Abstract

Windthrow is a common problem in forest management that can be predicted or simulated with the use of modelling tools. A hybrid mechanistic model, WindFIRM/ForestGALES_BC, was developed to quantify component windthrow processes for individual trees in heterogeneous stands and in variable retention harvesting scenarios. Harvesting scenarios can have complex shapes, sizes and distributions of cutblock openings and within cutblock retention of aggregated and individual trees. This model accounts for irregular openings and stand characteristics and is able to simulate the propagation of windthrow during storm events. It is also sensitive to wind direction which is evident from spatial outputs of model simulations. WindFIRM/ForestGALES_BC was also successfully integrated with a growth and yield model, TASS (Tree and Stand Simulator), to quantify the effects of openings created by windthrow on stand yields.

The flexibility of WindFIRM/ForestGALES_BC to substitute trees and modify crowns in spatial tree lists is demonstrated and a validation of the model was completed using field data from the STEMS (Silvicultural Treatments for Ecosystem Management in the Sayward) research installation on Vancouver Island. The results of the non-parametric tests show that the pattern of simulated windthrow through size classes is consistent with field plot data. However, contingency tables indicate that the model underestimates windthrow which is due to some suspected and unknown causes. The cumulative proportion of modelled windthrow has a consistent pattern with the cumulative proportion of actual windthrow from the field data.
The advances in WindFIRM/ForestGALES_BC make it a useful platform to integrate other process models (e.g. large woody debris recruitment in streams) and incorporate new functions obtained in future research. It will also serve as a good framework to guide data collection needs and priorities (e.g. high resolution wind data and simulation, soils and complex topography) related to the understanding of windthrow processes. Further refinements related to the effects of wind on tree stability in complex terrain, soils and tree sway dynamics will improve the model as a predictive tool. This will allow forest managers to simulate a range of scenarios to identify block and retention layouts, locations and individual tree characteristics that pose the highest windthrow risk.
Preface

I am the second author of the following publication and portions of Chapter 3 including Figure 3.1 and selected text in 3.1.1, 3.2.1 and 3.2.2 are from this paper.


My contributions to this publication involved initiating the original outline and providing content related to my tree winching and wind tunnel experiments, including Figure 3.1 in this thesis. I also wrote descriptions of the assumptions and empiricisms related to these experiments and identified the lack of representation of damage propagation and tree-to-tree variability in the current set of windthrow models. Final versions of this publication were reviewed and circulated among all of the authors by Dr. Barry Gardiner who managed this paper and was the principal author. The other co-authors made contributions related to their respective windthrow models and all shared in the final edits prior to submission.

Other previously published equations were integrated with WindFIRM/ForestGALES_BC, with permission, to calculate important components of the windthrow process. These contributions are explicitly identified where they are relevant in the research chapters.
# Table of Contents

Abstract ..................................................................................................................................... ii
Preface ....................................................................................................................................... iv
Table of Contents ........................................................................................................................ v
List of Tables ............................................................................................................................. viii
List of Figures ............................................................................................................................. x
Acknowledgements .................................................................................................................. xiv

1.0 Introduction ........................................................................................................................... 1
  1.1 Background to windthrow management and modelling ...................................................... 2
  1.2 Research objectives ........................................................................................................... 5
    1.3.1 Mechanistic foundations of a spatial windthrow model ............................................... 9
    1.3.2 Representation of spatial effects and windthrow dynamics ........................................ 10
    1.3.3 Validation of model outputs using STEMS data......................................................... 12
    1.3.4 Summary chapter including recommendations ......................................................... 13

2.0 Mechanistic Foundations of a Spatial Windthrow Model Using ForestGALES .................... 14
  2.1 Introduction ..................................................................................................................... 14
  2.2 Methods .......................................................................................................................... 17
    2.2.1 Overview of ForestGALES ....................................................................................... 17
    2.2.2 Critical assessment of ForestGALES for more complex stands ................................. 21
    2.2.3 Changes for more complex stands ............................................................................. 23
    2.2.4 Evaluation of ForestGALES vs ForestGALES_BC .................................................. 23
  2.3 Results Part 1 – Construction of a new windthrow model, ForestGALES_BC ................. 25
    2.3.1 Reorganization of objects and equations within objects to reflect complex stands ... 25
    2.3.2 Tree Characteristics object ....................................................................................... 26
    2.3.3 Stem Taper object .................................................................................................... 28
    2.3.4 Roughness object ..................................................................................................... 30
    2.3.5 Wind De-elevate object ........................................................................................... 32
    2.3.6 Wind Profile and Force objects ................................................................................. 34
    2.3.7 Bending Moment object ........................................................................................... 38
    2.3.8 Gap (VR Adjust) object ........................................................................................... 39
    2.3.9 Maximum Moment object ........................................................................................ 42
    2.3.10 Gust Factor object .................................................................................................. 44
  2.4. Results Part 2 - Sensitivity analyses, comparison of ForestGALES and ForestGALES_BC outputs .............................................................. 46
  2.5 Discussion ....................................................................................................................... 54
  2.6 Conclusions ..................................................................................................................... 60

3.0. Windthrow Prediction Accounting for Multiple Wind Directions, Diverse Harvesting Scenarios, and Windthrow Propagation ................................................................. 61
Appendix 3 – Tree-list Comparisons for Pruned and Non-pruned Pixels in the Aggregate Retention Treatment ................................................................................................................ 184
List of Tables

Table 1.1 Objects in ForestGALES_BC (both changed and unchanged from original ForestGALES model) with references to the relevant studies or models.........................9
Table 2.1. Summary of stand characteristics used as input data for model simulations.......24
Table 2.2. Linear equations used to calculate canopy characteristics (Byrne 2005 with permission).................................................................................................................27
Table 2.3. Linear equations used to calculate stem mass (kg) (Byrne 2005 with permission). ....................................................................................................................................27
Table 2.4. Species-specific branch width parameters for Equation 2.6 (Polsson 2007). ....28
Table 2.5. Species-specific coefficients used in Equation 2.7 (extracted from Kozak (1988) and Klos et al. (2007) with permission). ......................................................................30
Table 2.6. Canopy-top wind speeds calculated for a 100 km/h above canopy wind speed for spacing distances represented in Figure 2.4. ................................................................. 36
Table 2.7. Sample calculation of VRFetch based on Figure 2.5. .......................................... 40
Table 2.8. Coefficients and summary statistics for linear equations used to calculate critical resistive uprooting moment for western redcedar (Cw), western hemlock (Hw), lodgepole pine (Pl), interior hybrid spruce (Sx) and Douglas-fir (Fd) in ForestGALES_BC (Extracted from Byrne 2005 and Mitchell 1999 with permission). .43
Table 2.9. Published green wood MOR values for North American species used in ForestGALES_BC (Alden 1997). ................................................................................44
Table 3.1. Example of TASS generated tree list. Each tree has a unique ID code identifier.67
Table 3.2. Summary of input variables for ForestGALES_BC, their sources and the scale at which these variables are passed to ForestGALES_BC (i.e. stand, pixel or tree level). 73
Table 3.3. Input variables required to initiate stand conditions for TASS simulations and calculate windthrow.....................................................................................................75
Table 3.4. Description of gap size and aggregate retention treatments with TASS generated tree lists used for WindFIRM/ForestGALES_BC simulations........................................77
Table 4.1. Stand description by treatment unit (de Montigny 2004). .................................101
Table 4.2. Pre- and post- harvest stand attributes for treatments at STEMS (de Montigny 2004). ........................................................................................................................102
Table 4.3. Summary of cumulative proportion of stems windthrown by treatment* from plot re-measurements in 2003 and 2007...............................................................102
Table 4.4. Summary of input variables used to produce TASS-simulated trees at STEMS (from de Montigny 2004). .................................................................104
Table 4.5. Example of a tree-list produced by TASS. ......................................................106
Table 4.6. Summary of windthrow simulations using TASS-simulated tree-lists and a combination of TASS-simulated trees and plot trees for specific plot locations (i.e. Plots 10 and 25). ................................................................. 108

Table 4.7. Comparison of TASS-simulated and actual plot trees by treatment. .................. 115

Table 4.8. Numbers of windthrown trees using TASS-generated tree-lists over a range of wind speeds by treatment................................................................. 119

Table 4.9. Mean numbers of windthrown trees from STEMS plot data ......................... 119

Table 4.10. Effects of grid cell level spacing on canopy top wind speed. ......................... 127

Table 4.11. Windthrow simulation results (stems/ha) for Aggregate Retention (AR), Dispersed Retention (DR) and Commercial Thinning (CT) treatments using only TASS-simulated trees, for a 101 km/h above canopy southeast wind ...................... 131

Table 4.12. Summary results (windthrown stems per hectare) for species in each treatment due to a 101 km/h southeast wind ......................................................... 132

Table 4.13. Summary of Kolmogorov-Smirnov test results........................................... 136

Table 4.14. Summary of differences and similarities between the plot trees (STEMS) and TASS-simulated trees for all trees in Plots 10, 11 and 25................................. 137

Table 4.15. Simulation of 101 km/h southeast wind in Dispersed Retention treatment with insets showing results from grid cells where one-third of the crown length was removed for all trees ......................................................... 141

Table A2.1. Tree-list comparison for plot and simulated trees in Plot 10 (Aggregate Retention treatment) ......................................................................................... 181

Table A2.2. Tree-list comparison for plot and simulated trees in Plot 25 (Aggregate Retention treatment) ......................................................................................... 182

Table A2.3. Tree-list comparison for plot and simulated trees in Plot 11 (Aggregate Retention treatment) ......................................................................................... 183

Table A3.1. Tree-list comparison for the status of pruned and non-pruned trees in Pixel 150. .................................................................................................................. 184

Table A3.2. Tree-list comparison for the status of pruned and non-pruned trees in Pixel 293. .................................................................................................................. 184

Table A3.3. Tree-list comparison for the status of pruned and non-pruned trees in Pixel 393. .................................................................................................................. 184

Table A3.4. Tree-list comparison for the status of pruned and non-pruned trees in Pixel 563. .................................................................................................................. 185
List of Figures

Figure 2.1. Flow of inputs and objects used to calculate critical wind speed (CWS) in ForestGALES................................................................. 18

Figure 2.2. Flow of inputs and objects which calculate individual tree stability in ForestGALES_BC.......................................................... 26

Figure 2.3. Calculated vertical profile for horizontal wind speed given a sample mean stand height of 26 m and above canopy wind speed of 31 m/s (112 km/h) along with a pictorial representation of how individual trees are placed within the profile for the purpose of drag force calculations...................................................... 35

Figure 2.4. Graphical representation of vertical wind profile with decreasing stand density given a horizontal wind speed of 100 km/h at 10 m above the canopy........................................... 36

Figure 2.5. A sample of the layout used for VRFetch calculations. Numbers above circular points (30 m segment ends) in figure B give the percent retention of initial stand basal area. (Extracted from Scott 2005 with permission)................................. 40

Figure 2.6. Equation fit to relationship between summary of plot data and the proportion of windthrow at STEMS 1........................................... 42

Figure 2.7. Interpolated data points from Gardiner et al. 1997 with trendlines used in ForestGALES_BC to represent maximum and mean moments in a fully stocked stand................................................................. 45

Figure 2.8. Comparison of model outputs using height to DBH ratio (%) vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) with VR Fetch held constant at 120 in ForestGALES_BC and gap size held constant at 120 in original ForestGALES. Interior spruce (◊), lodgepole pine (□), western redcedar (Δ), western hemlock (+) and Douglas-fir (×).................................................. 48

Figure 2.9. Comparison of model outputs using DBH vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) with VR Fetch held constant at 120 in ForestGALES_BC and gap size held constant at 120 in original ForestGALES. Interior spruce (◊), lodgepole pine (□), western redcedar (Δ), western hemlock (+) and Douglas-fir (×).................................................. 49

Figure 2.10. Comparison of model outputs using spacing distance vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) for 5 randomly chosen trees with VR Fetch held constant at 120 in ForestGALES_BC and gap size held constant at 120 in original ForestGALES. Interior spruce (◊), lodgepole pine (□), western redcedar (Δ), western hemlock (+) and Douglas-fir (×).................................................. 50

Figure 2.11. Height to DBH ratio (%) vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) and VR Fetch (ie. 150, 180 and 210). Interior spruce (◊), lodgepole pine (□), western redcedar (Δ), western hemlock (+) and Douglas-fir (×)................................................... 51

Figure 2.12. DBH vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) and VR Fetch (ie. 150, 180 and 210). Interior spruce (◊), lodgepole pine (□), western redcedar (Δ), western hemlock (+) and Douglas-fir (×)................................................... 52
Figure 2.13. Change in critical wind speed with distance from edge (ie. 0, 30 and 60 m) as a proportion of the critical wind speed when VR Fetch is 120. Error bars are for 1 standard deviation and shown where noticeable. Interior spruce (◊), lodgepole pine (□), western redcedar (△), western hemlock (+) and Douglas-fir (×).

Figure 3.1. Schematic showing the source of input data and iterative loops between Windfirm and ForestGALES_BC to produce final tree list in the nested model WindFIRM/ForestGALES_BC 2.0 (Gardiner et al. 2008).

Figure 3.2. Main TASS III interface showing tree list with cutblock conditions before windthrow.

Figure 3.3. Block layout defined by WindFIRM with pure fetch and VRFetch trajectories indicated (A) and the propagation of windthrow in Iterations 1 (B), 2 (C), and 3 (D) which is a function of recalculated stand (pixel) values for VRFetch and spacing.

Figure 3.4. Propagation of windthrow within a sample localized pixel.

Figure 3.5. WindFIRM/ForestGALES_BC 2.2 and the TASS III interface used to predict and display windthrown trees. Windthrown trees are flagged in white in the image in the Check Windthrow dialogue box.

Figure 3.6. Simulation of windthrow for the same TASS tree list done using the research version of WindFIRM/ForestGALES_BC 2.1.

Figure 3.7. Predicted windthrow as a proportion of all trees in the simulation at increasing wind speed (U), at 10 m above the canopy, by treatment where, for example, “150 hole” is a 150 m by 150 m opening with no retention and “150 island” is the same size opening with a 50 m by 50 m retention patch in the middle. Wind direction is fixed at 135 degrees.

Figure 3.8. Predicted windthrow as a proportion of all trees in the simulation at increasing wind speed (U) by treatment where, for example, “150 hole” is a 150 m by 150 m opening with no retention and “150 island” is the same size opening with a 50 m by 50 m retention patch in the middle. Wind direction is fixed at 180 degrees.

Figure 3.9. Predicted windthrow as a proportion of all trees in the simulation at increasing wind speed (U) by treatment where, for example, “150 hole” is a 150 m by 150 m opening with no retention and “150 island” is the same size opening with a 50 m by 50 m retention patch in the middle. Wind direction is fixed at 315 degrees.

Figure 3.10. Windthrow damage in 1.56 ha opening and 0.25 ha retention patch (4 ha plot). Also shown are fewer trees simulated by TASS in the retention patch than in the surrounding stand.

Figure 3.11. Windthrow damage (at iterations 1 and 2) for a southeast wind of 160 km/h in the “150 hole” treatment which is a 2.25 ha opening (4 ha plot).

Figure 3.12. Windthrow damage for a south wind of 160 km/h in the “150 hole” treatment which is a 2.25 ha opening (4 ha plot).

Figure 3.13. Windthrow damage for a northwest wind of 160 km/h in the “150 hole” treatment which is a 2.25 ha opening (4 ha plot).
Figure 3.14. Proportion of stems in the DBH class that are windthrown for Iterations 1 ( ) and 2 ( ) for wind speeds of 140 km/h, 150 km/h, 160 km/h and 170 km/h and a wind direction of 135 degrees. ................................................................................................................................. 88

Figure 3.15. Proportion of stems in the height to diameter class that are windthrown for Iterations 1 ( ) and 2 ( ) for wind speeds of 140 km/h, 150 km/h, 160 km/h and 170 km/h and a wind direction of 135 degrees. ................................................................................................................................. 89

Figure 4.1. Location of STEMS I and the Snowden Demonstration Forest. ......................... 100

Figure 4.2. STEMS treatments which were used for validation and the plot locations. ....... 103

Figure 4.3. Using orthophotos to harvest variable retention scenarios from TASS generated tree-lists.............................................................................................................................................................................. 105

Figure 4.4. Location of STEMS and source of input wind data at Comox airport from Google Earth (Georgia Strait is the body of water on the right). .............................................................................................................. 109

Figure 4.5. Oblique view of terrain between wind data source at Comox and STEMS from Google Earth. .............................................................................................................................................................................. 110

Figure 4.6 Pre-harvest stand tables for STEMS plot data (1-3a) and TASS simulations (1-3b) for Aggregate Retention (row 1), Dispersed Retention (row 2) and Commercial Thinning (row 3) treatments. Douglas-fir (grey), western redcedar (black), western hemlock (white). .............................................................................................................................................................................. 115

Figure 4.7. Comparison of pre-harvest stock tables for STEMS plot data (1-3a) and TASS simulations (1-3b) for Aggregate Retention (row 1), Dispersed Retention (row 2) and Commercial Thinning (row 3) treatments. Fd (grey), Cw (black), Hw (white). .......... 116

Figure 4.8. 10-year peak gust wind record at Comox Airport for wind speed ( ) and direction (▲). ................................................................................................................................. 117

Figure 4.9. Wind rose showing the proportion of windthrow trees by direction in the Commercial Thinning treatment. .............................................................................................................................................................................. 118

Figure 4.10. Cumulative frequency of windthrown stems at increasing wind speeds for western redcedar (Δ), western hemlock (X) and Douglas-fir (□), by treatment type. ... 120

Figure 4.11. Extent and distribution of windthrow around the opening in the clearcut treatment. Windthrow was not recorded or mapped in the reserve patch (from de Montigny 2004). .............................................................................................................................................................................. 121

Figure 4.12. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of an 86 km/h northwest (315 degrees) wind in WindFIRM/ForestGALES_BC for clearcut treatment. .............................................................................................................................................................................. 121

Figure 4.13. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of a 101 km/h southeast (135 degrees) wind in WindFIRM/ForestGALES_BC for clearcut treatment. .............................................................................................................................................................................. 122

Figure 4.14. Overlay of edge windthrow survey and simulated windthrow 86 km/h northwest and 101 km/h southeast winds in the Clearcut with reserves treatment for both the southeast and northwest directions (TASS-simulated standing trees = blue; TASS-simulated windthrown trees = yellow). .............................................................................................................................................................................. 122
Figure 4.15. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of 86 km/h of northwest wind in WindFIRM/ForestGALES_BC for Aggregate Retention treatment. ................................................................. 123

Figure 4.16. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of 101 km/h of southeast wind in WindFIRM/ForestGALES_BC for Aggregate Retention treatment. ................................................................. 124

Figure 4.17. Overlay of edge windthrow survey and simulated windthrow for 86 km/h northwest and 101 km/h southeast winds in the Aggregate Retention treatment .... 125

Figure 4.18. Percent windthrow by plot based on STEMS field plot data in the Aggregate Retention treatment. Plots with no colour did not have trees. ......................... 126

Figure 4.19. Illustration of within-cell inter-tree spacing for two common edge scenarios in WindFIRM/ForestGALES_BC ........................................................................ 127

Figure 4.20. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of 101 km/h of southeast wind in WindFIRM/ForestGALES_BC for Dispersed Retention treatment. ................................................................. 128

Figure 4.21. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of 86 km/h of northwest wind in WindFIRM/ForestGALES_BC for Dispersed Retention treatment. ................................................................. 128

Figure 4.22. Overlay of edge windthrow survey and simulated windthrow for 86 km/h northwest and 101 km/h southeast winds in the Dispersed Retention treatment. .... 129

Figure 4.23. Percent windthrow by plot based on STEMS field plot data in the Dispersed Retention treatment. ................................................................. 130

Figure 4.24. Cumulative proportional frequency distributions of recorded windthrow (◊, solid line) from field plots at STEMS and simulated windthrow (····) at windspeeds of 86 (+), 94 ( ), 101 (x), 108 (□), and 115 (Δ) km/h from the southeast in ForestGALES_BC/WindFIRM (with respect to height). ........................................ 133

Figure 4.25. Cumulative proportional frequency distributions of recorded windthrow (◊, solid line) from field plots at STEMS and simulated windthrow (····) at windspeeds of 86 (+), 94 ( ), 101 (x), 108 (□) and 115 (Δ) km/h from the southeast in ForestGALES_BC/WindFIRM (with respect to DBH). ............................................... 134

Figure 4.26. Cumulative proportional frequency distributions of recorded windthrow (◊, solid line) from field plots at STEMS and simulated windthrow (····) at windspeeds of 86 (+), 94 ( ), 101 (x), 108 (□) and 115 (Δ) km/h from the southeast in ForestGALES_BC/WindFIRM (with respect to height to diameter ratio). .............. 135

Figure 4.27. Simulation of 101 km/h southeast wind with TASS-simulated trees and real tree replacements at Plot 10 in the Aggregate Retention treatment. ...................... 138

Figure 4.28. Simulation of 101 km/h southeast wind with TASS-simulated trees and real tree replacements at Plot 25 in the Aggregate Retention treatment. ...................... 139

Figure 4.29. Simulation of 101 km/h of 115 km/h northwest wind with TASS-simulated trees and real tree replacements at Plot 11, only, in the Aggregate Retention treatment. ..... 140
Acknowledgements

Like any project of this magnitude, it would not have been completed without the advice and support of many people and organizations. I wish to thank my supervisor Dr. Stephen Mitchell for his patience and guidance throughout this process and Drs. John Nelson and Valerie LeMay for their valuable insight and contributions. Tim Shannon served a vital role with respect to the programming of WindFIRM/ForestGALES_BC which would not have been possible without collaboration with Drs. Barry Gardiner, Juan Suarez and Bruce Nicoll at the UK Forestry Commission. I also thank Mario DiLucca and Ken Polsson at the BC Ministry of Forests and Range (now absorbed by the Ministry of Forests, Mines and Lands) for their support and collaboration and Louise de Montigny for supporting remeasurements at STEMS. Thanks also to Drs. Chris Peterson and Jonathan Fannin for their insightful comments and questions which helped improve the final draft of this dissertation.

