regenerated and planted Douglas-fir stands in coastal Washington, Oregon, and British Columbia. Dissertation. University of Washington.

In Review:

Baker, P.J., and J.S. Wilson. Identification of canopy stratification in tropical and temperate forests: a quantitative technique. Submitted to *Ecology* 10/97.

In Preparation:

Wilson, J.S. A comparison of tree size variation and wind stability in naturally regenerated and planted Douglas-fir stands. For submission to *Forest Ecology and Management*.

Wilson, J.S. Wind stability and management flexibility of Douglas-fir plantings. For submission to *Canadian Journal of Forest Research*.

Wilson, J.S. Developing a rating system for landscape-scale wind risk. For submission to *Forestry*.

Wilson, J.S. and C.D. Oliver. Comparing past and future landscape-scale wind risks in managed landscapes of the Pacific Northwest. For submission to *Western Journal of Applied Forestry*.

Wilson, J.S. and C.D. Oliver. Flexibility in forest management: Balancing risk and reward in the evaluation of wind stability: For submission to *Journal of Forestry*.

Wilson, J.S. and R. McHughhey. Visual analysis of forest information at the landscape scale. For submission to *Landscape and Urban Planning*.

Wilson, J.S. and P.J. Baker. Missing rings: implications for analysis of age distributions and stand development. For submission to *Canadian Journal of Forest Research*.

Gara, R.I. and J.S. Wilson. Relationships between fire and insects in forests of the Pacific Northwest. For submission to IUFRO Proceedings.

Reports:

McCarter J.B., J.S. Wilson, and P.J. Baker. 1996. *Landscape Management System User's Manual*. Landscape Management Project. College of Forest Resources. University of Washington. 97 p.

Wilson, J.S. 1993. *An Initial Survey of Alternative Silviculture Practitioners in the Pacific Northwest*. Ecotrust. Portland, OR. 26 p.

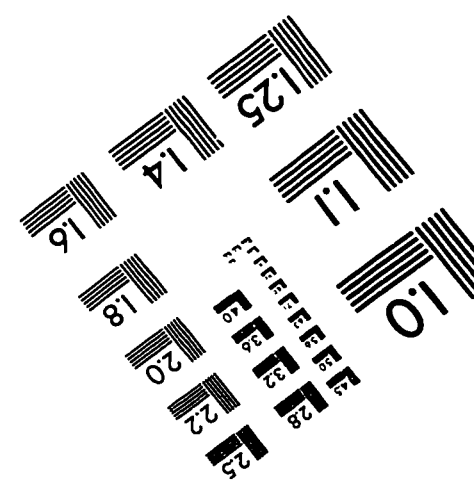
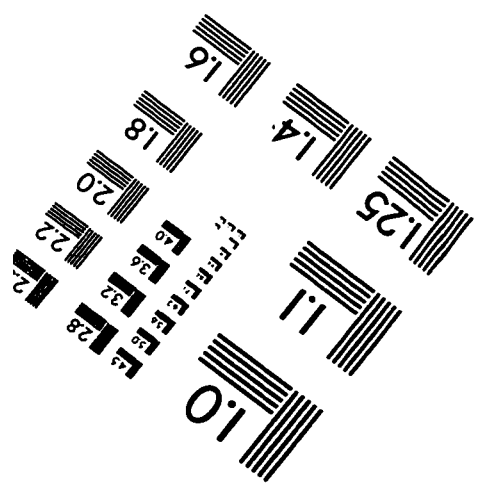
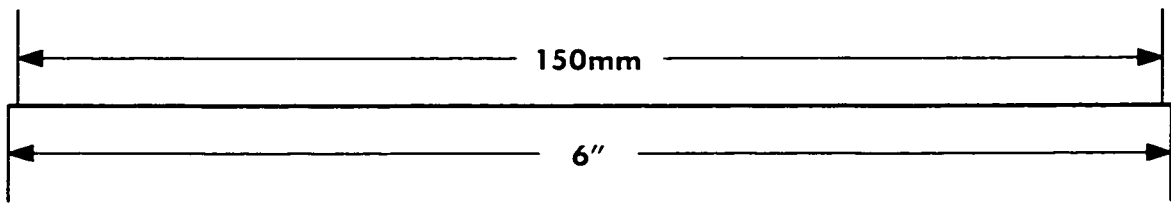
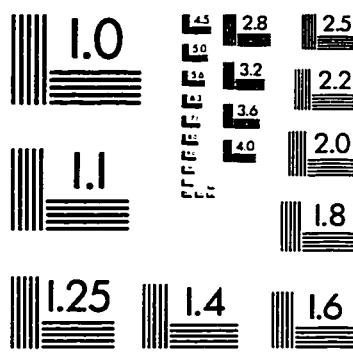
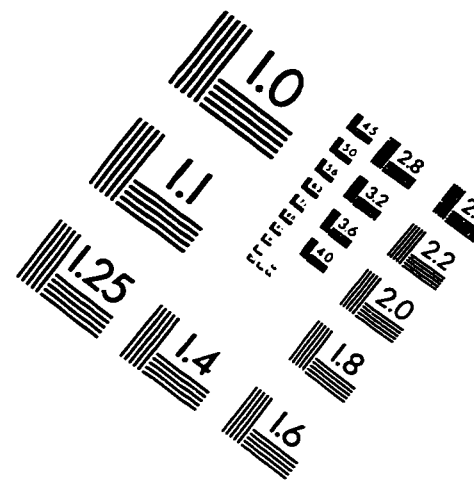
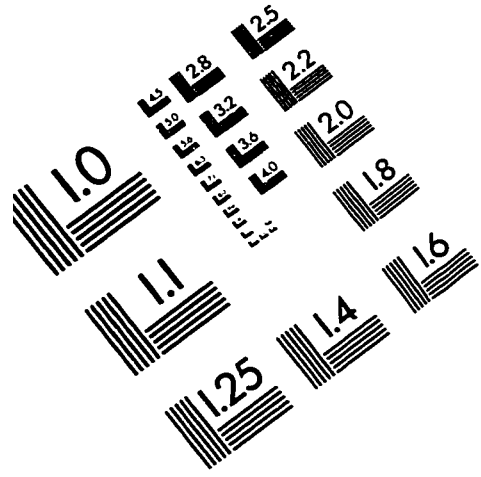
Schafer, P., A.J. Stoeckle, S. Day, and J.S. Wilson. 1991. *Economic Guidance for Water Quality Standards Handbook*. U.S. EPA Report. 54 p.

Kashmanian, R., A.J. Stoeckle, J.S. Wilson, C. McGuckin, K. Bell, P. Schafer, and J. Ottman. 1990. *Assessing the Market Segment for Environmental Consumers*, U.S. EPA Report. 91 p.

Kashmanian, R., A.J. Stoeckle, J.S. Wilson, J. Hassol, and T. Ferrand. 1989. *Promoting Source Reduction and Recyclability in the Marketplace*. U.S. EPA Report. 84 p.

Schafer, P., R.S. Wells, and J.S. Wilson. 1989. *Private Sector Asbestos Abatement Activities*. U.S. EPA Report. 150 p.

IMAGE EVALUATION TEST TARGET (QA-3)



APPLIED IMAGE, Inc
 1653 East Main Street
 Rochester, NY 14609 USA
 Phone: 716/482-0300
 Fax: 716/288-5989

© 1993, Applied Image, Inc., All Rights Reserved