On a more personal level, I want to thank my family, Lynn, Tyler and Calum. My parents, Donald and Shirley, have been an unfailing pillar of stability which has given me the courage to remain persistent despite the many challenges I have encountered. Completion of this project and thesis would not have been possible without your encouragement and support. I also wish to thank Dr. Vern Ruskin who has taught me about a great deal more than sailing and has been a great mentor and inspiration for my studies. Dennis Bendickson and Jace Standish have also been valuable sources of inspiration and support. I have enjoyed the discussions with the many fellow researchers, graduate and undergraduate students at UBC, the UK Forestry Commission and conferences. You are too numerous to name but have certainly enriched my experience.
1.0 Introduction

Windthrow refers to trees that are uprooted or broken by wind. In this research, ways of representing mechanistic windthrow processes which can spatially represent the stability of individual trees given a range of stand scenarios are proposed and tested. The challenge of this research was to move beyond stand-level simulation of windthrow and account for variable local wind and stand conditions which affect differences in wind loading within the stand and damage at the tree level. The primary objective of this research was to develop a practical decision support system that could be used by forest managers to assess the stability of individual trees and how this stability varies with stem and crown attributes, wind exposure and adjacency to other vulnerable trees in the stand. The ability to assess stability would help provide a quantitative foundation for decisions regarding which trees to retain following harvest, and also the need for and effectiveness of crown treatments. An equally important facet of this research was to develop a framework that breaks the windthrow process into sub-components to facilitate refinement and unit testing of equations and parameters. Researchers will be able to use this framework to identify and prioritize knowledge gaps and more easily communicate their significance to the overall process with practitioners and other researchers. As such, the framework provides an important link between research and application, and facilitates further research to meet management needs.

In this chapter, an overview of the importance of predicting and ameliorating windthrow damage in the context of current forest management practices is presented, along with a summary of the use and limitations of qualitative assessments and stand-level windthrow empirical models. In this research, mechanistic models, which use empirical equations to
describe mechanical processes, were used to quantify wind loading and resistance at the tree level. Therefore, a survey of mechanistic models and the tree winching and wind tunnel experiments upon which they are founded is presented. The current limitations of these models were identified prior to conducting the research on improvements to and linkages of windthrow and growth models. At the end of this chapter, the organization of the dissertation is given, along with a summary of how each chapter addresses the stated objectives.

1.1 Background to windthrow management and modelling

Windthrow can occur in many forests and the extent of windthrow damage might be predicted using a windthrow model. Losses due to windthrow vary with geographic location, edge orientation and individual tree characteristics. In Pacific Coastal forests of British Columbia (BC), Canada, and of Washington and Oregon, USA, increased variability in the spatial patterns of residual or leave trees (i.e., variable retention, VR) has become popular as a means to retain seed trees, single trees and patches for structure and habitat, and linear features as wildlife corridors, as well as other management objectives. Estimating the impact of wind on trees is critical in the development of a variable retention management plan, since these variations in spatial patterns of leave trees can impact the extent of windthrow losses. Windthrow can cause significant reductions in timber yield in VR areas; forest managers need to develop management plans which account for expected levels and impact of windthrow on the retained portion of the stand.

Many useful qualitative and quantitative tools have been developed to estimate windthrow losses at the stand level. Qualitative assessments are commonly used by decision makers to assess windfirmness (Miller et al. 1987, Stathers et al. 1994). While these are useful field
assessments, they do not provide a quantifiable link between tree and stand attributes and wind damage levels. Empirical models are also available to assess the probability and proportion of stand damage based on tree and stand attributes such as slenderness, spacing and fetch (Valinger and Fridman 1997, Lanquaye-Opoku and Mitchell 2005, Scott and Mitchell 2005). Neural networks have been used to predict damage at the stand level. However, the “black box” characteristics of neural networks may limit the ability to determine which of the relevant factors are most influential (Hanewinkel et al. 2004). Moreover, all of these methods predict windthrow at the stand level and do not enable analysis of the causal links between windthrow and tree and stand attributes, or the processes that drive windthrow.

Mechanistic models are hybrid process and empirical models that have been used to predict windthrow risk under different management scenarios. ForestGALES is one such model developed by the UK Forestry Commission (Gardiner et al. 2000). Other similar mechanistic models include HWIND and FOREOLE (Peltola et al. 1999, Ancelin et al. 2004, Peltola 2006). ForestGALES and the other mechanistic models estimate critical wind speeds required to uproot or break trees based on models of loading and resistance. Over 40 years of tree winching data were used to develop the resistance equations. However, the loading equations were based on fairly limited wind tunnel data. Like ForestGALES, FOREOLE uses surface roughness and momentum transfer (‘roughness method’) to estimate individual stem loading and critical wind speed within the stand. HWIND uses a vertical crown frontal area profile and wind profile at the stand edge (‘profile method’).
Canadian and UK researchers have been collaborating over the past several years to add Canadian tree species to ForestGALES (Ruel et al. 2000). Resistive turning moment equations are available for black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banksiana* Lamb.), and balsam fir (*Abies balsamea* (L.) Mill.), in Quebec (Achim 2004, Elie 2004), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn ex. D. Don), interior spruce (*Picea glauca* (Moench) Voss X *Picea engelmannii* Parry ex Engelmann) and lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) in BC (Byrne 2005). Data from wind tunnel experiments have also been used to calculate drag coefficients which enable adjustments to the loading equations for the four BC conifers (Rudnicki et al. 2004). ForestGALES has been validated in UK forests and some validation has been done for eastern Canadian forests (Gardiner et al. 2004, Gardiner et al. 2008). Researchers in the UK, France, Finland and, more recently, Japan are also modifying these models for local species and conditions.

A major limitation of the windthrow mechanistic models in their present form is that they do not account for wind direction and are designed primarily for single-storied and even-aged stands grown in relatively homogenous conditions. FOREOLE uses an empirical model based on the distribution of damage in field plots to estimate the proportion of damaged stems for a range of tree sizes and is based on the critical wind speed for the mean tree. This method uses a model to calculate individual tree failure based on wind speed and tree characteristics. However, parameters related to the wind profile, crown streamlining and tree attributes are the same as those found in ForestGALES and HWIND. FOREOLE is also non-directional in the sense that it assumes the wind blows directly towards the forest edge. Integrative models such as WINDA incorporate HWIND and Wind Atlas Analysis and
Application Program (WaSP) to predict the probability of edge damage at the landscape level (Blennow and Sallnas 2004). However, these predictions do not account for wind direction and assume flat or rolling terrain. Another system of HWIND-based integrative models has incorporated a growth and yield model, SIMA, to predict wind damage over a 20 year period (Zeng et al. 2006). Predictions are made at the regional scale and are non-directional.

To better match the variety of actual forest conditions, there is a need for a mechanistic model that reflects windthrow processes in more spatially complex terrain, wind regimes, forest types and forest management scenarios, and can better account for tree-level outcomes. In their current form, the mechanistic models do not represent the process of windthrow in more complex stands, where failure of one stem alters the wind regime for its surviving neighbours. Another major tree-level issue is the domino failure of trees where the failure of trees increases the wind exposure of their neighbours or directly impacts them in the process of falling. Therefore, methods of accounting for spatial variability and propagation of windthrow need to be developed to predict windthrow at the tree level in mixed species forests with horizontal and vertical heterogeneity. The development of an expanded model, which addresses these issues, is necessary for current and emerging applications in forest management and research.

1.2 Research objectives

In this dissertation, a mechanistic windthrow simulation model that can be used to predict windthrow in stands with vertical and horizontal spatial complexity due to natural variation and forest management scenarios is described and validated. Applications of this model are also demonstrated. Two central questions guided this research:
1. What spatial and temporal variations of tree, stand and meteorological attributes are required to represent the spatial variation of windthrow and the propagation of windthrow at the tree level in mixed species and multi-storied stands?

2. How can other models (e.g. growth and yield models) and readily available spatial datasets such as tree lists, cutblock boundaries, post-harvest retention levels, topography and wind flow be assembled and integrated with a tree level mechanistic model?

Since model simulations need to be reconciled with actual results from the field, the follow-up question was:

3. How well changes to the model reflect real stand conditions encountered in BC?

The data required to address these research questions can be divided into four broad categories: a) tree-level data, b) stand-level data, c) wind regime data, and d) terrain data. These data are the inputs for current mechanistic models and are distributed across various spatial and temporal scales. Mechanistic models, in their current form, calculate the critical wind speed (i.e. the speed at which windthrow occurs) for the mean tree in the stand; as a result, when one tree fails the entire stand fails. They are also unable to calculate and display spatial differences in windthrow across treatment areas. Therefore, a necessary requirement for the advancement of mechanistic windthrow models was to develop the capacity to quantify and display the effects that spatial data inputs have on the variation of windthrow within a stand at the tree level.
Based on the central questions, the objectives of this research were to:

1. Improve a mechanistic windthrow model structure designed to test changes to model equations independently from the overall model (i.e. unit test) to determine the effects of input variables on windthrow outcomes, help identify knowledge gaps and more easily integrate new equations related to these gaps.

2. Improve windthrow predictions with respect to tree size (dendrometric) and exposure (i.e. gap and fetch) and gust (i.e. peak to mean wind speed ratio) variables.

3. Enable mechanistic windthrow results for multiple individual trees to be represented spatially.

4. Model spatial differences in windthrow across a landscape which are sensitive to wind direction, upwind stand characteristics and tree attributes.

5. Demonstrate how simulated windthrow openings can be used to account for natural disturbance in tree level growth and yield simulations.

6. Quantify dynamic windthrow processes where the stability of residual trees is compromised by the failure of their neighbours (i.e. windthrow propagation).

7. Use spatial tree-lists for windthrow simulations and validate the results by comparing them to actual windthrow from field plot data.
8. Identify components of the model which require improvements and propose future research to address important knowledge gaps.

The model development process included the reverse engineering and restructuring of the underlying mechanistic model, ForestGALES, to enable the integration of species-specific and spatial functions into a model ‘WindFIRM’ that incorporates spatial inputs and calculates damage propagation. Each of these phases represents a considerable improvement in the capacity to represent the process of windthrow. This thesis has been divided into three main chapters where each one builds on the previous chapter. The topics covered in these chapters are:

1. Chapter 2, the development of ForestGALES_BC as a mechanistic foundation for a spatial windthrow model;

2. Chapter 3, the integration of ForestGALES_BC with WindFIRM to represent spatial effects and windthrow dynamics; and

3. Chapter 4, demonstration and validation of WindFIRM/ForestGALES_BC using field plot data from the STEMS (Silvicultural Treatments for Ecosystem Management in the Sayward) research installation of BC.

Each of these chapters is summarized in the following sections, followed by a brief description of the final dissertation chapter.
1.3.1 Mechanistic foundations of a spatial windthrow model

Chapter 2 describes the development of ForestGALES_BC which calculates the wind loading and resistance, as part of the overall windthrow model developed in this research. A reverse-engineering approach was used to examine the original ForestGALES model and its component parts or objects (Table 1.1). Objects were improved to reflect differences in tree characteristics and fetch to facilitate Chapter 3 where spatially explicit variations in windthrow were introduced. Fetch is the distance over which wind blows with either reduced or no obstructions. Even though not all objects were changed, explicit documentation of all objects was included in this chapter, since they are important to model outcomes, and documentation will facilitate further research (Research Objective 1).

Table 1.1 Objects in ForestGALES_BC (both changed and unchanged from original ForestGALES model) with references to the relevant studies or models.

<table>
<thead>
<tr>
<th>Object Name</th>
<th>Changed</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Wind</td>
<td>Y</td>
<td>(Gardiner et al. 2000)</td>
</tr>
<tr>
<td>Roughness</td>
<td>-</td>
<td>(Raupach 1994, Dunham et al. 2000,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gardiner et al. 2000)</td>
</tr>
<tr>
<td>Wind Profile and Force</td>
<td>Y</td>
<td>(Mayhead 1973, Rudnicki et al. 2004,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Byrne 2005)</td>
</tr>
<tr>
<td>Tree Characteristics</td>
<td>Y</td>
<td>(Byrne 2005)</td>
</tr>
<tr>
<td>Stem Taper</td>
<td>Y</td>
<td>(Kozak 1988, Klos et al. 2007)</td>
</tr>
<tr>
<td>Bending Moment</td>
<td>-</td>
<td>(Gardiner 1989)</td>
</tr>
<tr>
<td>Gap Factor</td>
<td>Y</td>
<td>(Scott 2005)</td>
</tr>
<tr>
<td>Maximum Moment</td>
<td>Y</td>
<td>(Alden 1997, Byrne 2005)</td>
</tr>
<tr>
<td>Gust Factor</td>
<td>Y</td>
<td>(Gardiner et al. 1997)</td>
</tr>
</tbody>
</table>

To improve these objects, a meta-modelling approach was used to incorporate the results and models from other studies and the revised model was named ForestGALES_BC. An integrated meta-model such as this could be considered a conceptual analytical tool to assemble information from multiple sources and enable human abstractions of complex
ecological processes for decision making (Kumar et al. 2010). Results were compared to
ForestGALES simulations based on their sensitivity to tree and gap sizes and distances from
the stand edge. The logic of ForestGALES_BC simulations was also evaluated using
expected results from empirical studies (Objective 2).

Although ForestGALES_BC represents an improvement to several objects over
ForestGALES, it is limited in representing the spatial variability within stands (e.g. soils,
root-interlocking, acclimative growth, etc.), particularly stands following VR silvicultural
treatments. The research presented in chapter 2 resulted in a more realistic model of
windthrow given the variable effects of upwind gaps and tree characteristics (i.e.
dendrometrics). The focus of this chapter was on the component calculations of wind
loading and resistance and the stands were still represented as being uniform to evaluate
these improvements compared to the original model. This first research chapter was an
important step in the model development process to parse the mechanistic portion of the
model and introduce the foundations required to integrate more comprehensive spatial
equations (Objective 3).

1.3.2 Representation of spatial effects and windthrow dynamics

Chapter 3 builds on the meta-modelling process introduced in Chapter 2 to modify the
windthrow model for more complex stands by integrating WindFIRM (Wind Forest
Instability Risk Model) and ForestGALES_BC (WindFIRM/ForestGALES_BC).
WindFIRM was originally developed as an ArcView extension in Avenue scripts and
subsequently converted to Python to integrate with ForestGALES_BC. It was designed to
characterize within-opening wind exposure due to fetch and boundary orientation and
spatially represent stand variability by assembling data from layers such as forest cover attributes, above-canopy wind speed and tree-lists for grid cells across a landscape. The coupling of ForestGALES_BC and WindFIRM builds on the ability of the model to calculate windthrow at the tree level for a wider range of silvicultural and harvest scenarios. This enabled the simulation and display of spatial windthrow results for an infinite range of harvest and wind scenarios (Objective 4). Spatial tree lists (i.e., species, tree sizes, and tree locations) were simulated using TASS (Tree and Stand Simulator), a single tree growth model developed for BC tree species, and passed to WindFIRM to aggregate and calculate input variables required by ForestGALES_BC to simulate tree level windthrow. TASS is a spatially explicit individual tree growth model that provides growth and yield estimates for decision support in the forests of British Columbia TASS (Mitchell 1975). The interdependence of TASS and WindFIRM/ForestGALES_BC also demonstrated a Decision Support System (DSS) structure, capable of modelling the differences in windthrow for multiple trees within the same stand and the impacts of these tree removals on growing spaces for future growth and yield projections (Objective 5).

Chapter 3 outlines the second of three steps in this research designed to better reflect the complexity of the windthrow process. Simple cutblock scenarios were simulated using the desktop version of TASS (TASS III) to represent a broad range of stand conditions that influence individual tree stability (e.g., fetch and spacing). Important contributions of this chapter are the demonstration of the sensitivity of damage to wind direction and quantification of the dynamic effects of increased exposure on residual trees due to the loss of their neighbours (propagation of windthrow). This was accomplished by apportioning the tree list into grid cells of 25 X 25 m to represent varying stand conditions across a stand or
group of stands (i.e., landscape), which affect the vertical wind speed profile and crown loading. Fetch variables were also calculated for each grid cell creating a mosaic of unique conditions across a landscape, which were automatically quantified using the spatial tree lists. These stand variable inputs were combined with individual tree data in ForestGALES_BC to calculate windthrow results for every tree in the stand which could then be summarized at any point in time.

Model simulations were evaluated and discussed based on the relative distribution of damage across a range of tree (i.e. diameter at breast height (DBH), height, and height-to-diameter ratio) and stand input variables (i.e. fetch and spacing). These results were distinct from those in Chapter 2 in that windthrow was estimated for multiple trees within the same stand, indicating where these vulnerable trees occur in the stand, and quantifying the dynamic effects of windthrow propagation (Objective 6).

1.3.3 Validation of model outputs using STEMS data

The research presented in Chapters 2 and 3 improved the windthrow model by more realistically reflecting the variation and dynamics of the tree, stand and wind characteristics. However, since a meta-modelling approach and simulations were used to create the spatial tree list and calculate windthrow at the individual tree level, validation was needed to compare simulated and actual windthrow. In Chapter 4, windthrow data from STEMS (de Montigny 2004), a 140 ha research installation, were used to validate WindFIRM/ForestGALES_BC. The data represented sites, stands and ranges of treatments that are within the ranges of conditions for which the linked model described in Chapters 2 and 3 was designed to simulate. Since the area of the STEMS research installation is larger
than could be simulated using the desktop version of TASS, Ken Polsson of the BC Ministry of Forests and Range (now Ministry of Forests, Mines and Lands) used TASS to provide simulated tree lists that represent the STEMS installation stands and data. Wind data were analyzed to determine the wind speeds and directions of the most likely wind events. Then, the linked WindFIRM/ForestGALES_BC model developed in Chapters 2 and 3 was used to simulate windthrow at STEMS. Windthrow simulations were then compared to field plot data based on the spatial distribution of windthrow, the amount of windthrow and cumulative distribution of windthrow (Objective 7).

1.3.4 Summary chapter including recommendations

The final chapter of this dissertation summarizes the main contributions of the research, and identifies and prioritizes some specific recommendations that will improve windthrow simulations (Objective 8). For example, there are some limits to the quantification of topographic variables used in this research due to the complexity of terrain and additional data will be required to couple local terrain effects on wind acceleration and funnelling with wind direction. There are also some improvements that could be made regarding the mechanics of the model to more accurately quantify spacing in partially populated grid cells and the mechanical effects of fetch using numerical wind modelling in small openings. Recommendations regarding future model validation are also presented.
2.0 Mechanistic Foundations of a Spatial Windthrow Model Using ForestGALES

2.1 Introduction

ForestGALES (Geographical Analysis of the Losses and Effects of Storms in Forestry) is a public domain software package developed by the UK Forestry Commission (Dunham et al. 2000, Gardiner et al. 2000) that can be used to predict the critical wind speed for tree failure and the probability of this critical wind speed in even-aged stands. ForestGALES has been used to predict windthrow for single-species plantations of mostly Sitka spruce (*Picea sitchensis* (Bong.) Carriere) in the UK (Dunham et al. 2000, Gardiner et al. 2000). In recent years, this model has been modified by the University of British Columbia (UBC) windthrow research group to include BC tree species (Byrne 2005).

ForestGALES is a hybrid mechanical and empirical model (mechanistic model) which combines the use of equations related to mechanical and meteorological processes with empirical equations that estimate wind load and resistance as a set of equations related to tree properties. The model is completely deterministic, meaning that the variability (i.e. error terms) associated with the component empirical equations and other random effects associated with the overall windthrow process are not included. There are also many simplifying assumptions with respect to stem and crown characteristics (dendrometrics) such as taper and the vertical crown profile. ForestGALES uses a single tree to represent the stand, meaning that when this representative tree fails, the whole stand fails. Additional simplifying assumptions were made on the representation of stand conditions which affect local peak and mean wind speeds such as gap size and distance from the edge.
Resistance and loading equations are the central part of critical wind speed estimation in ForestGALES. As a result, ForestGALES is the product of an accumulation of many years of tree winching and wind tunnel research. In modifying this model for use with BC species, winching and wind tunnel experiments were conducted on western redcedar (*Thuja plicata* (Donn ex D. Don) Spach), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and lodgepole pine (*Pinus contorta* Doug. ex Loud.), and hybrid spruce (*Picea engelmannii* Parry *X Picea glauca* (Moench) Voss) (Rudnicki et al. 2004, Byrne 2005, Byrne and Mitchell 2007). The winching experiments were used to fit models in which stem mass is a predictor of critical resistive turning moment for BC species. Critical resistive turning moment occurs when the applied force due to wind multiplied by the height of that force exceeds the maximum resistive moment at the base of the tree. The wind tunnel experiments were used to calculate species-specific drag coefficients.

ForestGALES has been improved and validated for very uniform plantations such as Sitka spruce in the UK (Gardiner et al. 2004). Some of these changes to the model are well documented in the literature; however, windthrow processes that are important for other types of stands and species may not be well represented by ForestGALES. For example, the model does not accurately represent the variability of even or uneven-aged mixed species stands in BC. To increase realism in ForestGALES in order to improve predictions in uneven-aged and/or mixed species stands of BC, the model will need to capture the spatial variability in tree properties and wind speeds within stands.
The objectives of the research presented in this chapter are to:

1. Restructure objects in ForestGALES and parse the model into component parts to enable unit testing of the key processes, identify knowledge gaps; and make it easier to integrate and modify equations related to these gaps as new research results become available;

2. Modify and integrate equations related to dendrometric, exposure and gust factors using a meta-modelling approach to improve mechanistic windthrow model predictions; and

3. Demonstrate how changes to the model facilitate the spatial representation of mechanistic windthrow results for multiple individual trees.

For the first objective, ForestGALES was deconstructed using a reverse-engineering approach to identify objects and equations within objects which represent important parts of the windthrow process. This is described in the Section 2.2. The need for modifications of these objects for use in more complex stands of BC is then explained. The restructured model, termed ForestGALES_BC, is then described. Specific changes to equations within objects are then described in Section 2.3 (Objective 2), within the context of each object and the model as a whole. Comparisons of ForestGALES and ForestGALES_BC simulations are given in Section 2.4. In Section 2.5, a discussion of the ForestGALES model is presented, including the logic behind the model changes, and results of model simulations, relative to spatial variability of BC forests (Objective 3). The main hypothesis in this chapter is that
changes to equations related to dendrometrics, exposure and peak to mean wind loads (i.e. gust factor) will improve windthrow predictions for more complex stands of BC.

2.2 Methods

2.2.1 Overview of ForestGALES

The principal premise of ForestGALES is that the above canopy wind speed required to uproot or break the representative tree (i.e. mean tree) in a stand is calculated. This is known as the critical wind speed and this occurs when the calculated wind load exceeds the maximum resistance (critical resistive turning moment) of the tree. As noted earlier in this dissertation, ForestGALES has been previously modified for Canadian species (i.e. earliest version of ForestGALES_BC) by adjusting the drag coefficients and critical resistive turning moment equations from the original model based on wind tunnel and tree pulling experiments in Quebec and British Columbia (Bergeron 2004, Elie 2004, Rudnicki et al. 2004, Byrne 2005, Byrne and Mitchell 2007). However, all other objects and equations within objects were retained. These include the simplifying assumptions associated with the stem and crown form, stand uniformity, directionality and gust factors.

A simplified view of ForestGALES shows inputs to and outputs from the model (Figure 2.1). Species, height, diameter at breast height (DBH) and spacing among trees are the primary inputs required to calculate the critical wind speed, the above canopy wind speed at which the tree fails, and the return period of that wind speed. Other inputs related to soil and site windiness may be included; however, these inputs are particular to use in UK. The two objects that control most of the calculations are the Tree Object, which supplies tree-level inputs derived from the user inputs to the Tree Mechanics object.
Within the Tree Object, stem taper and crown shape are simply represented. Stem diameter (i.e., taper) is calculated differently within the crown (i.e., above the canopy base) than below the crown (i.e., below the canopy base). Within the crown, diameter \(Diam_i\) at point \(i\) on the stem is estimated by:

\[
Diam_i = c_1(ht_{tree} - Z_i)
\]  

(2.1)

where \(ht_{tree}\) is the height of the tree, \(Z_i\) is the height above ground to a point \(i\), (i.e., \(Diam_i = 0\) when \(ht_{tree} = Z_i\)), and \(c_1\) is a constant which assumes a linear change in diameter (i.e., a conical shape) within the crown (Mattheck 1998). Stem diameter below the live crown is estimated using:

\[
Diam_i = c_2(ht_{mc} - Z_i)^{0.333}
\]  

(2.2)

where \(ht_{mc}\) is the height to the middle of the live crown, and \(c_2\) is a constant which is based on the assumption that constant stress below the crown and mid-crown load. This assumes an approximately neiloid shape below the crown canopy. Since the taper changes with tree
height only, not with tree DBH (diameter at 1.3 metres), changes in tree taper and diameter for a given height that occur with differing stand densities are not modelled. Also, the estimates of parameters $c_1$ and $c_2$ were only obtained for Sitka spruce ($Picea sitchensis$ (Bong.) Carrière) in UK using only 10 trees with narrow ranges of height (13.35 m – 17.05 m) and DBH (13.0 cm – 20.6 cm) (Gardiner 1989). Therefore, this represents a “standard” tree shape that might be expected for a tree of 15 m tall with DBH of 16.5 cm, and this standard tree shape is assumed for all trees regardless of species, DBH, and stand density.

Once $Diam_i$ is estimated at different heights, volume of each stem section is calculated using the section length and diameter based on the assumed shape of the “standard” tree. Section volumes are converted to mass ($mass_i$) using a constant wood density of 850 kg/m$^3$, again, regardless of species. Total stem mass ($m_{stem}$) is then the sum of section masses.

Total stem mass is used in two ways in the model. First, it is a predictor variable used to estimate the critical resistive turning moment ($M_{uproot}$) as follows:

$$M_{uproot} = b_0 + b_1 m_{stem} \quad (2.3)$$

where $b_0$ and $b_1$ are species-specific parameters estimated using tree winching experiments. It is important to note that the unit of stem mass is kg and moment is Nm. Therefore, the estimated parameters ($b_0$ and $b_1$) may only be used to convert kg to Nm. Any other units of mass would produce errors in the calculation of moment. Second, stem mass is used to determine the applied moment due to self loading ($M_{self-loading}$). The crown is assumed to be a “diamond” shape, with a conical shape above the mid-canopy (i.e., the mid-crown is assumed
to be the same for all trees in the stand) and an inverted cone below this point. Using this assumed crown shape, sectional branch widths (m) above and below the canopy mid-point are calculated using:

\[
\text{Branch}_{\text{width}_i} = \text{Canopy}_{\text{bdth}} \cdot \frac{(Z_i - \text{Canopy}_{\text{height}})}{(\text{Canopy}_{\text{mid-point}} - \text{Canopy}_{\text{height}})} \tag{2.4}
\]

\[
\text{Branch}_{\text{width}_i} = \text{Canopy}_{\text{bdth}} \cdot \frac{(1 - Z_i - \text{Canopy}_{\text{mid-point}})}{(ht_{\text{tan}} - \text{Canopy}_{\text{mid-point}})} \tag{2.5}
\]

Where \( Z_i \) is the height of the canopy section, \( \text{Canopy}_{\text{height}} \) is the height from ground to the base of the canopy (assuming all trees are the same), \( \text{Canopy}_{\text{mid-point}} \) is the height to the middle of the canopy (i.e., mid-crown) and \( \text{Canopy}_{\text{bdth}} \) is the maximum crown diameter estimated using an equation of mean DBH which is assumed to occur at the canopy mid-point. This is converted to \( \text{Canopy}_{\text{breadth}} \) which is different than \( \text{Canopy}_{\text{bdth}} \) in that it accounts for the triangular shape and porosity of the crown and is described in Section 2.3.2. In ForestGALES, the term “canopy” is interchangeable with “crown”, since the mean tree represents all trees in the stand, and, therefore, canopy represents the crown of all trees. The volume of the crown is based on the sectional branch widths and accounts for porosity using the converted value for \( \text{Canopy}_{\text{breadth}} \). Crown mass is calculated using a constant crown density which is 2.5 kg/m\(^3\) in ForestGALES.

The Tree Mechanics object contains many inter-related equations to calculate the effects of gaps, proximity to edges and wind gustiness. In ForestGALES, stand gaps are assumed to
be regularly spaced and shaped. There are two methods used to calculate wind loading on
trees: the roughness and profile methods. The roughness method is the default method where
the average drag force on trees is calculated using the roughness length, zero-plane
displacement and shear stress (i.e. momentum transfer into the stand). This average force is
considered the representative force acting on individual trees. The profile method calculates
the vertical wind speed profile above and within the canopy using roughness, zero-plane
displacement and average tree height- to-spacing ratio (assuming constant inter-tree
distances). The total wind loading on the tree is then the sum of loads on each vertical crown
section. The crown acts like a sail when the profile method is used to calculate applied wind
forces.

2.2.2 Critical assessment of ForestGALES for more complex stands

Overall, the simplifications of tree allometric relationships in the Tree Object do not
represent stands that are variable in stand structure and species. The simple tree taper,
crown shape, and crown biomass equations assume that these are constant across species,
DBH, stand densities, and spatial arrangements. For complex stands with many species and
a more variable vertical structure, these simplifying assumptions do not hold, and the
equations within the Tree Object do not represent trees well. Different species have
different crown forms which dictate the “sail area” but these differences are not represented
in ForestGALES. These dendrometric equations need to be changed to distinguish
differences in wind loading and resistance calculations in the Tree Mechanics object.

For the Tree Mechanics object, in terms of the wind loading on trees, the only way to
differentiate loads on individual trees using the roughness method is to weight the
distribution of momentum transfer over an area of forest based on voronoi diagrams representing the horizontal crown areas of individual trees. This is problematic when it comes to the application of wind loads on trees in multi-storied stands. Conversely, the profile method is more easily adapted for calculating variability in wind loading on individual trees within the canopy and shows more promise for more realistically representing loads in more complex stands. Also, the assumption that gaps are uniformly sized and distributed in space does not hold for complex stands, particularly complex spatial arrangements that occur when variable retention silvicultural treatments are used. VR treatments have been used in North America since the mid 1990’s to retain trees individually and in groups within openings to conserve uneven aged and multi storied attributes of the original stand (Mitchell and Beese 2002). Other jurisdictions where VR treatments have been used or proposed include Australia (Hickey et al. 2001), the UK (Kerr 1999) and more recently South America (Pastur et al. 2009). Changes are needed to better represent the spatial arrangements.

Changes to the gap equations in ForestGALES are needed to address management implications of VR silvicultural treatments; the ability of mechanistic models to account for retention within openings will have broad applications. However, making changes to the equations governing the effects of upwind gaps and tracking all the cascading effects on subsequent calculations of edge and gust factors would be very difficult, given the complex array of inter-related equations in the Tree Mechanics object. Also, many changes to the equations of ForestGALES have been made to improve the model for Sitka spruce plantations in the UK; the rationale for these adjustments is not completely documented. This makes model refinements for local stand conditions which vary by region problematic.
2.2.3 Changes for more complex stands

To better represent more complex stands of BC, ForestGALES_BC was developed by reorganizing the objects and replacing functions within some of these objects. This model has new equations for individual tree dendrometrics, gust factor, and the effects of variable upwind stand conditions. To facilitate the development of ForestGALES_BC, the ForestGALES was converted from the Borland Delphi Version 5 to Python Version 2.6. Both of these programming languages are object-oriented; however, Python is open-source and free to use whereas Delphi is proprietary. The changes to each object are described in the results, along with descriptions of equations within objects that were not changed.

The primary output of the Output object of ForestGALES is critical wind speed which is problematic for more spatially and structurally variable stands. This issue is not addressed in this chapter, but will be revisited in Chapter 3 of this dissertation.

2.2.4 Evaluation of ForestGALES vs ForestGALES_BC

A range of wind and stand conditions were simulated to assess the effectiveness of ForestGALES_BC versus ForestGALES for more complex forests of BC. Since the output of ForestGALES is critical wind speed rather than an assessment of tree stability for a given wind speed, critical wind speeds were calculated with ForestGALES_BC, also, to enable direct comparison of the two models.

Data from four tree winching sites in BC were used as inputs to the two models. A detailed description of these data is given in Byrne (2005) and Byrne and Mitchell (2007). A brief description is given here. Site 1 a mixed western redcedar and western hemlock stand on a
gentle north facing slope in a very moist variant of Coastal Western Hemlock biogeoclimatic zone (Meidinger and Pojar 1991). Sites 2 and 3 were mixed spruce and subalpine fir (*Abies lasiocarpa* (Hook) Nutt.) stands about 120 km northeast of Prince George, BC on the McGregor Plateau which occupies the wettest and coldest variant in the Sub Boreal Spruce biogeoclimatic zone. Site 4 was a mixed pine and spruce stand was approximately 50 km south of Prince George in the dry and warm variant of the Sub Boreal Spruce zone. All sites were naturally regenerated. Four circular 400 m$^2$ plots were measured at each site in undamaged stands. Stand input data from each site is summarized in Table 2.1.

<table>
<thead>
<tr>
<th>Site</th>
<th>Species *</th>
<th>$h_{\text{stand}}$ avg. (m)</th>
<th>$DBH_{\text{stand}}$ avg.</th>
<th>spacing distance (m)</th>
<th>height range (m)</th>
<th>$DBH$ range (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cw</td>
<td>23.0</td>
<td>35.3</td>
<td>5.4</td>
<td>12.2 – 30.1</td>
<td>12.1 – 67.9</td>
</tr>
<tr>
<td>1</td>
<td>Hw</td>
<td>23.0</td>
<td>35.3</td>
<td>5.4</td>
<td>10.6 – 30.7</td>
<td>9.4 – 49.5</td>
</tr>
<tr>
<td>1</td>
<td>Fd</td>
<td>23.0</td>
<td>35.3</td>
<td>5.4</td>
<td>27.2 – 41.9</td>
<td>49.5 – 77.5</td>
</tr>
<tr>
<td>2</td>
<td>Sx 1</td>
<td>21.8</td>
<td>29.5</td>
<td>4.1</td>
<td>15.1 – 34.0</td>
<td>12.0 – 60.8</td>
</tr>
<tr>
<td>3</td>
<td>Sx 2</td>
<td>19.1</td>
<td>30.3</td>
<td>4.4</td>
<td>15.8 – 55.4</td>
<td>12.5 – 29.5</td>
</tr>
<tr>
<td>4</td>
<td>Pl</td>
<td>22.1</td>
<td>24.0</td>
<td>2.9</td>
<td>16.5 – 39.0</td>
<td>15.7 – 33.8</td>
</tr>
</tbody>
</table>

* western redcedar (Cw), western hemlock (Hw), Douglas-fir (Fd), Engelman/white hybrid spruce (Sx), lodgepole pine (Pl).

The first series of simulations was generated using ForestGALES (Roughness method), ForestGALES (Profile method) and ForestGALES_BC (Profile method) to compare critical wind speed outputs at 0, 30 and 60 metres from the edge. The VRFetch input variable which is a measure of gap size modified by the amount of retention within the gap (Scott 2005), was held constant at 120 m in ForestGALES_BC and, as its closest parallel, gap size was held constant at 120 m in ForestGALES. Trial simulations of other gap sizes were conducted in ForestGALES, but it was found that critical wind speeds varied only 1 or 2 m/s for gap sizes over 120 m.
The next series of simulations was generated using ForestGALES_BC to analyze the sensitivity of critical wind speed to both VR Fetch and distance from the edge. VR Fetch values between 120 and 150 m had a very small influence on critical wind speeds, so VR Fetch values of 150, 180 and 210 m were used and compared with ForestGALES distance from the edge for these same values. Finally, the effects of spacing were compared between simulations for a representative of each species. Results of the simulations were summarized and used to compare the effectiveness of ForestGALES versus ForestGALES_BC for modelling windthrow in these stands.

2.3 Results Part 1 – Construction of a new windthrow model, ForestGALES_BC

2.3.1 Reorganization of objects and equations within objects to reflect complex stands

Only a subset of equations of ForestGALES were modified to better reflect complex stands in ForestGALES_BC. However, since many of the changed equations are affected by or may impact other equations, a more complete description of these impacts is also presented here. The text explicitly indicates which equations have been changed and which have not been changed from the original model.

As a means of communicating these changes, and also to facilitate further changes, the new model, ForestGALES_BC was organized into objects as shown in Figure 2.2. Equations were organized into objects used to calculate tree loading (blue) and resistance (yellow) which are the two primary calculations in mechanistic windthrow models. Other objects (green) were also required to organize preparatory equations used to calculate inputs for both
loading and resistance equations. The Flag Tree object simply compares the applied load to the maximum resistance and flags individual trees for failure if the load exceeds resistance.

Each of these objects is described, including inputs used in the object and outputs passed to the next object for windthrow simulations. Wind speed and direction are the primary user-defined inputs.

### 2.3.2. Tree Characteristics object

The Tree Characteristics object aggregates and calculates individual tree attributes (e.g. branch lengths, stem mass and stem taper) that are passed to other objects of ForestGALES_BC (Figure 2.2). The way individual tree and stand attributes are aggregated and imported in this object in Chapter 3 represents a major departure from how they are calculated in the original ForestGALES. However, these values are user defined in this chapter to enable the evaluation of the models. Individual tree and stand attributes are inputs used to calculate canopy characteristics which are used in the Roughness object to calculate zero plane displacement and surface roughness. Canopy breadth and depth are used in the Roughness object to calculate auxiliary variables used in the Wind Profile and Force objects.
Both crown variables are calculated using species-specific regression models based on data from the BC tree winching database (Table 2.2). Species-specific independent (predictor) variables were chosen based on the lowest root mean square errors (RMSE).

Table 2.2. Linear equations used to calculate canopy characteristics (Byrne 2005 with permission).

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Independent Variable</th>
<th>Sp. *</th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>SE$b_0$</th>
<th>SE$b_1$</th>
<th>RMSE</th>
<th>$R^2$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy depth $ht * DBH^2$</td>
<td>Cw</td>
<td>9.17</td>
<td>0.80</td>
<td>0.66</td>
<td>0.14</td>
<td>1.87</td>
<td>0.57</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hw</td>
<td>8.48</td>
<td>1.35</td>
<td>0.88</td>
<td>0.19</td>
<td>2.33</td>
<td>0.71</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pl</td>
<td>1.66</td>
<td>0.28</td>
<td>5.77</td>
<td>0.21</td>
<td>2.17</td>
<td>0.06</td>
<td>0.2087</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sx</td>
<td>0.17</td>
<td>0.55</td>
<td>2.66</td>
<td>0.13</td>
<td>2.20</td>
<td>0.49</td>
<td>0.0007</td>
<td></td>
</tr>
<tr>
<td>Canopy bdth $DBH$</td>
<td>Pl</td>
<td>-1.08</td>
<td>16.59</td>
<td>1.05</td>
<td>3.46</td>
<td>1.83</td>
<td>0.65</td>
<td>0.0006</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sx</td>
<td>3.28</td>
<td>6.61</td>
<td>0.73</td>
<td>2.54</td>
<td>0.72</td>
<td>0.25</td>
<td>0.0191</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cw</td>
<td>5.36</td>
<td>0.46</td>
<td>0.23</td>
<td>0.05</td>
<td>0.64</td>
<td>0.79</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hw</td>
<td>3.55</td>
<td>0.73</td>
<td>0.26</td>
<td>0.06</td>
<td>0.69</td>
<td>0.88</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
</tbody>
</table>

* western redcedar (Cw), western hemlock (Hw), lodgepole pine (Pl), Engelman/white hybrid spruce (Sx).

$SE$ and $RMSE$ are the standard errors and root mean square errors respectively.
Regressions are significant for $p$-values less than the critical value ($\alpha=0.05$).

Similarly, stem mass is calculated for each tree in the list using linear equations fitted using data from the BC tree winching database (Table 2.3). This is different than in ForestGALES where stem mass is calculated from the product of stem density and volume, and equations to calculate volume and the stem mass are the same for all species.

Table 2.3. Linear equations used to calculate stem mass (kg) (Byrne 2005 with permission).

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Independent Variable</th>
<th>Sp. *</th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>SE$b_0$</th>
<th>SE$b_1$</th>
<th>RMSE</th>
<th>$R^2$</th>
<th>p ($\alpha=0.05$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{stem}$ $ht*DBH^2$</td>
<td>Cw</td>
<td>117.91</td>
<td>174.16</td>
<td>37.67</td>
<td>8.11</td>
<td>106.29</td>
<td>0.95</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hw</td>
<td>57.71</td>
<td>301.45</td>
<td>42.73</td>
<td>9.61</td>
<td>115.09</td>
<td>0.98</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pl</td>
<td>95.46</td>
<td>272.83</td>
<td>54.98</td>
<td>18.17</td>
<td>91.08</td>
<td>0.95</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sx</td>
<td>44.26</td>
<td>258.19</td>
<td>45.48</td>
<td>22.34</td>
<td>97.77</td>
<td>0.89</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
</tbody>
</table>

* western redcedar (Cw), western hemlock (Hw), lodgepole pine (Pl), Engelman/white hybrid spruce (Sx).

$SE$ and $RMSE$ are the standard errors and root mean square errors respectively.
Regressions are significant for $p$-values less than the critical value ($\alpha=0.05$).

The species- specific crown form equation in ForestGALES-BC was taken from the TASS model where sectional branch widths ($Width_{branch}$) are estimated as follows:
and A, B, C are estimated parameters for each species (Table 2.4). The differences between the tree height ($h_{tree}$) and the height of each tree section ($h_{tree_i}$) are used to calculate the vertical position ($Z_i$) that corresponds to the sectional branch widths.

<table>
<thead>
<tr>
<th>Species</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>western redcedar</td>
<td>9.0678</td>
<td>0.975</td>
<td>21.275</td>
</tr>
<tr>
<td>western hemlock</td>
<td>4.52</td>
<td>0.887</td>
<td>9.619</td>
</tr>
<tr>
<td>Douglas-fir</td>
<td>3.517</td>
<td>0.975</td>
<td>6.096</td>
</tr>
<tr>
<td>lodgepole pine</td>
<td>1.73</td>
<td>0.975</td>
<td>2.734</td>
</tr>
<tr>
<td>hybrid spruce</td>
<td>2.9</td>
<td>0.975</td>
<td>6.4</td>
</tr>
</tbody>
</table>

The application of Eq. 2.6 is constrained to heights of each section that are within the crown. As a result, the inputs to the Tree Characteristics model must include height to live crown (or crown length) as well as species, DBH, and height. No error term is used in the application of this equation in the model.

Wood decay rates are also assembled in this object which can be output from ForestGALES_BC and used in a separate large woody debris model that can be used when windthrown trees become a structural component of small fish bearing streams (Bahuguna 2008) and other uses.

**2.3.3. Stem Taper object**

Taper functions were replaced in the Stem Taper object using a variable exponent taper equation developed by Kozak (1988) as follows:
\[
\hat{d}_{\text{tree}_i} = a_0 \cdot DBH_{\text{tree}}^{a_1} \cdot DBH_{\text{tree}}^{a_2} \cdot X_i \cdot b_1 \cdot Z_i + b_2 \cdot \ln(Z_i + 0.001) + b_3 \cdot e^{Z_i} + b_4 \cdot e^{Z_i + DBH_{\text{tree}}/ht_{\text{tree}}} \tag{2.7}
\]

where

\[
X_i = \left(1 - \frac{ht_{\text{tree}}/ht_{\text{tree}}}{(1 - \sqrt{p})}\right)
\]

and

\[
Z_i = \frac{ht_{\text{tree}}}{ht_{\text{tree}}}
\]

The variable \(Z_i\) in Equation 2.7 is used to calculate the predicted diameter \(\hat{d}_{\text{tree}_i}\) for each stem section \(i\) which replaces the sectional diameters \(diam_i\) calculated in the original model as described earlier. The sectional diameters for each tree are also dependent on DBH \(DBH_{\text{tree}}\) which is distinct from the average stand DBH \(DBH\) which is used to calculate canopy characteristics in the Tree Characteristics object. This is a new development to accommodate differences in wind loading for individual trees within a stand. For the same reason, the height of sections within each individual tree \(ht_{\text{tree}_i}\) is distinct from relative heights above the ground \(Z_i\).

The coefficients estimated by Kozak (1988) were used for all species except hybrid spruce, where the coefficients estimated by Klos et al. (2007) were used (Table 2.5). Since these
estimated parameters are unique to each species for even-aged stand grown trees, this enabled a more realistic representation of taper in ForestGALES_BC.

Table 2.5. Species-specific coefficients used in Equation 2.7 (extracted from Kozak (1988) and Klos et al. (2007) with permission).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>western hemlock</th>
<th>western redcedar</th>
<th>Douglas-fir</th>
<th>lodgepole pine</th>
<th>hybrid spruce</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>1.6789</td>
<td>1.2170</td>
<td>1.0245</td>
<td>0.7746</td>
<td>0.6977</td>
</tr>
<tr>
<td>$a_1$</td>
<td>1.0369</td>
<td>0.8426</td>
<td>0.8881</td>
<td>1.0403</td>
<td>1.1086</td>
</tr>
<tr>
<td>$a_2$</td>
<td>1.0003</td>
<td>1.0000</td>
<td>1.0004</td>
<td>0.9970</td>
<td>0.9931</td>
</tr>
<tr>
<td>$b_1$</td>
<td>-1.2568</td>
<td>1.5532</td>
<td>0.9509</td>
<td>0.7458</td>
<td>0.2342</td>
</tr>
<tr>
<td>$b_2$</td>
<td>0.1834</td>
<td>-0.3972</td>
<td>-0.1809</td>
<td>-0.1302</td>
<td>-0.0653</td>
</tr>
<tr>
<td>$b_3$</td>
<td>-2.8069</td>
<td>2.1102</td>
<td>0.6141</td>
<td>0.5588</td>
<td>0.1814</td>
</tr>
<tr>
<td>$b_4$</td>
<td>1.7413</td>
<td>-1.1142</td>
<td>-0.3511</td>
<td>-0.3242</td>
<td>0.0491</td>
</tr>
<tr>
<td>$b_5$</td>
<td>0.1365</td>
<td>0.0942</td>
<td>0.0569</td>
<td>0.1987</td>
<td>0.1233</td>
</tr>
<tr>
<td>$p$</td>
<td>0.2</td>
<td>0.3</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

2.3.4. Roughness object

The Roughness object of ForestGALES was also used in ForestGALES_BC with no changes. This object is used to condition the vertical wind profile which affects applied wind loads. Its primary purpose is to calculate the zero-plane displacement ($d_0$), which is the height at which the wind profile changes from a logarithmic to an exponential form, and surface roughness ($Z_0$), which requires tree and stand (dendrometric) inputs calculated in the Tree Characteristics object. Changes to the dendrometric equations impose changes to zero-plane displacement and surface roughness that use these variables as inputs. The equations in the Roughness object require two primary inputs: mean stand height ($h_{stand}$) and spacing ($S_{distance}$). Other inputs calculated in the Tree Characteristics object include maximum crown width ($Canopy_{bdth}$) and crown depth ($Canopy_{depth}$). Prior to the calculation of zero-plane displacement, two auxiliary input parameters, canopy breadth ($Canopy_{breadth}$) and lambda ($\lambda$),
are calculated in the Roughness object. As mentioned, canopy breadth accounts for the porosity (default value is 0.788) and the triangular shape of the tree crown, while lambda is a dimensionless coefficient:

\[
Canopy_{breadth} = \frac{Canopy_{breadth} * 0.788}{2}
\]  

(2.8)  

\[
\lambda = 2 \times \left( \frac{Canopy_{breadth} \times Canopy_{depth}}{S^2_{distance}} \right)
\]  

(2.9)  

Subsequently, zero-plane displacement (m), which is the height at which wind profile changes from a logarithmic to an exponential form, is calculated using:

\[
d_0 = \left[ 1 - \left( \frac{1 - e^{-\sqrt{7.5 \times \lambda}}}{\sqrt{7.5 \times \lambda}} \right) \right] \times h_{stand}
\]  

(2.10)  

Prior to the calculation of surface roughness, the auxiliary variable, gamma (\( \gamma \)) which is an empirically derived parameter in the original model, is calculated using:

\[
\gamma = \frac{1}{C_{surface} + \frac{C_{element} \times \lambda}{2}}
\]  

(2.11)  

where \( C_{surface} \) (constant = 0.003) is the surface drag coefficient and \( C_{element} \) (constant = 0.3) is the element drag coefficient (Raupach 1994). However, if lambda is greater than 0.6, gamma is a constant as shown in Equation 2.11.
Finally, surface roughness is calculated using:

$$\gamma = C_{\text{surface}} + C_{\text{element}} \times 0.3$$  \hspace{1cm} (2.12)$$

$$Z_0 = (ht_{\text{stand}} - d_0) \times e^{-\frac{2\gamma}{(\ln 2 - 0.5)}}$$  \hspace{1cm} (2.13)$$

where $k$ is von Karman’s constant (0.4). Zero-plane displacement (Equation 2.10) and surface roughness (Equation 2.13) are then passed as inputs to calculate the vertical wind speed profile in the Wind Profile and Force object.

The choice and derivations of these ForestGALES equations (Eq. 2.8 to Eq. 2.13) are described in Dunham et al. (2000) and Gardiner et al. (2000). In ForestGALES_BC, these equations were organized into a separate object to calculate the roughness and zero-plane displacement thereby facilitating future modelling of differences in these variables between different stand types (e.g. early mature vs. old growth, even-aged vs. uneven-aged) as new experimental data become available. Another reason to separate this as an independent object is to make it easier to test the effects of any potential future changes to these equations prior to their integration into the model.

2.3.5. Wind De-elevate object

ForestGALES calculates critical wind speed and this is problematic when analyzing the results of thousands (or millions) of different individual trees with, potentially, as many different critical wind speeds. An added complication is that these critical wind speeds change as windthrow propagates through a stand. Therefore, it was necessary change
equations in the Wind De-elevate object to model stability of individual trees within a stand and to model damage propagation at specified above-canopy wind speed rather than calculating the critical wind speed for mean tree representing all trees of a stand as in ForestGALES. Wind speeds which recur at predictable intervals, for example the 2, 5, 10, 20 or 40 year return period for a given location can be simulated. Alternatively, the stability of the stand over a graduated range of expected wind speeds can be simulated and the wind speed above which an ‘unacceptable’ level of damage occurs can be identified.

In ForestGALES, the minimum wind speed required for uprooting or breakage (i.e. critical wind speed) is calculated at the canopy top or mean stand height \( h_{\text{stand}} \). Note that resistance to uprooting is based on the regressions from tree winching experiments whereas resistance to breakage is based on breaking strength and stem diameter (i.e. MOR). In ForestGALES_BC, using the surface roughness \( Z_0 \) and zero-plane displacement \( d_0 \) of the stand calculated in the Roughness object, a logarithmic wind profile is used to represent the wind speed at the zero-plane displacement relative to the above canopy wind speed at 10 metres above the stand (Gardiner et al. 2000). Stand height plus 10 metres was assumed to represent wind speeds as measured by meteorological stations and was also the height of wind speeds predicted by landscape-level numerical wind models (Tinis et al. 2006). Therefore, the canopy top wind speed \( U_{\text{canopy}} \) in ForestGALES_BC is calculated using:

\[
U_{\text{canopy}} = \frac{U_{10} \ln \left( \frac{h_{\text{stand}} - d_0}{Z_0} \right)}{\ln \left( \frac{10}{Z_0} \right)}
\]

(2.14)
where \( U_{10} \) is the above canopy wind speed. The zero-plane displacement and surface roughness are dependent on stand height and spacing \( (S_{\text{distance}}) \).

### 2.3.6 Wind Profile and Force objects

The Wind Profile and Force objects calculate the vertical wind speed profile within and above the canopy, normalized to the canopy top wind speed, based on the surface roughness and zero-plane displacement calculated in the Roughness object. The equations in this object are not changed from the original ForestGALES, however, it uses inputs from objects where equations have been changed. The normalized vertical wind speed profile is represented by 100 sectional wind speed factors \( (U_{\text{factor}}) \) which is the adjustment factor used to calculate the sectional horizontal wind speeds at heights relative to the ground and \( S_{\text{factor}} \) is average stand spacing divided by the mean height. Within the canopy, the equation is:

\[
U_{\text{factor}} = e^{-[2.4+\ln(S_{\text{factor}})+1.62]i-100}
\]  

(2.15)

Above the canopy, the equation is:

\[
U_{\text{factor}} = \frac{\ln\left[\left(\frac{i*ht_{\text{tan,d}}}{100}\right) - d_0\right]/Z_0}{\ln\left(ht_{\text{tan,d}} - d_0\right)/Z_0}
\]

(2.16)

where constants were developed by Dunham et al. (2000) for uniform stands. It is very likely that these are not correct for more structurally variable stands of BC, but in the absence of
wind profile data for irregular stands they were retained in ForestGALES_BC. Nominal sectional horizontal wind speeds at heights above the ground are calculated using:

\[ U_i = U_{\text{factor}} \times U_{\text{canopy}} \]  

(2.17)

where \( U_{\text{canopy}} \) is the canopy top wind speed calculated in the Wind De-elevate object (Equation 2.15).

ForestGALES_BC uses the profile method to calculate the applied wind force on individual trees and account for vertical heterogeneity. In the profile method, wind loads on individual trees are calculated based on their position within the vertical wind profile and their individual crown attributes (Figure 2.3).

Figure 2.3. Calculated vertical profile for horizontal wind speed given a sample mean stand height of 26 m and above canopy wind speed of 31 m/s (112 km/h) along with a pictorial representation of how individual trees are placed within the profile for the purpose of drag force calculations.
The shape of the vertical wind speed profile is determined by spacing within the canopy and stand height, roughness and zero-plane displacement above the stand (Equations 2.15 and 2.16). The canopy top wind speed increases with spacing for a given above canopy wind speed (Table 2.6). Spacing also affects the shape of the vertical wind speed profile above and within the canopy (Figure 2.4).

Table 2.6. Canopy-top wind speeds calculated for a 100 km/h above canopy wind speed for spacing distances represented in Figure 2.4.

<table>
<thead>
<tr>
<th>Average spacing distance (m)</th>
<th>Canopy-top wind speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.4 a</td>
<td>3</td>
</tr>
<tr>
<td>Figure 2.4 b</td>
<td>12</td>
</tr>
<tr>
<td>Figure 2.4 c</td>
<td>24</td>
</tr>
<tr>
<td>Figure 2.4 d</td>
<td>36</td>
</tr>
</tbody>
</table>

Figure 2.4. Graphical representation of vertical wind profile with decreasing stand density given a horizontal wind speed of 100 km/h at 10 m above the canopy.
A streamlining coefficient ($S_{t_i}$) is calculated (Equation 2.17) for each vertical crown section which reduces the crown area depending on wind speed and the ability of the tree to orient foliage in the wind direction to reduce the crown frontal area.

$$S_{t_i} = c * U_i^{-n} \quad (2.17)$$

The streamlining coefficient is calculated using this nonlinear fit to the measured crown frontal areas over a range of wind speeds from wind tunnel experiments. The parameters ($c$ and $n$) are species-specific and control the rate of crown frontal area reduction with wind speed (Mayhead 1973, Rudnicki et al. 2004, Byrne 2005).

Sectional drag forces ($F_{drag_i}$) are calculated substituting the streamlining coefficient for the drag coefficient in the classical drag formula as follows:

$$F_{drag_i} = \frac{1}{2} * \rho * S_{t_i} * U_i^2 * A_i \quad (2.18)$$

The sectional still-air frontal area ($A_i$) is the product of the branch length ($l_{branch_i}$) and section length ($l_{section_i}$), which are calculated in the Tree Characteristics object. The sectional drag forces are then multiplied by the height of each section ($ht_{section_i}$) to calculate sectional moments ($M_{wind_i}$) which are summed to calculate the total applied moment due to the force of the wind as follows:
A fundamental assumption in ForestGALES is that trees act like cantilever beams, fixed at the base, when subject to a transverse point load. The centre of pressure on the tree is assumed to be at 80% of its height in the original ForestGALES model; therefore, the point load on each tree is calculated as:

\[ M_{\text{wind}} = \sum (F_{\text{drag}} \cdot ht_{\text{section}}) \]  \hspace{1cm} (2.19)

This simplification is consistent with the assumption that trees behave like cantilever beams with a single point load. This single output from the Wind Profile and Force objects also avoids unnecessary model complexity in the Bending Moment object.

2.3.7. Bending Moment object

The bending and self-loading equations in ForestGALES_BC have been separated as an object to enable unit testing. The Bending Moment object imports the drag force from the Wind Profile and Force objects and applies it as a horizontal point load \( F_{\text{drag}} \) on the tree.

No changes were made to the equation that bends the tree under this load, which was based on mechanical tests of 10 Sitka spruce trees in southern Scotland (Gardiner 1989). The wind load is applied at a height of 0.8 times the tree height and this load is iterated in the model to account for the changes in the self-loading components of each section due to displacement.

Although no changes were made in the bending equation, the crown and stem form equations (Tree Characteristics and Stem Taper objects) were changed resulting in changes in sectional...
drag and deflection which, in turn, affect the self-loading component of the applied moment on the tree.

2.3.8. Gap (VR Adjust) object

The Gap (VR Adjust) object is used to adjust individual tree stability calculations based on the effects of upwind openings in the canopy. The Gap object has been modified in ForestGALES_BC to account for the effects of retaining individual trees (dispersed retention) or groups of trees (aggregate retention) or combinations of dispersed and group retention (variable retention) during harvesting. Rather than using the empirical equations in ForestGALES that are derived from field studies, wind tunnel observations, or numerical simulations of wind behaviour in gaps or partially thinned stands, I have used a geometric index of tree exposure, VRFetch. The reasons for this are that field and wind tunnel data is not available for complex stands, and numerical simulations (such as large eddy simulations) require a large amount of computation which would require days to run for even simple gap and retention scenarios. VRFetch is a measure of tree exposure which depends on the size of forest openings and the amount of retention within the openings in four cardinal and four intercardinal directions (Scott 2005, Scott and Mitchell 2005). To calculate this index a harvest area is stratified according to removal levels (i.e., basal area retained) (Figure 2.5). Then, from any point in the harvest area, a line is drawn for 300 m in the eight directions and the line is divided into 30 metre segments (Figure 2.5).
VRFetch is the sum of the products of distance and removal level (i.e., 100 - percent retained) for each 30 metre section of the 300 m distance in each of the eight directions. For all eight directions, VRFetch can take a maximum value of 2400 m for a fully exposed tree.

A sample calculation of VRFetch is given in Table 2.7, where it is assumed that the removal levels are similar beyond the edge of the area shown in Figure 2.5 and VRFetch is calculated for all wind directions. In the application of the model, the input wind speed and direction are inputs; therefore, only one wind speed is used and VRFetch is calculated for a maximum distance of 300 m.

Table 2.7. Sample calculation of VRFetch based on Figure 2.5.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Calculation</th>
<th>VR Fetch (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1 * (100% * 30) + 9 * (0% * 30)</td>
<td>30</td>
</tr>
<tr>
<td>NE</td>
<td>1 * (50% * 30) + 1 * (100% * 30) + 8 * (0% * 30)</td>
<td>45</td>
</tr>
<tr>
<td>E</td>
<td>1 * (100% * 30) + 1 * (0% * 30) + 8 * (100% * 30)</td>
<td>270</td>
</tr>
<tr>
<td>SE</td>
<td>5 * (0% * 30) + 5 * (100% * 30)</td>
<td>150</td>
</tr>
<tr>
<td>S</td>
<td>2 * (100% * 30) + 8 * (0% * 30)</td>
<td>60</td>
</tr>
<tr>
<td>SW</td>
<td>2 * (100% * 30) + 50% * 30 + 7 * (0% * 30)</td>
<td>75</td>
</tr>
<tr>
<td>W</td>
<td>2 * (0% * 30) + 100% * 30 + 3 * (0% * 30) + 4 * (100% * 30)</td>
<td>150</td>
</tr>
<tr>
<td>NW</td>
<td>10 * (0% * 30)</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL VR Fetch (Σ subtotals)</strong></td>
<td><strong>780</strong></td>
<td></td>
</tr>
</tbody>
</table>
Accurate nonlinear relationships were found between VRFetch and the proportion of windthrow within plots, in both old-growth and second growth stands (Scott 2005, Scott and Mitchell 2005). Based on these models, the absolute amount of damage varies according to stand conditions and above canopy wind speeds. I fitted a nonlinear equation to the proportion of damage at STEMS 1 (Silviculture Treatments for Ecosystem Management in the Sayward, 1st Installation) for a range of VRFetch values (Figure 2.6). Accordingly, an adjustment factor was calculated in the VRFetch object of ForestGALES_BC and used to reduce the maximum resistive turning/breaking moment using the relationship between VRFetch and the proportion of stand damage represented by plot data (Equation 2.22).

While the downward adjustment of the resistive moment is counter-intuitive, it has the same result and is consistent with the way Gust Factor was used in ForestGALES. Despite its simplifying assumptions, ForestGALES is a complex model and many adjustments are made for programming efficiency. This approach was retained in ForestGALES_BC as a legacy of the original model and to avoid the potential for confounding outputs from objects which remain relatively unchanged, particularly the Bending Moment object.
Figure 2.6. Equation fit to relationship between summary of plot data and the proportion of windthrow at STEMS 1.

\[ \hat{y} = 0.0088^{0.0196x} \]

This empirical adjustment factor \( VR_{adjust} \), which is passed to the Maximum Moment object, allows ForestGALES_BC to account for the effects of horizontal heterogeneity in the upwind stand conditions. This adjustment factor is assumed to maximize at 1.5 times the applied moment where uni-directional VRFetch is 210.

2.3.9. Maximum Moment object

The primary purpose of the Maximum Moment object is to calculate the critical (maximum resistive) uprooting and breaking moments. ForestGALES_BC uses separate calculations for breakage and uprooting and applies whichever mode of failure has less resistance. The critical uprooting moment is calculated using Equation 2.3. Table 2.8 shows the coefficients of Equation 2.3 used in ForestGALES_BC, which were calculated from Canadian tree
winching data (Byrne 2005), with stem mass as the predictor for western redcedar, western hemlock, lodgepole pine, and interior spruce (Byrne 2005) and DBH as the predictor for Douglas-fir (Mitchell 1999).

Table 2.8. Coefficients and summary statistics for linear equations used to calculate critical resistive uprooting moment for western redcedar (Cw), western hemlock (Hw), lodgepole pine (Pl), interior hybrid spruce (Sx) and Douglas-fir (Fd) in ForestGALES_BC (Extracted from Byrne 2005 and Mitchell 1999 with permission).

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Sp.</th>
<th>b₀</th>
<th>b₁</th>
<th>SE₀₀</th>
<th>SE₀₁</th>
<th>RMSE</th>
<th>R²</th>
<th>n</th>
<th>DBH range (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹mstem</td>
<td>Cw</td>
<td>4415.3</td>
<td>94.5a</td>
<td>8120.27</td>
<td>9.06</td>
<td>20721</td>
<td>0.83</td>
<td>23</td>
<td>15-57</td>
</tr>
<tr>
<td></td>
<td>Hw</td>
<td>-1125.0</td>
<td>77.4a</td>
<td>7273.16</td>
<td>5.52</td>
<td>18738</td>
<td>0.91</td>
<td>20</td>
<td>15-52</td>
</tr>
<tr>
<td></td>
<td>Pl</td>
<td>-27333.0‡</td>
<td>145.6b</td>
<td>10470.00</td>
<td>11.44</td>
<td>16023</td>
<td>0.93</td>
<td>13</td>
<td>19-39</td>
</tr>
<tr>
<td></td>
<td>Sx</td>
<td>-5362.2</td>
<td>118.6c</td>
<td>4932.59</td>
<td>9.55</td>
<td>9378</td>
<td>0.91</td>
<td>17</td>
<td>16-40</td>
</tr>
<tr>
<td></td>
<td>Fd</td>
<td>350.87</td>
<td>13.04</td>
<td>60.50</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹Based on tree winching data from Byrne (2005).
²Based on tree winching data from Mitchell (1999).

SE and RMSE are the standard errors and root mean square errors, respectively, $R^2$ is the coefficient of determination, $n$ is the number of trees winched in the sample and $m_{stem}$ is stem mass.

The critical breaking moment is calculated based on published green wood MOR values for North American species and on the assumption that the tree breaks at the base (Equation 2.23; Table 2.9). The model could be programmed to break the tree at its weakest point which may occur anywhere along the stem but given the assumptions embedded in the tree form, the lack of data related to strength reduction due to decay and the computational time required by this added level of complexity the current assumption that the tree breaks at the base was retained in ForestGALES_BC.

$$M_{break(critical)} = \frac{MOR \ast \pi \ast Diam_{0}^{3}}{32} \quad (\text{Gardiner et al. 2000}) \quad (2.22)$$
Table 2.9. Published green wood MOR values for North American species used in ForestGALES_BC (Alden 1997).

<table>
<thead>
<tr>
<th>Species</th>
<th>MOR (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>western redcedar</td>
<td>3.66 × 10⁶</td>
</tr>
<tr>
<td>western hemlock</td>
<td>4.80 × 10⁷</td>
</tr>
<tr>
<td>lodgepole pine</td>
<td>3.89 × 10⁷</td>
</tr>
<tr>
<td>hybrid spruce</td>
<td>3.51 × 10⁷</td>
</tr>
<tr>
<td>Douglas-fir</td>
<td>5.30 × 10⁷</td>
</tr>
</tbody>
</table>

The adjustment factor calculated in the VRFetch object is used to modify the resistance of the tree to uprooting or breakage. The height of breakage can be modified manually in the Maximum Moment object to calculate breakage at any desired height. A knot factor is included in the Maximum Moment object, but currently the value for this factor is 1 for all species and it is in place as a nominal placeholder to highlight the need to perform bending tests on local species and integrate the effects of additional factors such as site quality in the future.

2.3.10. Gust Factor object

At its most basic level, the gust factor is the ratio between the load induced by the peak wind and that induced by the mean wind speed during a given time interval. Field and wind tunnel experiments have been conducted to measure the relationship between peak and mean wind speeds and their corresponding effects on tree loads in specific stand conditions (Gardiner et al. 1997).

The gust factor in ForestGALES_BC has been recalculated based on data from field and wind tunnel experiments conducted by the UK Forestry Commission (Gardiner et al. 1997). Data from these studies were plotted and polynomial equations were fitted to describe the
normalized mean and maximum moments for trees within stands, at different distances from the stand edge (Figure 2.7). The resulting models (Equations 2.23 and 2.24) are used to calculate the normalized mean and maximum moments within two tree lengths from the edge. These moments are constant beyond two tree lengths from the edge of an opening.

\[ M_{\text{normalized(mean)}} = 0.0048 \cdot l_{ht}^4 - 0.0654 \cdot l_{ht}^3 + 0.312 \cdot l_{ht}^2 - 0.6127 \cdot l_{ht} + 0.4934 \] (2.23)

\[ M_{\text{normalized(max)}} = 0.0091 \cdot l_{ht}^4 - 0.133 \cdot l_{ht}^3 + 0.6683 \cdot l_{ht}^2 - 1.3286 \cdot l_{ht} + 1.0581 \] (2.24)

The gust factor \((G_{\text{factor}})\) is then a ratio between the normalized mean and maximum bending moments as shown in Equation 2.26.

\[ G_{\text{factor}} = \frac{M_{\text{normalized(max)}}}{M_{\text{normalized(mean)}}} \] (2.25)
The uprooting moment ($M_{uproot(critical)}$) and breaking moment ($M_{break(critical)}$) are imported from
the Maximum Moment object and are adjusted using the gust factor as a divisor to calculate
the final critical resistive moment. While using the gust factor to adjust resistance and not
load is counter-intuitive; it makes no difference mathematically and, as mentioned, is a
legacy of how these equations work in the original ForestGALES. In ForestGALES_BC
when the applied moment due to the sum of wind forces on the crown and the self loading
forces due to the displaced stem exceed the final critical resistive moment, the tree is flagged
for failure. This is a different approach than in ForestGALES, where the entire stand is
deemed to have failed if the critical resistive moment for the mean (representative) tree is
exceeded.

2.4. Results Part 2 - Sensitivity analyses, comparison of ForestGALES and ForestGALES_BC outputs

Model outputs were analysed in two primary ways. First, simulations from
ForestGALES_BC were compared to output from the original ForestGALES using both the
roughness and profile methods (Figures 2.8 – 2.10). Note that ForestGALES_BC only uses
the profile method. The bases of model comparisons were the sensitivity of critical wind
speed (i.e. the minimum wind speed that causes failure) to diameter, height-to-diameter ratio
and spacing for a range of distances from the edge. The sensitivity of critical wind speed to
VRFetch for a range of distances from the edge was assessed in ForestGALES_BC only,
since ForestGALES cannot account for variable retention in upwind gaps (Figures 2.11 and
2.12). Changes in the proportional decrease in critical wind speed with increasing VRFetch
were also assessed (Figure 2.13). Critical wind speeds decreased with height-to-diameter
ratio and increased with DBH for both ForestGALES and ForestGALES_BC. However,
critical wind speed increased with distance from the edge in ForestGALES_BC and
decreased with distance from the edge in ForestGALES. Critical wind speed also decreased
with spacing in both models and, again, increased with distance from edge in
ForestGALES_BC and decreased with distance from edge in ForestGALES. Critical wind
speed marginally decreased with VRFetch in ForestGALES_BC and this pattern held
regardless of distance from the edge. Finally, the proportional decrease in critical wind speed
was the same for similar VRFetch values regardless of distance from the edge.
Figure 2.8. Comparison of model outputs using height to DBH ratio (%) vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) with VR Fetch held constant at 120 in ForestGALES_BC and gap size held constant at 120 in original ForestGALES. Interior spruce (◊), lodgepole pine (□), western redcedar (∆), western hemlock (+) and Douglas-fir (×).
Figure 2.9. Comparison of model outputs using DBH vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) with VR Fetch held constant at 120 in ForestGALES BC and gap size held constant at 120 in original ForestGALES. Interior spruce (◊), lodgepolepine (□), western redcedar (△), western hemlock (+) and Douglas-fir (×).
Figure 2.10. Comparison of model outputs using spacing distance vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) for 5 randomly chosen trees with VR Fetch held constant at 120 in ForestGALES_BC and gap size held constant at 120 in original ForestGALES. Interior spruce (◊), lodgepole pine (□), western redcedar (∆), western hemlock (+) and Douglas-fir (×).
Figure 2.11. Height to DBH ratio (%) vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) and VR Fetch (ie. 150, 180 and 210). Interior spruce (◊), lodgepole pine (□), western redcedar (Δ), western hemlock (+) and Douglas-fir (×).

Figure 2.11. Height to DBH ratio (%) vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) and VR Fetch (ie. 150, 180 and 210). Interior spruce (◊), lodgepole pine (□), western redcedar (Δ), western hemlock (+) and Douglas-fir (×).
Figure 2.12. DBH vs. critical wind speed by distance from edge (ie. 0, 30 and 60 m) and VR Fetch (ie. 150, 180 and 210). Interior spruce (◊), lodgepole pine (□), western redcedar (∆), western hemlock (+) and Douglas-fir (×).
Figure 2.13. Change in critical wind speed with distance from edge (ie. 0, 30 and 60 m) as a proportion of the critical wind speed when VR Fetch is 120. Error bars are for 1 standard deviation and shown where noticeable. Interior spruce (○), lodgepole pine (□), western redcedar (△), western hemlock (+) and Douglas-fir (×).
2.5 Discussion

ForestGALES_BC was modified to reflect the variability of stem and crown form among different species and to enable the quantification of the effects of variable retention which allows for more realistic damage predictions as described in the Results. Following these changes, comparisons between ForestGALES and ForestGALES_BC outputs were made to assess the overall effect of the many changes made to model components. Windthrow simulations from both models were evaluated for different stem sizes, reflected by DBH, and stem form (i.e. height to diameter ratio) for a range of gap sizes and distances from the edge. Outputs were examined for a range of tree sizes because, from the literature, generally, large trees have more stem mass and a higher resistive turning moment (Moore 2000, Bergeron 2004, Cucchi et al. 2004, Achim et al. 2005, Elie and Ruel 2005, Byrne and Mitchell 2007). Therefore, it is reasonable to expect critical wind speed to increase with DBH. Conversely, slender trees are less resistant to windthrow than well-tapered trees (Mitchell 1999) meaning that critical wind speed should decrease with increasing height to diameter ratio.

Empirical windthrow studies show that damage increases with the size of upwind gaps (fetch) (Scott and Mitchell 2005, Rollerson et al. 2009) and decreases with distance from newly formed stand edges. For example, Lanquaye-Opoku and Mitchell (2005) used aerial photographs and GIS software to map stand edges and found that most damage along recently exposed edges occurred within the first 50 metres from the edge. Keeping in mind that a lower critical wind speed indicates greater damage susceptibility, a realistic model would have decreasing critical wind speeds with increasing fetch values and increasing critical wind speeds with distance from stand edges. Finally, routine storm winds which are
known to cause damage to freshly exposed clearcut edges, range roughly between 50 and 100 km/h on the BC coast (Cullen 2002). Therefore, critical wind speeds should be near these values for clearcut edge trees.

Some general trends appear when comparing ForestGALES_BC with ForestGALES. In particular, ForestGALES_BC output shows that critical wind speed increases whereas ForestGALES output shows it decreases with distance from the edge (Figures 2.8 and 2.9). Lanquaye-Opoku and Mitchell (2005) found that most wind damage occurred within the first 25 metres of newly formed edges with a smaller proportion occurring in the second 25 metre edge segment (e.g. Lanquaye-Opoku and Mitchell 2005) and little damage beyond 50 m. The ForestGALES_BC output is more consistent with these results than the ForestGALES output.

Critical wind speed is more varied with tree size at the edge in ForestGALES and this variability decreases with distance from the edge. In contrast, ForestGALES_BC output shows less variability in critical wind speeds with tree size at the edge and more variability with distance from the edge. This could be because ForestGALES_BC does a better job of representing the difference in wind loading according to tree size and relative canopy position. Less variability in critical wind speed with respect to tree size and height to diameter ratio at the edge also seems reasonable because the sheltering effects of the canopy are less pronounced. Another source of this variability in the critical wind speed is that in ForestGALES_BC, crown length is a user input supplied to the model and can be unique to each tree. Also, species-specific equations are used to calculate the vertical crown profile from the crown length.
ForestGALES output also shows a strong relationship of wind damage to height-to-diameter ratio, but it is more variable at the edge, particularly in the case of lodgepole pine using the roughness method (Figure 2.9). Critical wind speed decreases with height to diameter ratio in both ForestGALES and ForestGALES_BC which is consistent with expectations. Burton (1997) and Scott (2005) both found increasing windthrow with increasing slenderness in their studies of windthrow outcomes in BC forests. However, critical wind speed predictions in ForestGALES range between approximately 25 and 250 km/h for edge trees and between 25 and 150 km/h for trees within the stand which is counter intuitive since one would expect higher critical wind speeds away from the edge. The range of critical wind speeds (i.e. 25 to 150 km/hr) calculated by ForestGALES_BC, especially at the edge, is more consistent with common storm wind speeds that damage trees in BC (Stathers et al. 1994). It seems unlikely that edge trees, even in a windy climate like the UK, could withstand wind speeds up to 250 km/h.

The critical wind speeds calculated by ForestGALES_BC and ForestGALES were also compared with respect to stem spacing distance (Figure 2.10). Generally, critical wind speed decreases with increased spacing in both ForestGALES and ForestGALES_BC. This may seem intuitively correct, and would be correct if stands had recently been spaced to different densities. However, the sensitivity of critical wind speed to inter-tree spacing is higher in ForestGALES_BC, particularly for western redcedar and lodgepole pine. The data used to construct the vertical wind profile equations in ForestGALES came from a stand with 1.7 metre spacing and do not account for differences in acclimative growth in trees grown at different initial spacings (Nicoll et al. 2008). Studies have shown that trees on stand edges are more windfirm. Further tree winching studies of trees grown at wider initial spacing or in
more exposed locations would help quantify increased resistance due to acclimation. Differences in acclimative growth can also occur between dominant trees and trees within the canopy which are more sheltered by their neighbours. While wind tunnel studies show no difference in the vertical wind speed profiles in uniform and multi-storied stands, measurements of the resistance of dominant trees with low height to diameter ratios in the latter would improve the representation of multi-storied stands in ForestGALES_BC. Mason (2002) reviewed the literature on stability in regular and irregular stands and suggested that increased acclimation in dominants in irregular stands was an important factor.

One of the major improvements in ForestGALES_BC is that it is now sensitive to variable upwind stand conditions including gaps which include aggregate or dispersed retention. VRFetch is used to quantify the effects of residual basal area within openings on the downwind trees. As expected, critical wind speed decreases with increases in VRFetch. This reduction is independent of the distance of the tree from the stand edge. ForestGALES_BC calculates an adjustment to the normalized applied moment which maximizes at a factor of 1.5 when VRFetch is 210. This results in a proportional decrease in critical wind speed of approximately 0.3. Comparisons of normalized moments calculated by empirical VRFetch functions to normalized moments using large eddy simulations given the same VRFetch values (Clark and Mitchell 2007) suggest the empirical equation used in ForestGALES_BC may underestimate the effect of upwind retention levels on crown loading by as much as 50%.

Clark and Mitchell (2007) systematically examined the effects of retention aggregate size and spacing on maximum bending moments using large eddy simulation for a series of simple
gap and aggregate retention scenarios. Mitchell and Byrne (2009) calculated VRFetch values for the Clark and Mitchell scenarios and found that maximum moments with respect to VRFetch were greater than those calculated by the empirical equation that is currently used in ForestGALES_BC. The empirical VRFetch data were taken from actual stands with complex layout scenarios and, similar to the way stem mass predicts critical resistive turning moment, it aggregates many factors related to tree loading which cannot be fully accounted for in a large eddy simulation at this time.

Studies of windthrow outcomes in harvested cutblocks with retention have found that the severity and proportion of windthrow is highest in small aggregates (Burton 2001). New data and technological advances (i.e. computing power) will serve to greatly enhance the accuracy of windthrow predictions. However, improvements cannot be limited to more data and improved functions within this model. More accurate spatial models which can quantify the effects of a wider range of stand and gap conditions need to be developed to represent this variability. Therefore, Chapter 3 covers the integration of this improved model with a spatial component to simulate a wider variety of stand conditions.

Any future changes should be accompanied by ongoing validation of results and sensitivity analyses of function parameters. Chapter 4 marks the beginning of this process where the effectiveness of the integrated model in characterizing damage patterns in complex retention patterns is examined. Model simulations in ForestGALES_BC and field measurements in Gardiner et al. (1997) also suggest that some species may be more sensitive to spacing than others. Future studies that examine the sensitivity of applied moments with respect to site, species and spacing would aid model improvements.
The advantage of moving equations into separate objects is that, in the future, it will be easier to create and test new equations. An example could be equations that characterize differences in the shape of the vertical wind profile due to differences in stand types. In the absence of wind profile data for irregular stands, the equations used for regular stands were retained in ForestGALES_BC. Differences in the vertical wind speed profile affect the centre of pressure which is important in the windthrow process. For example, a less dense stand would cause the centre of pressure to drop. However, the empirical equation used to calculate VRFetch partially captures this process. Also, research which accounts for the effects of the dynamics of tree movement in the wind (James et al. 2006, Moore and Maguire 2008) and the effects of tree interactions (Schelhaas et al. 2007) on windthrow outcomes could also be incorporated into this object or possibly the Bending Moment object to test these factors independent from the model. The error equations of the resistance equations could also be used to introduce some randomness to the equations in the future and help reduce the deterministic nature of the model. This will better reflect the stochastic nature of windthrow.

In future, the Bending Moment object could use the taper data to calculate sectional breaking moments and automatically identify the height of failure for broken stems. The desired height of assessment would depend on the location of factors such as decay, disease and defects which affect breaking strength. Wood decay equations (Bahuguna 2008) could be added to the Tree Characteristics object and be used in ForestGALES_BC to adjust the resistance of live (or dead) trees with decay to windthrow. Other potential additions to the model include incorporating the effects of crown pruning treatments, or site and root modifications (e.g. effects of road excavations on edge trees) or root interlocking. These
input factors could be identified at the individual tree level using additional fields in the tree list. The equations could be easily unit tested within the structure of ForestGALES_BC.

2.6 Conclusions

The structure of ForestGALES_BC has been designed with a set of discrete objects so that it will be easy to refine existing equations and incorporate new equations. Dividing model equations into several objects facilitates unit testing and sensitivity analyses of model components before they are re-integrated. This addresses the first objective of this chapter which was to restructure the model to enable the integration and independent testing of new equations and to identify of knowledge gaps in the model. Changes to the gap equations have improved the realism of critical wind speed predictions compared to ForestGALES. Variability in dendrometrics between species is better represented and these changes have made ForestGALES_BC more flexible to deal with tree and stand variability in natural or managed forests. This addresses the second objective in this chapter which was to improve windthrow predictions with respect to tree size (dendrometric), exposure and gust factor variables. The third objective, to enable windthrow results for multiple individual trees to be represented spatially, was partially met by changing the output from the calculation of critical wind speed to flagging a tree for failure at a given input wind speed. This was a necessary step to set the stage for integration with the spatial model WindFIRM which will be covered in the next chapter.
3.0. Windthrow Prediction Accounting for Multiple Wind Directions, Diverse Harvesting Scenarios, and Windthrow Propagation

3.1. Introduction

3.1.1. Decision support systems and windthrow prediction

Windthrow is the process behind damage to trees from wind events resulting in breakage or uprooting. This process varies with weather, stand, tree, soil, site quality and topographic factors and their interactions. Wind damage can be in a form of stem failure and uprooting (Mergen 1954, Somerville 1979, Stathers et al. 1994, Moore 2000). Tree failure within a stand may also trigger subsequent failure of neighbouring trees, either through direct contact as a tree falls or due to the resulting changes in wind patterns which increase the wind load on neighbouring trees (windthrow propagation).

There are three general approaches to windthrow prediction: 1) qualitative (diagnostic) assessments, 2) empirical (statistical) modelling, and 3) mechanistic modelling. Windthrow management in British Columbia (BC), Canada has typically been based on risk assessment using qualitative approaches to identify the factors that predispose a stand to windthrow and to estimate the likelihood and severity of damage. An example is the windthrow hazard classification system developed by Mitchell (1998) that forms the basis for the BCMOF 712 Windthrow Assessment field cards.

Empirical windthrow models use field data to predict windthrow likelihood as a function of landscape, site, stand, and/or tree attributes (Valinger and Fridman 1997, Mitchell et al. 2001,
Lanquaye-Opoku and Mitchell 2005, Scott and Mitchell 2005). These models predict tree-level or stand-level outcomes. Geographic Information Systems (GIS) have been used in the development of some of these models – specifically, for the calculation of topographic and edge exposure indices, data assembly and for the display of model results.

Mechanistic windthrow models can be used to calculate the critical wind speed required to uproot or break individual trees and the probability of these occurrences (Gardiner et al. 2000). Mechanistic models are a hybrid between mechanical and empirical models (in a general sense) meaning that empirical relationships are used to estimate some processes. For example, easily-measurable tree attributes such as diameter and height can be used to estimate stem mass, which, in turn, is used to estimate the maximum resistance of trees to applied loads (Nicoll et al. 2005). Similarly, crown drag for a given wind speed can be estimated from crown frontal area or crown mass based on the results of wind tunnel experiments (Rudnicki et al. 2004). These dendrometric and biomechanical relationships vary among species but can be quite accurate for a given species (Byrne 2005, Byrne and Mitchell 2007). In the mechanistic model ForestGALES, the empirically-derived loading and resistance components are integrated using simple beam theory to calculate critical above canopy wind speed at which the tree would uproot or break (Gardiner et al. 2000, Ruel 2000).

Mechanistic models have been used to predict windthrow in uniform forests in Great Britain (ForestGALES), Finland (HWIND), Sweden (WINDA), France (FOREOLE) and in balsam fir (Abies balsamea (L.) Mill.) stands in Quebec, Canada (Gardiner et al. 2000, Ancelin et al. 2004, Blennow and Sallnas 2004, Achim et al. 2005). However, each of these models calculates windthrow based on stand-level values, assuming uniformity of trees within
stands. As a result, they are not accurate for quantifying the complexities of variable edge shapes, partial retention of trees during harvesting, or structural complexity as a result of species and size mixtures in a stand (Gardiner et al. 2008). Also, none of these models have the capacity to model damage propagation through stands as trees progressively fail during a storm event.

Increased use of partial harvesting and movement toward complex stands and continuous cover (Pommerening and Murphy 2004) create the need for more sophisticated windthrow prediction models that can be coupled with growth and yield models to create decision support systems (DSS) for silviculture and forest planning. For example, variable retention (VR) is an adaptive management strategy intended to promote conservation of ecosystem function and biological diversity. This approach retains structural legacies - trees of varying sizes, snags, down woody debris, etc. - from the original stand after harvest to maintain some of the original forest attributes as the next generation of trees develop (Beese 2001, Mitchell and Beese 2002). Consequently, residual trees are exposed to different wind speeds and directions than within the original stand depending on geographic location, edge orientation and gap size.

Early silvicultural experiments with dispersed retention, where individual trees are retained within the cutblock opening for structural and regeneration purposes, experienced 20% (D'Anjou 2002, Scott 2005) to 50% (de Montigny 2004) loss of the retained trees. Reported windthrow losses in aggregated group retention, where groups of trees are retained within openings, are lower but still range from 10% to 25% of the residual trees (Scott and Beasley 2001, de Montigny 2004, Scott and Mitchell 2005). Loss of retained trees to windthrow will
affect the growth and yield projections for overstory trees and will impact regeneration and growth of the understory.

The integration and use of growth and yield models have been used to simulate future stand conditions for the projection of windthrow due to silvicultural treatments (Cucchi et al. 2005). For example, HWIND has been integrated with a growth and yield model (SIMA) to assess long term effects of forest management at the landscape scale, particularly under a clearcutting regime (Zeng et al. 2007). However, these projections are at the stand level and do not account for wind direction or retention within openings. This means that while there are many models which are able to predict the amount of wind damage and calculate its effects on long term stand yields, none can predict where in the stand this damage occurs in relation to wind directions nor can they calculate wind damage for residual trees or groups of trees within an opening and the effects of this retention on the wind loading of downwind trees.

Growth and yield models, such as the single-tree distance dependent growth model, Tree and Stand Simulator (TASS; Mitchell 1975) and the stand-level derivative of TASS called TIPSY can be used to forecast growth in these variable retention stands by mapping the spatial distributions of residual trees. By coupling windthrow models with models such as TASS in a DSS, predictions of windthrow can be made at a higher spatial resolution (e.g. tree level) based on more accurate spatial maps of stand openings, thereby better reflecting actual wind damage patterns. An improved DSS for prediction of windthrow and windthrow impacts on future stand conditions should have the following characteristics. It should be able to account for the variability in tree attributes, stand structure, and harvest patterns, and be
easily configured for local stand, terrain and weather conditions. Simulated damage should reflect the propagation of damage into freshly exposed stand edges, the dependence of damage on fetch, and the irregular spatial patterns of windthrow that sometimes result. Model outcomes should be consistent with observed tree-level windthrow in terms of the amount and characteristics (e.g., height-to-diameter ratios, dominance) of windthrown trees. When integrated with tree-level growth and yield models, this DSS could be used to assess silviculture and forest-level plans and be used to forecast short- and long-term stand conditions and timber yields.

In this chapter, I describe the integration of ForestGALES_BC (Version 1.0) with WindFIRM. The purpose of integrating WindFIRM with ForestGALES_BC is to develop a DSS that simulates the effects of spatial heterogeneity imposed by stand management scenarios and uneven-aged stand structures on the stability of individual trees and enables the effects of windthrow on growth and yield predictions to be assessed using TASS. The veracity of a windthrow model used for decision support can be evaluated based on the following criteria:

- The dynamic process of windthrow propagation during a storm event should be quantified and spatially represented.
- Slender trees should be more prone to windthrow than strongly tapered trees.
• Larger more dominant trees should have greater resistance and experience lower damage (i.e. windfirmness) than smaller co-dominant trees which are more protected their neighbours.

• Windthrow damage should increase with increasing fetch values.

• Simulated damage levels should be similar to observed damage when normal storm wind speeds are used as inputs.

• Damage patterns should be sensitive to wind direction in that more damage occurs in wind exposed locations and less damage occurs in wind sheltered locations.

3.1.2. WindFIRM background

WindFIRM (Wind, Forest Instability Research Model) was originally developed by Dr. Steve Mitchell’s windthrow research group in the Department of Forest Sciences, Faculty of Forestry, University of British Columbia (UBC), Vancouver, BC, Canada to run stand-level empirical models and enable the spatial representation of harvest-edge windthrow likelihood (Lanquaye-Opoku and Mitchell 2005, Scott and Mitchell 2005). The original WindFIRM model (hereafter called WindFIRM 1.0) assembles spatial data layers including a cutblock boundary layer. It creates a buffer of a specified depth outside the cutblock boundary and then divides this buffer into segments of a specified length. For each segment, it characterizes within-opening wind exposure due to fetch and boundary orientation and extracts attributes at the segment centroid from spatial layers such as forest cover attributes, above-canopy wind
speed, and topographic exposure. It then passes these data to logistic models (Lanquaye-Opoku 2003) to calculate stand-level windthrow likelihood for each segment and displays the result as a colour coded edge segment map. However, WindFIRM 1.0 does not allow spatial modelling of windthrow and, therefore, windthrow of complex spatial patterns and partial harvest as in VR harvests.

### 3.1.3. TASS background

The Tree and Stand Simulator (TASS) (Mitchell 1975) is a spatially-explicit individual-tree growth model that provides growth and yield estimates for decision support in the forests of BC. TASS simulates crown competition in a three-dimensional space and assigns a unique x, y coordinate to each tree in the tree list it produces to represent a stand (Table 3.1).

<table>
<thead>
<tr>
<th>ID code</th>
<th>Age (yrs.)</th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Species</th>
<th>Height (m)</th>
<th>DBH (cm)</th>
<th>Crown Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>60</td>
<td>4.42</td>
<td>198.91</td>
<td>Hw</td>
<td>19.68</td>
<td>30.34</td>
<td>15.49</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>7.06</td>
<td>198.51</td>
<td>Hw</td>
<td>26.40</td>
<td>43.34</td>
<td>23.78</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>13.04</td>
<td>198.40</td>
<td>Hw</td>
<td>26.92</td>
<td>42.28</td>
<td>24.29</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>16.15</td>
<td>198.62</td>
<td>Hw</td>
<td>21.63</td>
<td>27.37</td>
<td>13.35</td>
</tr>
<tr>
<td>7</td>
<td>60</td>
<td>18.90</td>
<td>198.24</td>
<td>Hw</td>
<td>32.13</td>
<td>41.84</td>
<td>29.42</td>
</tr>
</tbody>
</table>

1 Spatial x and y coordinates for each tree in the list.
2, 3, 4, 5 Dendrometric attributes for each tree in the list which are required for windthrow calculations in ForestGALES_BC.

Since TASS is a spatially-explicit growth model, it can be used for a wide variety of management purposes including modelling product recovery, carbon stocks, and other uses. For example, TASS has been used to augment LiDAR-generated tree lists to calculate the effects of natural disturbances on carbon sequestration in the United Kingdom (Suarez et al. 2009).
TASS also provides the database for stand-level forecast model, Table Interpolation Program for Stand Yield (TIPSY) (Mitchell et al. 2000). In 2003/04, TIPSY was expanded to include factors that reduce regenerated yields for aggregated and dispersed patterns resulting from VR harvesting systems (Di Lucca 2004, Di Lucca et al. 2004). In 2006, TIPSY was updated again to account for the effects of windthrow at the stand level using empirical windthrow risk models developed for BC by Lanquaye-Opoku and Mitchell (2005). For this augmented TIPSY model, input variables including post-harvest crown cover across an opening, average group or crown size, initial edge length and top height are used as input variables to models that predict the likelihood of windthrow (Di Lucca et al. 2006). Windthrow losses are then used to calculate VR adjustment factors (VRAF). These factors reduce stand yields in response to windthrow and increase the edge lengths to expand the opening size, which is logical around the outside edge of the harvest opening, but problematic with respect to windthrow losses in retention patches within the opening. Also, the windthrow models used in this version of TIPSY are stand-level empirical models that do not differentiate between tree size classes or species.

In TASS, spatial tree lists are forecasted to the next time period. These spatial tree lists enable the spatial representation of individual trees at any time. As a result, the tree lists can be updated at any time to reflect windfirming treatments and windthrow losses. Linkages to improved windthrow models allowed TASS to reflect changes in the stand structure due to windfirming treatments and dynamic processes such as windthrow propagation, including the domino effects of fallen trees (Di Lucca et al. 2009). The use of TASS also enabled the modelling of the often scattered pattern of windthrow. Although individual trees were
modelled using the TASS and ForestGALES_BC model, these trees could be aggregated to
the stand level to provide stand-level yields under different harvest scenarios.

3.1.4. Research objective and chapter structure

The overall objective of the research described in chapter was to create a decision support
tool for windthrow which can:

1. Model spatial differences in windthrow across a landscape which are logical
   considering wind direction, upwind stand characteristics and tree attributes.

2. Demonstrate how simulated windthrow openings can be used to account for natural
disturbance in tree level growth and yield simulations.

3. Quantify dynamic windthrow processes where the stability of residual trees is
   compromised by the failure of their neighbours (windthrow propagation).

To meet these objectives, WindFIRM/ForestGALES_BC 2.1 (research version) and 2.2
(TASS executable version) were developed to create a spatial environment and enable
prediction of windthrow throughout partially harvested or unharvested stands. Further,
WindFIRM and ForestGALES_BC were integrated, and then these were further integrated
with TASS as described in the Methods section. The Results section first provides an
explanation of how windthrow is represented within TASS III. Then, windthrow propagation
simulations are demonstrated and these show the sensitivity of the model outputs to wind
speed/direction and retention level, and the distribution of resulting wind damage across tree
size (e.g. diameter) and slenderness (e.g. height-to-diameter ratio) classes. In the Discussion section, the strengths and weaknesses of the model for simple cutblock scenarios are presented. Conclusions are then given regarding the improved windthrow model, including recommendations for validation and further sensitivity analyses that are presented in Chapter 4.

3.2 Methods

To enable windthrow prediction for individual trees in more complex stands where damaging winds can come from several directions, WindFIRM 1.0 and ForestGALES_BC 1.0 underwent a number of modifications to be integrated into a hybrid model WindFIRM/ForestGALES_BC. First, both ForestGALES_BC 1.0 and WindFIRM 1.0 were re-written in the open-source, object-oriented programming language Python (www.python.org). Two versions of WindFIRM/ForestGALES_BC were subsequently created, a research version (version 2.1) and an executable version which is called by TASS III (version 2.2).

WindFIRM/ForestGALES_BC version 2.1 incorporated ForestGALES_BC 1.0 as well as new data manipulation and visualization tools. ESRI shape files, denoting the proposed harvest areas, can be edited with the open-source map viewer OpenEV (http://openev.sourceforge.net). These were converted to text files for further manipulation and analysis. All data and configuration files used in the model were stored in text format. Most output reporting files and raster maps were also in text format. OpenEV could also be
used for viewing the output raster maps of stand damage and VRFetch\(^1\) (Scott and Mitchell 2005). Binary JPEG files were produced for viewing maps and figures. Detailed instructions on how to run the version 2.1 are given in Appendix 1.

In WindFIRM/ForestGALES_BC version 2.2, post-windthrow lists of surviving trees are passed back to TASS to forecast growth and to display the forecasts. The executable in WindFIRM/ForestGALES_BC version 2.2 instructs the model to first calculate pixel\(^2\) or neighbourhood-level input parameters such as fetch values and inter-tree spacing (averaged for 25 metre by 25 metre pixels) to modify within canopy wind speed. The model then calculates the loading and resistance of individual trees based on species-specific models using stem and crown attributes (dendrometrics).

### 3.2.1. WindFIRM and ForestGALES_BC

The primary function of WindFIRM is to manage an array of tree locations to be passed between growth models such as TASS and mechanistic windthrow models such as ForestGALES_BC. TASS produces spatial tree lists with the x, y-coordinates for each tree and the tree attributes. Z-coordinates are not supplied by TASS and not currently used in the model but a digital elevation model (DEM) could be brought in by WindFIRM. WindFIRM also calculates additional parameters from spatial arrangements of harvest areas and tree-list data supplied by TASS and assembled user inputs such as wind speed and direction.

---

\(^1\) VRFetch is a measure of tree exposure which depends on the size of forest openings and the amount of retention within the openings in eight cardinal directions. It is a function of gap sizes and basal area retention levels within 300 metres upwind of the point of assessment. First, a harvest treatment is stratified according to removal levels and, from any point in the block; lines are projected in eight cardinal directions for 300 metres and divided into 30 metre segments. VRFetch is the sum of the products of distance and removal level for each 30 metre section in all cardinal directions (Scott 2005).

\(^2\) A pixel is a grid cell or raster with visual data.
WindFIRM processes and assembles these data for grid points, corresponding to the centroids of 25m X 25m pixels across the spatial extent of the stand.

ForestGALES needs stand density information to calculate within- and above-canopy wind profiles. In the new windthrow model, rather than using stand-level average density and other attributes as in other windthrow models, this information is averaged for the immediate neighbourhood of each tree in the tree-list at the pixel level. This pixel-level information is also used to calculate fetch (wind exposure). Fetch variables can be calculated for each tree in the tree list, based on upwind stand density and arrangement, but this would be computationally intensive. Accordingly, fetch values of the new model are calculated using basal area retention in upwind pixels, and the resulting fetch value is applied to all trees within the target pixel. For this analysis, above-canopy wind speed and direction are single values input by the user for the whole stand based on local knowledge. However, these values could be replaced with a gridded layer of meteorological data or data from a numerical wind prediction model (Figure 3.1). For example, there are now 5 years of numerical wind model prediction summaries at 1.6 km grid resolution for BC (Modzelewski and Bakhshaii 2006).

In the new model, tree and stand data are gathered in WindFIRM and passed to ForestGALES_BC (Table 3.2). As described more fully in Chapter 2, ForestGALES_BC uses this input information to calculate the critical wind speed for each tree in the tree list and then this is compared to the expected wind speed for a given upwind tree retention pattern. If the critical wind speed is exceeded, the tree is marked as windthrown in the tree list, and removed from the list.
Table 3.2. Summary of input variables for ForestGALES_BC, their sources and the scale at which these variables are passed to ForestGALES_BC (i.e. stand, pixel or tree level)

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Units</th>
<th>Source</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>m/s</td>
<td>User-defined or wind model</td>
<td>Stand</td>
</tr>
<tr>
<td>Wind direction</td>
<td>degrees</td>
<td>User-defined or wind model</td>
<td>Stand</td>
</tr>
<tr>
<td>Species</td>
<td>name symbol (i.e. Cw for western redcedar)</td>
<td>TASS tree list</td>
<td>Tree</td>
</tr>
<tr>
<td>Height</td>
<td>m</td>
<td>TASS tree list</td>
<td>Tree</td>
</tr>
<tr>
<td>DBH</td>
<td>cm</td>
<td>TASS tree list</td>
<td>Tree</td>
</tr>
<tr>
<td>Crown length</td>
<td>m</td>
<td>TASS tree list</td>
<td>Tree</td>
</tr>
<tr>
<td>VRFetch</td>
<td>m</td>
<td>WindFIRM (calculated)</td>
<td>Pixel</td>
</tr>
<tr>
<td>Spacing</td>
<td>m</td>
<td>WindFIRM (calculated)</td>
<td>Pixel</td>
</tr>
<tr>
<td>Stand height</td>
<td>m</td>
<td>WindFIRM (calculated)</td>
<td>Pixel</td>
</tr>
<tr>
<td>Patch dimensions</td>
<td>m²</td>
<td>TASS or GIS layer</td>
<td>Stand</td>
</tr>
<tr>
<td>Opening dimensions</td>
<td>m²</td>
<td>TASS or GIS layer</td>
<td>Stand</td>
</tr>
</tbody>
</table>

The reduced tree list is then returned to WindFIRM from ForestGALES_BC and reflects windthrow of susceptible trees for the specified above-canopy wind speed. WindFIRM then re-calculates pixel-level stand attributes and upwind fetch from the reduced tree lists and passes them back to ForestGALES_BC. This allows the re-calculation of the wind profiles, gust factors and fetch indices given the fact that some upwind trees may have been windthrown in the previous iteration. This iterative loop stops when there are no more stem losses for the above-canopy wind speed specified (Figure 3.1). The iterative loop between WindFIRM and ForestGALES_BC enables calculation and representation of the propagation of windthrow during a wind storm with sustained high winds, a process where failure of one tree changes the wind environment for downwind neighbouring trees and increases the wind load on these trees. The tree list that reflects the final stand condition is then passed back to WindFIRM for graphical representation. Post-windthrow tree lists, stand damage maps and residual fetch values are produced by the windthrow model as outputs for decision support.
3.2.2. WindFIRM/ForestGALES_BC and TASS

In the new windthrow model, the new version of WindFIRM/ForestGALES_BC was then integrated within TASS to enable combined analysis of stand growth, harvesting effects on windfirmness and subsequent modelling of tree growth in partially damaged stands.

WindFIRM/ForestGALES_BC version 2.2 was embedded within TASS III using an executable, which is called when the user activates the ‘Windthrow’ option in TASS. Prior to using the ‘Windthrow’ option in TASS III, the user must define the stand conditions including site index, species composition, stand age and opening and retention dimensions (Table 3.3).

---

3 This previously published figure was part of my contribution to this paper describing the structure and function of WindFIRM/ForestGALES_BC.
Table 3.3. Input variables required to initiate stand conditions for TASS simulations and calculate windthrow.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot length *</td>
<td>m</td>
</tr>
<tr>
<td>Plot width *</td>
<td>m</td>
</tr>
<tr>
<td>Region origin (row, column) **</td>
<td>m</td>
</tr>
<tr>
<td>Region length **</td>
<td>m</td>
</tr>
<tr>
<td>Region width **</td>
<td>m</td>
</tr>
<tr>
<td>Grid units ***</td>
<td>m</td>
</tr>
<tr>
<td>Latitude</td>
<td>Degrees</td>
</tr>
<tr>
<td>Site index</td>
<td>m</td>
</tr>
<tr>
<td>Species</td>
<td>Name (symbol)</td>
</tr>
<tr>
<td>Trees/ha</td>
<td>#</td>
</tr>
<tr>
<td>Seedling Age †</td>
<td>Years</td>
</tr>
<tr>
<td>Height (seedling) †</td>
<td>cm</td>
</tr>
<tr>
<td>Age Distribution ‡</td>
<td>Normal, Poisson, Uniform</td>
</tr>
<tr>
<td>Spatial Distribution ‡</td>
<td>Random, Clumped</td>
</tr>
<tr>
<td>Grow To … (i.e. length of simulation)</td>
<td>Year, Age, Top Height, Mean DBH, Mean Height, Crown Closure.</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>km/h</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>Degrees</td>
</tr>
</tbody>
</table>

* Identifies the dimensions of the total area being simulated.

** Identifies the location and dimensions of regions within the total area that will be cut or planted depending on user preferences.

*** Specifies the grid used to locate planted trees or natural regeneration.

† Variables for planted trees only.

‡ Variables for natural regeneration only.

In the model, once a stand of trees is established, openings and retention patches may be created to simulate growth or simple harvest and retention scenarios in TASS III (Figure 3.2).
Wind speed and direction are then used by the new windthrow model and the tree list is updated for windthrown trees. There are some limitations to the sizes and type of harvest areas that can be simulated using the new windthrow model. Using a command line version of TASS, several harvest area shapes can be simulated; however, using the current user interface in TASS III, only square cutblock shapes, with or without square internal reserves can be simulated. The size of the area to be simulated is also limited to a few hundred square metres depending upon the processing speed of the computer used in simulations. This
imposes at least two constraints on simulation results. First, VRFetch is not very sensitive below 125 m making it necessary to increase the wind speed to simulate any detectable damage. Second, WindFIRM checks for VRFetch 300 m in the upwind direction which creates some glitches at this smaller scale.

3.2.3. Simulations using the new WindFIRM/ForestGALES_BC and TASS model

For this research, a set of simulations were run using TASS generated tree lists in the research version of WindFIRM/ForestGALES 2.1 to examine predicted stem damage patterns. Three gap sizes, with and without aggregate retention, were simulated, and five wind speeds (130, 140, 150, 160 and 170 km/h) and three directions (135, 180 and 315 degrees) were applied to the retention treatment (Table 3.4).

Table 3.4. Description of gap size and aggregate retention treatments with TASS generated tree lists used for WindFIRM/ForestGALES_BC simulations.

<table>
<thead>
<tr>
<th>Treatment Name</th>
<th>Plot Dimensions</th>
<th>Opening Dimensions</th>
<th>Retention Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 hole</td>
<td>200 m X 200 m</td>
<td>100 m X 100 m</td>
<td>-</td>
</tr>
<tr>
<td>100 island</td>
<td>200 m X 200 m</td>
<td>100 m X 100 m</td>
<td>50 m X 50 m</td>
</tr>
<tr>
<td>125 hole</td>
<td>200 m X 200 m</td>
<td>125 m X 125 m</td>
<td>-</td>
</tr>
<tr>
<td>125 island</td>
<td>200 m X 200 m</td>
<td>125 m X 125 m</td>
<td>50 m X 50 m</td>
</tr>
<tr>
<td>150 hole</td>
<td>200 m X 200 m</td>
<td>150 m X 150 m</td>
<td>-</td>
</tr>
<tr>
<td>150 island</td>
<td>200 m X 200 m</td>
<td>150 m X 150 m</td>
<td>50 m X 50 m</td>
</tr>
</tbody>
</table>

* e.g. “150 hole” is a 150 m by 150 m opening with no retention and “150 island” is the same size opening with a 50 m by 50 m retention patch in the middle.

The following conceptual figures illustrate how damage should propagate in relation to exposure defined by fetch (Figures 3.3 and 3.4).
Figure 3.3. Block layout defined by WindFIRM with pure fetch and VRFetch trajectories indicated (A) and the propagation of windthrow in Iterations 1 (B), 2 (C), and 3 (D) which is a function of recalculated stand (pixel) values for VRFetch and spacing.

Using this new windthrow model, individual tree predictions can be extracted and spatially represented. This facilitates examining the characteristics of damaged trees, along with the spatial distribution of damage and propagation as illustrated in another conceptual figure (Figure 3.4).

Figure 3.4. Propagation of windthrow within a sample localized pixel.
3.2.4. Evaluation of model simulations

In initial simulations using WindFIRM/ForestGALES_BC 2.0, tree lists were edited to represent simple block and retention layouts. These simulations were checked to ensure spatial windthrow outcomes were consistent with the expected wind-sheltering effects of within-block retention using images of model outputs. Then, more extensive simulations were assessed in two parts. First, images from the windthrow simulations using the TASS interface were compared to images from WindFIRM/ForestGALES_BC simulations to check for a successful linkage of the windthrow calculations in TASS. For each pixel in the stand, WindFIRM sums the retained basal area in each upwind pixel up to 300 m distant from the target pixel and re-calculates a value for VRFetch for this upwind direction. The failure of upwind trees reduces the basal area per hectare of standing trees which reduces the amount of shelter they provide for downwind pixels. VRFetch is recalculated for each iteration to quantify this change in exposure until there are no additional vulnerable trees upwind and the damage progression stops. Therefore, the second part of the evaluation assessed the ability of WindFIRM/ForestGALES_BC to represent windthrow propagation and sensitivity to wind direction using images which show the spatial distribution of damage for each iteration. The model outputs were also assessed with respect to exposure by plotting the relationship between the proportion of damage and wind speed for all layout scenarios, which represented different initial values for VRFetch. Finally, the distribution of modelled damage was assessed by plotting the proportion of windthrow in the tree list by DBH class and by height-to-diameter ratio class.

---

4 See Chapter 2 for a sample calculation and figures which explain the derivation of uni-directional VRFetch.
3.3 Results

3.3.1. Initial examination of model outcomes and comparison of windthrow simulations in TASS III versus WindFIRM/ForestGALES_BC 2.0

Initial checks on model outputs found that the model was successful in producing spatial windthrow outcomes consistent with the expected wind-sheltering effects of within block retention. With WindFIRM/ForestGALES_BC integrated into TASS, it was possible to use the TASS III visualization tools to show damage results for individual trees for simple cutblock design scenarios. To illustrate this, a tree list was simulated for a 200 metre by 200 metre 60-year old western hemlock stand which is representative of many second growth stands in coastal BC. A simple square cutblock (150 metres by 150 metres) with a residual patch (50 metres by 50 metres) was simulated in TASS III as previously shown in Figure 3.2. The spatial distribution of windthrow resulting from an 80 km/h above-canopy wind coming from 135° is shown in Figure 3.5.
Figure 3.5. WindFIRM/ForestGALES_BC 2.2 and the TASS III interface used to predict and display windthrown trees. Windthrown trees are flagged in white in the image in the Check Windthrow dialogue box.

The results from the TASS III interface compare very well within the results from WindFIRM/ForestGALES_BC simulations done on the same tree list but in the Python environment (Figure 3.6).
Figure 3.6. Simulation of windthrow for the same TASS tree list done using the research version of WindFIRM/ForestGALES_BC 2.1.

Tree lists representing before and after the windthrow event can also be saved by the user to examine the attributes of windthrown trees more closely.

3.3.2. Windthrow propagation and the sensitivity of windthrow to wind speed/direction and retention levels

Under the scenarios outlined in Table 3.4, windthrow increased with gap size and there was more sensitivity to wind speed in the larger openings (Figures 3.7, 3.8 and 3.9). These figures show that the retention of an aggregate of trees within the openings also results in fewer windthrown trees in the largest openings; however, the reverse was true for smaller openings (i.e. < 125 metres on a side). This is inconsistent with expected results, and was further investigated. In order to simulate the openings with retention in TASS III, trees are first harvested to create the full opening then the retention aggregate was ‘replanted’ to
recreate the retained trees in this location. It was observed, during the TASS III simulation,
that the stand density in the small retention aggregate defaulted to a much smaller number per
hectare upon stand initiation (i.e. planting density) thus creating higher wind loading in the
retained aggregate than in the surrounding stand (Figure 3.10).

Figure 3.7. Predicted windthrow as a proportion of all trees in the simulation at increasing wind speed
(U), at 10 m above the canopy, by treatment where, for example, “150 hole” is a 150 m by 150 m
opening with no retention and “150 island” is the same size opening with a 50 m by 50 m retention
patch in the middle. Wind direction is fixed at 135 degrees.

Figure 3.8. Predicted windthrow as a proportion of all trees in the simulation at increasing wind speed
(U) by treatment where, for example, “150 hole” is a 150 m by 150 m opening with no retention and
“150 island” is the same size opening with a 50 m by 50 m retention patch in the middle. Wind
direction is fixed at 180 degrees.
Figure 3.9. Predicted windthrow as a proportion of all trees in the simulation at increasing wind speed (U) by treatment where, for example, “150 hole” is a 150 m by 150 m opening with no retention and “150 island” is the same size opening with a 50 m by 50 m retention patch in the middle. Wind direction is fixed at 315 degrees.

Figure 3.10. Windthrow damage in 1.56 ha opening and 0.25 ha retention patch (4 ha plot). Also shown are fewer trees simulated by TASS in the retention patch than in the surrounding stand.
WindFIRM/ForestGALES_BC creates a shapefile which maps the status of each stem (i.e. live or windthrown) cumulatively or by iteration as well as the treatment layout (e.g. Figures 3.11, 3.12 and 3.13). This enables the spatial analysis of different treatments, wind speeds and directions.

Figure 3.11. Windthrow damage (at iterations 1 and 2) for a southeast wind of 160 km/h in the “150 hole” treatment which is a 2.25 ha opening (4 ha plot).
Figure 3.12. Windthrow damage for a south wind of 160 km/h in the “150 hole” treatment which is a 2.25 ha opening (4 ha plot).
These results were also examined for windthrow propagation at each iteration. The “150 hole” treatment was used to demonstrate and evaluate the number of stems damaged in each iteration, as well as the distribution of DBHs and height-to-diameter ratios. The damage was skewed towards smaller DBH trees (Figure 3.14). The results also showed that more slender trees with higher height-to-diameter ratios were windthrown in the first iteration, as might be expected (Figure 3.15). There were also more trees in the higher height-to-diameter ratio classes damaged in the second iteration.
The proportion of damaged trees increased as wind speed increases. The stands simulated were all single species and even-aged, but with a variety of tree sizes. There were also multiple opening sizes with and without retention to capture a range of irregular stand conditions. As a result, the sensitivity of the model outputs to varying tree size and form inputs and to the characteristics of upwind gaps was examined. Further, the size of the stand was relatively small (4 ha) to enable multiple simulations to be conducted in a reasonable amount of time; however, this limited the fetch across the openings.

Figure 3.14. Proportion of stems in the DBH class that are windthrown for Iterations 1 (■) and 2 (□) for wind speeds of 140 km/h, 150 km/h, 160 km/h and 170 km/h and a wind direction of 135 degrees.
Figure 3.15. Proportion of stems in the height to diameter class that are windthrown for Iterations 1 (■) and 2 (□) for wind speeds of 140 km/h, 150 km/h, 160 km/h and 170 km/h and a wind directions of 135 degrees.

3.4 Discussion

Modifications of WindFIRM/ForestGALES_BC included the ability to account for upwind stand conditions and automatic adjustments of the wind profile for a range of stand conditions across a landscape, and the ability to display a spatial map of the windthrown trees that result from different harvest spatial patterns, wind speeds and directions. The model structure enables integration of spatial layers and facilitates the addition of new functions. The model also calculates and represents windthrow propagation through the stand in a realistic manner. No previous mechanistic windthrow models have simulated this process of damage propagation. The post-windthrow tree lists could be used in growth and yield models to forecast post-windthrow tree and stand development. These advancements are important to the development of decision support tools which need to quantify more of the dynamic windthrow processes.
Model results are consistent with prior empirical work which suggests that damage concentrates near cutblock edges and that slender trees are more prone to windthrow (Petty and Swain 1985, Peltola et al. 1999, Burton 2001, Lanquaye-Opoku and Mitchell 2005, Scott and Mitchell 2005, Rollerson et al. 2009). This was exemplified by the damage results which were skewed towards the higher height-to-diameter ratio classes (Figure 3.15), and the majority of this damage occurred in the first iteration. Dominant trees are generally more windfirm than co-dominant trees in the stand (Coutts 1986, Beese and Bryant 1999, Mitchell 2000, Pastur et al. 2009). A lower proportion of stems in the largest size classes were windthrown in the WindFIRM/ForestGALES_BC simulations. In fact, the largest DBH class at the higher wind speeds showed a large decrease in wind damage from the next smallest diameter class (Figure 3.14). The model also reflects the expected trend of increasing windthrow with fetch. The 100, 125 and 150 hole and island treatments represent progressively greater values for VRFetch which are related to progressively increasing amounts of windthrow (Figures 3.7 to 3.9). VRFetch, which is a measure of gap size and the amount of retention within the gap, is a strong predictor of the proportion of windthrow. Therefore, higher retention within blocks reduces the proportion of windthrow (Scott 2005).

At wind speeds of 170 km/h, 15-20% of trees in most height-to-diameter classes and 10-15% of trees in most DBH classes were windthrown in the simulated stands. Based on observed wind damage in BC partial cuts and the local wind regime, these windthrow levels seem conservative. Threshold wind speeds which cause damage vary depending on stand, soil and treatment factors along with the wind climate to which trees have become acclimated. Stathers et al. (1994) suggested that few recently exposed trees can withstand mean wind speeds of 100 km/h. Beese (2001) reported significant damage in shelterwood and patch cut
treatments at wind speeds of 32 km/h measured at a height of 3 metres in hemlock dominated stands at the Montane Alternative Silvicultural Systems (MASS) study southwest of Campbell River, BC. A study of wind climatology in northern BC identified extreme winds as those which exceed 72 km/h (Sagar and Jull 2001). However, storm winds often exceed these values and many exposed trees remain standing indicating an ability to withstand wind speeds higher than 100 km/h. For example, during a wind storm on December 15, 2006 peak wind speeds of 158 km/h and 118 km/h were recorded at Race Rocks (west of Victoria, BC) and Point Atkinson (West Vancouver, BC), respectively (Environment Canada 2010). While this storm caused widespread damage, not all exposed trees blew down. Nonetheless, WindFIRM/ForestGALES_BC predictions likely underestimate the damage within the range of test opening and retention scenarios. Higher than expected input wind speeds (e.g. > 130 km/h) were required to produce detectable damage in these simulations and is most likely due to the constraints on the opening size imposed by the limited size of tree list simulations which were possible in TASS III.

WindFIRM/ForestGALES_BC is sensitive to wind direction (Figure 3.11 to 3.13). The lack of symmetry exhibited by these figures could be due to some glitches in the way that VRFetch is calculated in these very small tree list simulations. Greater computational capacity may improve these results by increasing the capacity to simulate larger tree lists. The veracity of the model predictions will be examined further in Chapter 4 where model results were compared to actual windthrow occurrence in simulations based on stand, harvest design and wind climate conditions at the Silviculture Treatments for Ecosystem Management in the Sayward (STEMS) study area on Vancouver Island.
The integration of WindFIRM/ForestGALES_BC with TASS demonstrates how windthrow predictions can be presented to forest managers in an integrated decision support tool for harvesting design and post harvesting damage and stand growth projections. It will be necessary to improve the capacity of this integrated package to represent complex cutblock design scenarios rather than simple geometric shapes, but even the simple scenarios enable managers to evaluate consequences of cutblock design scenarios on fetch and shelter.

Even under the current model constraints, WindFIRM/ForestGALES_BC calculates windthrow predictions for individual trees under a variety of scenarios. The post-windthrow tree lists can be used by the improved version of TASS III to simulate subsequent stand growth in these openings. The successful linkages and integration of simulated tree lists from TASS with WindFIRM/ForestGALES_BC will improve the quality of current assessments of timber supply by predicting short term windthrow loss rates. It will also improve the future predictions of stand yields where understory responds to loss of overstory trees to windthrow. Many researchers have looked at the landscape scale implications of windthrow (e.g. Blennow and Sallnas 2004, Zeng et al. 2007). However, these models and studies quantify stand level losses rather than edge damage and are not sensitive to wind direction. WindFIRM/ForestGALES_BC allows the loss of individual trees along edges to be tallied.

Using WindFIRM to iterate tree lists through ForestGALES_BC enables the simulation of windthrow propagation, the process by which the failure of trees affects the exposure and susceptibility of their surviving neighbours. Improved representation of the loss of upwind trees is one aspect of damage propagation. Direct impact by falling trees is likely to be
another factor in damage propagation patterns observed in the field (Schaetzl et al. 1986, Rollerson and McGourlick 2001). Since tree position, mass and fall direction are all represented in the model, this domino effect could be evaluated in future modelling work. Other neighbour-neighbour interactions such as damping that dissipate wind loading could also be explored (Rudnicki et al. 2001, Rudnicki et al. 2008).

WindFIRM/ForestGALES_BC was designed without additional attribute information; differences because of root systems, soils, sway dynamics and complex topography are currently not modelled. Other advances such as the characterization of tree-to-tree interactions will also help improve the veracity of the model. Damage is lower than expected in most scenarios which could be due to the low sensitivity of outputs to low fetch values (e.g. Figures 2.6, and 3.7 to 3.9). Also, higher than expected windthrow occurs in partially populated pixels which can artificially increase the average spacing inputs causing higher wind loads on the trees. For example, the island treatments (i.e. treatments with a residual patch) in smaller openings (e.g. 100 and 125 m) experienced greater damage than the same openings with no retention (Figures 3.7 to 3.9). This is due to fewer trees being planted in the residual patch than the surrounding stand as a consequence of a glitch in TASS III which resulted in higher spacing and causing more damage to be simulated in the residual patch (Figure 3.10). Future research and programming related to these anomalies and factors will aid the development of equations that will improve the model.

### 3.5 Conclusions

WindFIRM/ForestGALES_BC is can simulate windthrow at the individual tree level and it is sensitive to changes in wind direction, upwind stand conditions (i.e. fetch) and tree attributes
such as DBH and height-to-diameter ratio. For example, more slender trees and fewer large trees are being damaged and damage increases with opening size and wind speed. It is also sensitive to wind direction and results show a trend of more damage to downwind edges than sheltered edges. These attributes of the model outputs meet the first objective of this chapter, which was to simulate the spatial differences of windthrow across landscapes which are logical and sensitive to wind direction, upwind stand characteristics and individual tree attributes. The linkage between WindFIRM/ForestGALES_BC and TASS satisfies the second objective which was to demonstrate how simulated windthrow openings can be used to account for natural disturbance in tree level growth and yield models. With respect to the criteria for an improved decision support system (DSS) identified at the beginning of this chapter, WindFIRM/ForestGALES_BC is a spatial mechanistic windthrow model which can simulate the dynamics of windthrow due to the propagation of damage through a stand. This meets the third objective which was to quantify processes where the stability of residual trees is compromised the failure of their neighbours. While it appears to under-represent windthrow, especially in small openings, WindFIRM/ForestGALES_BC results are consistent with prior work that has found that damage increases with fetch values. With the exception of the smallest openings within-block retention reduces the incidence of windthrow, which is consistent with prior studies.

While the scenarios presented in this chapter were geometrically simple, WindFIRM/ForestGALES_BC has the versatility to represent a very wide range of stand composition and harvesting scenarios. The capacity of the model to produce edited tree lists that represent complex post-harvesting scenarios, and the potential for the user to substitute simulated trees with data from actual trees will be demonstrated in Chapter 4.
Emphasis was placed on the ability of the model to integrate with other models such as TASS and to add new equations that better characterize the spatial effects of windthrow, as they become available. Consequently, WindFIRM/ForestGALES_BC is valuable decision support tool which is adaptable and can accommodate the addition new data and equations as they become available.
4.0 Validation of WindFIRM/ForestGALES_BC Using STEMS I Data

4.1 Introduction

The WindFIRMS/ForestGales_BC hybrid model described in Chapters 2 and 3 of this thesis was evaluated for realistic predictions of windthrow. However, to further evaluate the accuracy and effectiveness of WindFIRM/ForestGALES_BC, I compared model results to permanent plot (PSP) data from a large field experiment with a range of partial harvests called the Silviculture Treatments for Ecosystem Management in the Sayward (STEMS) installation (de Montigny 2004) on Vancouver Island, British Columbia (BC). STEMS was installed in 2001 to examine regeneration and stand dynamics across a range of overstory retention levels in partial harvests with great variation in spatial patterns of retained trees in second growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) / western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forests. These data are ideally suited for testing the WindFIRM/ForestGALES_BC model, since: (1) the model was developed using results from winching and wind tunnel studies on trees from similar coastal BC stands; (2) the STEMS installation site is a wind-exposed area with a history of windthrow in recently harvested stands and has relatively uniform soil and topography; (3) the wide range of retention patterns represented at STEMS allowed for a wider test of model validation; and (4) windthrow was recorded at the tree level for plots within each treatment unit of the STEMS installation.
The objectives of this research were to:

1. Demonstrate the range of harvest retention levels and patterns that can be simulated using the improved spatial resolution in the model.

2. Validate the windthrow model outcomes by comparing to actual windthrow data

3. Assess model outputs in response to changes in critical input parameters such as wind speed and tree attributes via sensitivity analyses.

4. Based on the validation and sensitivity analyses, identify components of the windthrow model which require improvements and propose future research to address important knowledge gaps.

Initially, in the simulations, the spatially explicit tree-lists of the STEMS installation immediately following the harvest treatments were used as a guide to general similar tree-lists using the spatially explicit growth model TASS that was linked in the hybrid windthrow model. Although TASS begins growth of stands assuming a stand replacing event, the TASS tree-list generated was based on the STEMS tree-list immediately following the harvest. The resulting tree-lists of TASS may not be exactly the same as the STEMS installation; however, the TASS growth model is the most accurate of available spatially explicit growth models for even-aged stands in BC.

For the validation, the hypotheses tested were:
1. $H_0$: There are no differences between the amount and distribution of simulated windthrow and recorded windthrow for the STEMS treatment units.

2. $H_1$: There are differences in simulated and recorded windthrow and these are due to differences in how the pre-harvest stand conditions at STEMS are represented using the TASS-simulated tree-list data.

3. $H_2$: There are differences in simulated and recorded windthrow and these are due to functions used in WindFIRM/ForestGALES_BC.

4. $H_3$: There are differences in simulated and recorded windthrow and these are due to both the representation of pre-harvest stand conditions at STEMS and the functions used in WindFIRM/ForestGALES_BC.

This validation was used to determine the strengths and weaknesses of the hybrid windthrow model and to highlight the ability to characterize complex harvest and retention patterns and spatially represent patterns of tree level windthrow under exposure to different wind speeds and directions. Since the validation results may be due to the TASS tree-list not reflecting the STEMS tree-list after harvest, the hybrid windthrow model was also run using the actual STEMS tree-list data for selected locations. Also, crown modification through alteration of the input tree-lists was also simulated, to indicate how the windthrow model can be used to simulate these changes. In all cases, windthrow simulation outcomes were compared to actual windthrow data for the STEMS installation for measures taken after the harvest event.
Accuracy of windthrow predictions was evaluated for individual trees and the relationship between stand-level damage and above canopy wind speeds were investigated.

Wind direction and speed are the other primary windthrow model inputs. Sensitivity analyses were conducted and outcomes of changing these model inputs were evaluated. The validation and sensitivity analyses enabled a complete evaluation of what the model does well and where it needs improvement, leading to recommendations on the collection of data for future validations and future model refinement.

### 4.2 Methods

#### 4.2.1. Description of the STEMS installation

STEMS I is the first of three replications of a long-term silvicultural experiment in the Sayward Landscape Unit on Vancouver Island, BC. As noted, the installation was established in 2001 in the Snowden Demonstration Forest northeast of Campbell River (Figure 4.1).
The Snowden Forest is located in the CWHxm (Coastal Western Hemlock very dry maritime) biogeoclimatic zone (Green and Klinka 1994). The forest is primarily composed of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) with minor components of western redcedar (*Thuja plicata* Donn ex D. Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (de Montigny 2004). There are seven treatments in the area including extended rotation with Commercial Thinning, Aggregate and Uniform Dispersed Retention systems, group selection and modified patch cut systems, clearcut and a non-treatment control (Tables 4.1 and 4.2). In the Dispersed Retention treatment, approximately 15 – 20 stems per hectare were selected for crown pruning where 30 – 50 % of the crown was removed (de Montigny 2004). As noted, the STEMS installations represented a wide range of spatial patterns. This presented an opportunity to demonstrate the flexibility of WindFIRM/ForestGALES_BC to...
simulate tree-level differences in the amount of windthrow with respect to crown modification. However, the disadvantage of this great range of spatial diversity, with respect to validation, is that it was not possible to accurately duplicate the crown treatments and the distribution of treated trees in the simulation. Therefore, validation in this chapter focuses on the ability of the model to simulate a wide range of layout and crown treatments and compare the distribution and patterns of windthrow with recorded windthrow in the field. Validation with absolute windthrow results from the field may be problematic at this stage due to the limitations of using TASS-derived trees.

Each treatment was randomly assigned to seven treatment areas at each installation area and repeated over several installation areas resulting in a randomized complete block design. For each treatment area of every installation, fixed area plots of 0.10, 0.05 and 0.01 hectares, depending on tree size, were used to measure pre-treatment and post-treatment stand conditions (de Montigny 2004).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species composition</th>
<th>Stems per hectare</th>
<th>Volume (m³/ha)</th>
<th>Mean diameter (cm)</th>
<th>Mean height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregated Retention F8C1H1</td>
<td>822</td>
<td>458</td>
<td>27.8</td>
<td>30.1</td>
<td></td>
</tr>
<tr>
<td>Dispersed Retention F10 (leave)</td>
<td>35</td>
<td>45</td>
<td>40.0</td>
<td>32.9</td>
<td></td>
</tr>
<tr>
<td>Commercial Thinning F9C1(H)</td>
<td>515</td>
<td>350</td>
<td>30.6</td>
<td>30.2</td>
<td></td>
</tr>
<tr>
<td>Clearcut w/ reserves F10(HD)</td>
<td>694</td>
<td>498</td>
<td>31.1</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>Modified Patch Cuts F10</td>
<td>967</td>
<td>467</td>
<td>27.5</td>
<td>27.5</td>
<td></td>
</tr>
<tr>
<td>Group Selection F8H1C1</td>
<td>819</td>
<td>439</td>
<td>28.4</td>
<td>29.0</td>
<td></td>
</tr>
</tbody>
</table>

* Douglas-fir (F), western redcedar (C), western hemlock (H), red alder (*Alnus rubra* Bong.) (D). The number beside each species symbol is multiplied by 10 times to determine the percent stand composition (e.g. 8 = 80%).
Table 4.2. Pre- and post- harvest stand attributes for treatments at STEMS (de Montigny 2004).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Pre</th>
<th>Post</th>
<th>%Δ</th>
<th>Pre</th>
<th>Post</th>
<th>%Δ</th>
<th>Pre</th>
<th>Post</th>
<th>%Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregated Retention</td>
<td>1208</td>
<td>247</td>
<td>80</td>
<td>55</td>
<td>10</td>
<td>82</td>
<td>571</td>
<td>96</td>
<td>83</td>
</tr>
<tr>
<td>Dispersed Retention</td>
<td>1210</td>
<td>51</td>
<td>96</td>
<td>55</td>
<td>6</td>
<td>89</td>
<td>571</td>
<td>57</td>
<td>90</td>
</tr>
<tr>
<td>Commercial Thinning</td>
<td>1325</td>
<td>636</td>
<td>52</td>
<td>69</td>
<td>37</td>
<td>46</td>
<td>712</td>
<td>388</td>
<td>46</td>
</tr>
<tr>
<td>Clearcut</td>
<td>747</td>
<td>0</td>
<td>100</td>
<td>53</td>
<td>0</td>
<td>100</td>
<td>571</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Modified Patch Cut</td>
<td>763</td>
<td>575</td>
<td>25</td>
<td>44</td>
<td>6</td>
<td>18</td>
<td>452</td>
<td>372</td>
<td>18</td>
</tr>
<tr>
<td>Control</td>
<td>607</td>
<td>607</td>
<td>0</td>
<td>53</td>
<td>53</td>
<td>0</td>
<td>610</td>
<td>610</td>
<td>0</td>
</tr>
<tr>
<td>Group Selection</td>
<td>725</td>
<td>578</td>
<td>20</td>
<td>48</td>
<td>41</td>
<td>15</td>
<td>491</td>
<td>405</td>
<td>19</td>
</tr>
</tbody>
</table>

* Merch. Vol. is based on 10 cm top diameter 30 cm stump height.

Data from the initial measurement and the 2003 and 2007 re-measurement were supplied by the British Columbia Ministry of Forests and Range (BCMoFR). Tree species, height, diameter and status (standing live, standing dead, windthrown, etc.) were recorded, along with plot locations. Table 4.3 summarizes the cumulative proportion of windthrow for 2003 and 2007 re-measurements.

Table 4.3. Summary of cumulative proportion of stems windthrown by treatment* from plot re-measurements in 2003 and 2007.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>n</th>
<th>2003 Windthrow (cumulative proportion)</th>
<th>S.E.</th>
<th>2007 Windthrow (cumulative proportion)</th>
<th>S.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregated Retention</td>
<td>25</td>
<td>0.351</td>
<td>0.091</td>
<td>0.374</td>
<td>0.096</td>
</tr>
<tr>
<td>Commercial Thinning</td>
<td>16</td>
<td>0.056</td>
<td>0.014</td>
<td>0.061</td>
<td>0.015</td>
</tr>
<tr>
<td>Dispersed Retention</td>
<td>21</td>
<td>0.581</td>
<td>0.070</td>
<td>0.628</td>
<td>0.063</td>
</tr>
<tr>
<td>Modified Patch Cut</td>
<td>27</td>
<td>0.015</td>
<td>0.009</td>
<td>0.016</td>
<td>0.009</td>
</tr>
<tr>
<td>Control</td>
<td>17</td>
<td>0.004</td>
<td>0.002</td>
<td>0.006</td>
<td>0.003</td>
</tr>
<tr>
<td>Group Selection</td>
<td>20</td>
<td>0.022</td>
<td>0.017</td>
<td>0.031</td>
<td>0.018</td>
</tr>
</tbody>
</table>

Standard error (SE) refers to variation of windthrow between plots (n) within each treatment.
* No windthrow plot data for clearcut treatment.

Since all trees were removed from the treatment area boundary for the clearcut treatment, the only windthrow possible is outside of the treatment area boundary. A map of edge damage was made during the plot re-measurements. Maps of the simulated windthrow were
compared with maps from the edge survey to qualitatively compare the distribution and extent of windthrow along the edges.

Also, very little windthrow was found in the patch cut, control and group selection plots. Simulations for these treatments did not produce any windthrow for the input wind speeds used in this chapter. Therefore, the focus of this validation was on the Commercial Thinning, Aggregate and Dispersed Retention treatments which had significant amounts of recorded windthrow (Figure 4.2).

Figure 4.2. STEMS treatments which were used for validation and the plot locations.
4.2.2. Simulation of STEMS in TASS

Initially, tree-lists were generated using TASS to represent the tree-lists obtained for the STEMS installations following harvest. For these simulated tree-lists, two primary input variables were needed – the proportion of stems per ha by species (i.e., species mix) and the site index (SI in metres at breast height age of 50 years). Using TASS and the site indices and species mixes provided by the British Columbia Ministry of Forests and Range (BCMoFR) for the STEMS treatment units, a spatial tree-list at stand initiation was produced and these trees were projected for 60 years, the approximate age of the STEMS plots at time of harvest (Table 4.4).

Table 4.4. Summary of input variables used to produce TASS-simulated trees at STEMS (from de Montigny 2004).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species Mix (%)</th>
<th>SI 50&lt;sup&gt;5&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fd*</td>
<td>Cw*</td>
</tr>
<tr>
<td>Aggregated Retention</td>
<td>77</td>
<td>9</td>
</tr>
<tr>
<td>Dispersed Retention</td>
<td>71</td>
<td>9</td>
</tr>
<tr>
<td>Commercial Thinning</td>
<td>79</td>
<td>4</td>
</tr>
</tbody>
</table>

* Fd = Douglas-fir, Cw = western redcedar, Hw = western hemlock

Following generation of the tree-lists and projection to 60 years, the harvest was simulated for each treatment area to match the treatments of the STEMS data. The generation of tree-lists and simulated harvests in TASS were prepared by BCMoFR staff. To achieve a similar spatial distribution of harvested versus non-harvested trees to that of the STEMS treatment areas, a grid was overlaid on an orthographic photograph of the STEMS treatment areas and each grid cell was classified as harvested or not harvested (Figure 4.3). The TASS-simulated tree-list at 60 years was then overlaid with this image to obtain an irregularly-shaped

<sup>5</sup> SI 50 (Site Index at 50 years) is the height of the largest DBH site tree at age 50.
treatment boundary and to select the trees to be removed from the list, thus duplicating the boundaries and retention of the STEMS treatment areas (Polsson 2007).

The WindFIRM portion of the hybrid windthrow model was then used to assign a status to each tree (record) based on the probability (either 100% or 0%) of windthrow (Pfall) as well as a location on the grid (Cell ID). These fields were merged with the tree-list data from TASS at time of harvest (Table 4.5).
Table 4.5. Example of a tree-list produced by TASS.

<table>
<thead>
<tr>
<th>Tree ID</th>
<th>Age (years)</th>
<th>X coordinate</th>
<th>Y coordinate</th>
<th>Species*</th>
<th>Height (m)</th>
<th>DBH (cm)</th>
<th>Crown Length (m)</th>
<th>PFall</th>
<th>Cell ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>60</td>
<td>84.1</td>
<td>372.9</td>
<td>Fdc</td>
<td>28.7</td>
<td>22.0</td>
<td>5.4</td>
<td>0</td>
<td>340</td>
</tr>
<tr>
<td>11</td>
<td>60</td>
<td>133.1</td>
<td>372.9</td>
<td>Fdc</td>
<td>30.6</td>
<td>25.6</td>
<td>8.4</td>
<td>0</td>
<td>342</td>
</tr>
<tr>
<td>13</td>
<td>60</td>
<td>216.6</td>
<td>372.9</td>
<td>Fdc</td>
<td>31.2</td>
<td>31.5</td>
<td>8.3</td>
<td>0</td>
<td>345</td>
</tr>
<tr>
<td>18</td>
<td>60</td>
<td>331.9</td>
<td>372.9</td>
<td>Fdc</td>
<td>28.7</td>
<td>18.7</td>
<td>4.3</td>
<td>0</td>
<td>350</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
<td>349.6</td>
<td>372.9</td>
<td>Fdc</td>
<td>28.0</td>
<td>29.1</td>
<td>6.4</td>
<td>0</td>
<td>350</td>
</tr>
<tr>
<td>21</td>
<td>60</td>
<td>375.4</td>
<td>372.9</td>
<td>Fdc</td>
<td>29.5</td>
<td>25.3</td>
<td>5.7</td>
<td>0</td>
<td>352</td>
</tr>
<tr>
<td>27</td>
<td>60</td>
<td>447.6</td>
<td>372.9</td>
<td>Fdc</td>
<td>31.9</td>
<td>27.0</td>
<td>8.3</td>
<td>0</td>
<td>354</td>
</tr>
<tr>
<td>30</td>
<td>60</td>
<td>458.9</td>
<td>372.9</td>
<td>Fdc</td>
<td>27.2</td>
<td>19.5</td>
<td>3.9</td>
<td>0</td>
<td>355</td>
</tr>
</tbody>
</table>

* Douglas-fir (Fdc)

Although WindFIRM has the capacity to perform a similar operation where polygons taken from orthophotos or maps can be represented at the grid cell level (25m x 25m) and trees can be harvested to reflect retention levels within these grid cells, the method described here was chosen in the Aggregate and Dispersed Retention treatments because the boundaries and retention were easily defined. As a result, this method resulted in an improved characterization of the irregular patterns of individual tree retention for these treatments.

Although the use of orthographic photographs was preferred for some treatments, it was not always possible to identify boundaries. For the Commercial Thinning treatment, instead the tree-list management tools in WindFIRM were used to create polygons and apply the harvest treatment within the polygon. The pre-harvest basal area in the Commercial Thinning treatment was 68 m²/ha with a post-thinning basal area of 36 m²/ha. Therefore, grid cells within the treatment polygon were automatically thinned from below to 53% of the pre-harvest basal area to simulate the residual density.
4.2.3. Windthrow simulations

The tree-lists at time of harvest were generated using TASS and WindFIRM to represent the Aggregate Retention, Dispersed Retention and Commercial Thinning treatments of the STEMS installation. WindFIRM/ForestGALES_BC was then run using these simulated tree-lists to simulate growth and windthrow over time. The outcomes were then compared to the actual data for the STEMS installation, using validation tests later described. However, these results include any inaccuracies caused by using representative tree-lists from TASS instead of field data measured at time of harvest. As a result, simulations using the actual field data were also obtained.

For this second set of simulations, the field-measured species, height and DBH of trees replaced the TASS generated values, but the spatial positions were retained. Trees were randomly (without replacement) chosen from the plot data until all locations were filled. If any positions remained vacant the random selection was re-initiated. It should be noted that future versions of the model should include a method of inputting these data to the hybrid windthrow model; for this study, this replacement was done manually.

Wind direction and speed are the other primary model inputs. As a result, these parameters were varied for all runs to evaluate the sensitivity of model outcomes to these important model inputs (Table 4.6).
Table 4.6. Summary of windthrow simulations using TASS-simulated tree-lists and a combination of TASS-simulated trees and plot trees for specific plot locations (i.e. Plots 10 and 25).

<table>
<thead>
<tr>
<th>Name</th>
<th>Tree-list source data</th>
<th>Wind speed (km/h)</th>
<th>Wind direction (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT_SIM_1</td>
<td>TASS-simulated</td>
<td>86.4</td>
<td>135</td>
</tr>
<tr>
<td>WT_SIM_2</td>
<td>TASS-simulated</td>
<td>93.6</td>
<td>135</td>
</tr>
<tr>
<td>WT_SIM_3</td>
<td>TASS-simulated</td>
<td>100.8</td>
<td>135</td>
</tr>
<tr>
<td>WT_SIM_4</td>
<td>TASS-simulated</td>
<td>108.0</td>
<td>135</td>
</tr>
<tr>
<td>WT_SIM_5</td>
<td>TASS-simulated</td>
<td>115.2</td>
<td>135</td>
</tr>
<tr>
<td>WT_SIM_6</td>
<td>TASS-simulated</td>
<td>86.4</td>
<td>315</td>
</tr>
<tr>
<td>WT_SIM_PLOT_10</td>
<td>TASS-simulated and Plot data</td>
<td>100.8</td>
<td>135</td>
</tr>
<tr>
<td>WT_SIM_PLOT_25</td>
<td>TASS-simulated and Plot data</td>
<td>100.8</td>
<td>135</td>
</tr>
</tbody>
</table>

Tree-lists representing each treatment were run through WindFIRM/ForestGALES_BC at five wind speeds between 86 – 115 km/h (24 and 32 m/s) at 7 km/h (2 m/s) intervals (Table 4.8) and compared with recorded windthrow damage for the STEMS installations (Table 4.9). These wind speeds were selected based on the range of highest wind speeds recorded at Comox during the years 2000 to 2010 and were assumed to be close to the peak wind speeds that caused the windthrow damage at STEMS. The highest wind speeds were from the southeast (approximately 135 degrees) and the meteorological data and a wind rose constructed from fallen trees indicated that this was the dominant wind direction (Figures 4.8 and 4.9). However, there was evidence of damage due to northwest winds in one plot which is the reason for the single simulation at 315 degrees (WT_SIM6).

A common technique to determine the dominant damaging wind direction is to create a wind rose from the orientation of recorded windthrow (Jane 1986). Many plots in the Aggregate and Dispersed Retention treatments had very few and sometimes no trees on them. Every plot in the Commercial Thinning treatment had windthrown trees. Therefore, this treatment was used to build the wind rose.
Environment Canada provides wind speed and direction measurements for long term weather stations; however, the data are spatially coarse due to the large distances between these weather stations. The nearest Environment Canada weather station with continuous records for both peak gust and hourly mean wind speed is at Comox airport which is approximately 100 kilometres southeast of STEMS (Figure 4.4).

While the distance between the two points is considerable, the terrain between the two points is very gentle and STEMS is located on the first notable rise in topography away from the open water (Figure 4.5). In the absence of continuous wind records at or near the STEMS site, the wind records at Comox airport were considered the closest approximation of the actual peak wind which have occurred at STEMS.
Wind records at Comox Airport were downloaded from the Environment Canada website and were graphed to determine trends in peak wind speeds and directions (Environment Canada 2010).

Comox airport is located adjacent to the water and fully exposed to open water to the southeast. Therefore, it is assumed that peak wind speeds at Comox are higher than peak wind speeds at STEMS. Using the meteorological data, wind speed of 101 km/h was selected for all subsequent simulations, based on the 10-year mean of the highest peak winds at Comox of 28 m/s (100.8 km/h). The STEMS site has the greatest exposure to the southeast and coupled with meteorological data and a wind rose constructed from fallen trees, it was assumed that the dominant damaging winds originated from 135 degrees.
also supported by meteorological data which shows the highest peak winds originate out of the southeast (Figure 4.8).

**4.2.4. Validation criteria**

Plot data from STEMS were used to compare actual windthrow to simulated windthrow. The amount of windthrow, calculated by WindFIRM/ForestGALES_BC, for a given above-canopy wind speed was calculated for each treatment type, species and individual tree attributes (dendrometrics). Simulated windthrow levels and the characteristics of trees affected were compared to actual field-measured cumulative windthrow levels in the STEMS treatment units up to the last measurement in 2008.

Model outcomes were evaluated using contingency tables and cumulative frequency distributions to examine the general accuracy of windthrow predictions across the affected treatment areas. Contingency tables and Chi-square tests were used to compare predicted and actual numbers of windthrow trees with respect to class variables including treatment and species. Cumulative distributions of simulated and actual windthrow were compared for continuous variables using the Kolmogorov-Smirnov test (Conover 1980). The continuous variables used for the validation were height, DBH and height-to-diameter ratio. The reason for using height and DBH is that these are the critical input variables which are supplied to ForestGALES_BC in the tree-list generated by TASS. These dimensions are used to calculate stem mass which is the predictor variable for critical resistive turning moment. Any differences in the TASS-simulated height and DBH and the actual height and DBH from the plot data may, in part, explain differences in predicted and actual windthrow. Height-to-diameter ratio was included because this is a common predictor of windthrow (Scott 2005).
Species is an important class variable to consider in the validation because the crown streamlining functions in ForestGALES_BC are species-dependent (Rudnicki et al. 2004, Byrne 2005). Empirical studies at STEMS found that windthrow damage increased as within block retention decreased (Scott and Mitchell 2005). The fetch variable used to adjust individual tree stability in the current form of ForestGALES_BC is based on these studies. Therefore, windthrow predictions in WindFIRM/ForestGALES_BC should reflect this trend at STEMS to support the logic of the model.

For each contingency table used to compare simulated and actual windthrow for class variables, Chi-Square tests for differences in probabilities were used to evaluate observed ($O$) and expected ($E$) windthrow for all treatments ($j$).

$$H_0: (O_{ij} = E_{2j}, \text{ for all } i, j)$$

$$H_1: (O_{ij} \neq E_{2j}, \text{ for all } i, j)$$

The test statistic was calculated using,

$$T = \sum_{i=1}^{c} \sum_{j=1}^{r} \frac{(O_{ij} - E_{ij})^2}{E_{ij}}, \quad 4.1$$

where,

$$E_{ij} = \frac{n_i C_j}{N}, \quad 4.2$$
and $n_i$ is the row total and $C_j$ is the column total. The null hypothesis was rejected if the calculated value $T$ exceeds $\chi^2_{1-(r-1)(c-1)}$. However, if some of the $E_{ij}$'s are smaller than 5 this test may be inaccurate (Conover 1980).

For each cumulative frequency distribution used to compare simulated and actual windthrow for continuous variables, a Kolmogorov-Smirnov goodness-of-fit test (two-sided test) was used to test for differences in the cumulative distribution functions for simulated ($F(x)$) windthrow and actual windthrow from plot ($F^*(x)$) data using the following hypothesis:

$$
H_0: F(x) = F^*(x), \text{ for all } x \text{ from } -\infty \text{ to } +\infty \\
H_1: F(x) \neq F^*(x), \text{ for at least one value of } x
$$

The test statistic for the two-sided Kolmogorov-Smirnov goodness-of-fit test is calculated using,

$$
T = \sup_x \left| F^*(x) - F(x) \right|
$$

where $T$ is the greatest (denoted by “sup” for supremum) vertical distance between $F(x)$ and $F^*(x)$ (Conover 1980).

4.2.5. Model sensitivity

Some peak winds originated out of the northwest but these occurred primarily in the summer months. Simulations using 86 km/h northwest winds (the highest velocity recorded at Comox from this direction) were run along with the selected windspeed of 101 km/h to
demonstrate the sensitivity of WindFIRM/ForestGALES_BC to wind direction. To enable visualization of the model’s sensitivity to wind direction, geo-referencing was used to overlay the mapped windthrow along the edges and the simulated predictions in ArcGIS 9.3.1 (ESRI 2009). The intention of this was to demonstrate the flexibility of the model to simulate windthrow at different locations for different input wind speeds and directions then display spatial results within the same frame. Shapefiles and their associated database files along with text files representing tree-lists used in the simulations were created using WindFIRM/ForestGALES_BC. This enabled a more quantitative analysis of windthrow for TASS-simulated trees and plot trees for selected plots in the Aggregate Retention.

As well as sensitivity to windspeed and direction, the effects of crown modification were also evaluated in the Dispersed Retention treatment. Four grid cells where all the TASS-simulated trees blew down in the initial windthrow simulation were chosen and the crowns of all trees within the grid cells were reduced by one-third to display the effects of crown reduction on windthrow in the model.

**4.3 Results**

**4.3.1. Stand simulations using TASS**

TASS derived tree-lists were similar to the actual STEMS data based on height and DBH (Table 4.7). However, pre-harvest stand and stock tables differed (Figures 4.6 and 4.7).
Table 4.7. Comparison of TASS-simulated and actual plot trees by treatment.

<table>
<thead>
<tr>
<th></th>
<th>TASS-Simulated</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td><strong>Height (m)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate Retention</td>
<td>28.7</td>
<td>9.2 – 35.8</td>
</tr>
<tr>
<td>Commercial Thinning</td>
<td>28.7</td>
<td>10.8 – 35.5</td>
</tr>
<tr>
<td>Dispersed Retention</td>
<td>28.7</td>
<td>10.1 – 35.8</td>
</tr>
<tr>
<td><strong>DBH (cm)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate Retention</td>
<td>24.7</td>
<td>6.5 – 57.3</td>
</tr>
<tr>
<td>Commercial Thinning</td>
<td>24.7</td>
<td>7.2 – 55.4</td>
</tr>
<tr>
<td>Dispersed Retention</td>
<td>24.8</td>
<td>7.8 – 52.3</td>
</tr>
</tbody>
</table>

Figure 4.6 Pre-harvest stand tables for STEMS plot data (1-3a) and TASS simulations (1-3b) for Aggregate Retention (row 1), Dispersed Retention (row 2) and Commercial Thinning (row 3) treatments. Douglas-fir (grey), western redcedar (black), western hemlock (white).
The leading species, Douglas-fir, follows a generally normal distribution for both the TASS-simulated trees and the plot data at STEMS. However, the plot data show that there is more volume in the smallest and largest diameter classes compared to the simulated tree-lists (Figure 4.7). There are also more stems of western redcedar and western hemlock in the small diameter classes that were not represented in the TASS-simulated tree-lists (Figure 4.6). Direct comparisons of the distributions with respect to height were not made because height was not recorded for every tree in the plots. As a result, differences in windthrow...
outcomes might be due to the use of simulated tree-lists. However, simulations were also run using actual tree-lists augmented by TASS-generated spatial positions, since spatial locations of trees were not recorded on the STEMS plots.

4.3.2. Wind speeds for study area and model sensitivity to varying wind speeds

Most of the strong winds occur in the winter months and originate from the southeast direction for this study area. The three strongest peak winds in the past 10 years originated from approximately 130 degrees (+/- 5 degrees) and occurred in February 1999 (102 km/h), December 2002 (113 km/h) and November 2007 (115 km/h) (Figure 4.8).

![Figure 4.8. 10-year peak gust wind record at Comox Airport for wind speed (■) and direction (▲).](image)

The dominant direction of fall represented by the wind rose in the northwest direction indicates that most of the damaging winds occurred from the southeast (Figure 4.9).
Several windthrow simulations were run at wind speeds within the range of the highest wind speeds recorded at Comox during the period 2000 to 2010. This resulted in large changes in the amounts of windthrow damage (Table 4.8). This sensitivity analysis to wind speed indicates the importance of this input to the windthrow model. Since the meteorological station at Comox is adjacent to open water and STEMS is inland, the highest recorded wind speeds (e.g. 115.2 km/h) were not expected to extend as far inland as the STEMS site. Thus the lower value of 100.8 km/h was considered representative of the best available estimate of the highest wind speed to cause windthrow at the site and was used for all subsequent simulations.
Table 4.8. Numbers of windthrown trees using TASS-generated tree-lists over a range of wind speeds by treatment.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>24 m/s (86.4 km/h)</th>
<th>26 m/s (93.6 km/h)</th>
<th>28 m/s (100.8 km/h)</th>
<th>30 m/s (108.0 km/h)</th>
<th>32 m/s (115.2 km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregated Retention</td>
<td>14</td>
<td>19</td>
<td>27</td>
<td>44</td>
<td>70</td>
</tr>
<tr>
<td>Dispersed Retention</td>
<td>16</td>
<td>18</td>
<td>23</td>
<td>31</td>
<td>46</td>
</tr>
<tr>
<td>Commercial Thinning</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>9</td>
</tr>
</tbody>
</table>

The numbers of simulated trees were compared to the actual numbers of windthrown trees from the field plots based on an input wind speed of 100.8 km/h (Table 4.9). Taking account of the sampling error for the plot data, the numbers of windthrown trees in the simulation for the Aggregate Retention treatment were similar to the observed damage in the field. However, fewer trees were windthrown in the simulations for the Dispersed Retention treatment than were observed in the field, and many fewer trees were windthrown in the simulation for the Commercial Thinning treatment than were observed in the field.

Table 4.9. Mean numbers of windthrown trees from STEMS plot data.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. Plots</th>
<th>Windthrown Trees (stems/ha)</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregated Retention</td>
<td>11</td>
<td>55</td>
<td>19</td>
</tr>
<tr>
<td>Dispersed Retention</td>
<td>19</td>
<td>32</td>
<td>3</td>
</tr>
<tr>
<td>Commercial Thinning</td>
<td>12</td>
<td>71</td>
<td>24</td>
</tr>
</tbody>
</table>

The importance of the windspeed model input is further emphasized when windthrow is shown by species and treatment (Figure 4.10).
4.3.3. Validation and sensitivity analyses using TASS-generated tree-lists

As noted in the methods, all trees were cut within the treatment areas for the clearcut treatment. As a result, windthrow can only occur outside the treatment boundaries. However, the areas of windthrow were field-mapped along the edges (Figure 4.11).
Figure 4.11. Extent and distribution of windthrow around the opening in the clearcut treatment. Windthrow was not recorded or mapped in the reserve patch (from de Montigny 2004).

Therefore, the spatial distributions of windthrow along edges were simulated for two windspeeds and directions (86 km/h from the northwest and 101 km/h from the southeast) for the Clearcut treatment area to show sensitivity of damage to wind speeds and directions represented by the meteorological data (Figures 4.12 and 4.13).

Figure 4.12. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of an 86 km/h northwest (315 degrees) wind in WindFIRM/ForestGALES_BC for clearcut treatment.
Figure 4.13. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of a 101 km/h southeast (135 degrees) wind in WindFIRM/ForestGALES_BC for clearcut treatment.

Geo-referencing was used to overlay the mapped windthrow along the edges and the simulated predictions using the meteorologically based windspeeds of 86 km/h from the northwest and 101 km/h from the southeast in ArcGIS (Figure 4.14).

Figure 4.14. Overlay of edge windthrow survey and simulated windthrow 86 km/h northwest and 101 km/h southeast winds in the Clearcut with reserves treatment for both the southeast and northwest directions (TASS-simulated standing trees = blue; TASS-simulated windthrown trees = yellow).
The general distribution of windthrow appears consistent with the edge survey and with what would be expected given the relative exposure of trees around the opening.

WindFIRM/ForestGALES_BC simulations were also sensitive to wind speed and direction in the Aggregate Retention treatment (Figures 4.15 and 4.16). For example, most of the damage was concentrated along downwind edges and patches which had the higher fetch values in the direction of the wind.

![Figure 4.15](image)
Figure 4.16. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of 101 km/h of southeast wind in WindFIRM/ForestGALES_BC for Aggregate Retention treatment.

The distribution of simulated windthrow for 86 km/h northwest and 101 km/h southeast winds within and around the opening appears reasonable when compared with the edge survey (Figure 4.17).
Figure 4.17. Overlay of edge windthrow survey and simulated windthrow for 86 km/h northwest and 101 km/h southeast winds in the Aggregate Retention treatment. 

Also, tree-level windthrow data were available for the Aggregate Retention treatment (Figure 4.18). Therefore, a further comparison was possible between simulated results and the percent of windthrown trees in the field.
Figure 4.18. Percent windthrow by plot based on STEMS field plot data in the Aggregate Retention treatment. Plots with no colour did not have trees.

The quantity of simulated windthrow (Figure 4.17) appears higher that what was indicated by the field data (Figure 4.18), especially in the northern part of the treatment unit where there are higher fetch values and for grid cells that have a less regular spatial distribution. To illustrate the within-cell spacing effect on windthrow, Figure 4.19 shows two grid cells where, trees in both grid cells have roughly the same inter-tree spacing, but the numbers of trees differ.
Since the model calculates spacing across the entire area of the grid cell (625 m$^2$), the stand on the right of Figure 4.19 has a mean inter-tree distance of 12.5 m whereas the stand on the left has an mean inter-tree distance of 3.0 m (Table 4.10). Wider spacing means that more of the above canopy wind speed profile drops into the stand and applies a higher wind loads on the trees (see Section 2.3.6.). The number of stems within a grid cell affects the calculated spacing and canopy top wind speed; therefore, some partially populated grid cells experience larger than expected simulated damage, even on leeward edges.

<table>
<thead>
<tr>
<th></th>
<th>Left grid cell (Figure 4.19)</th>
<th>Right grid cell (Figure 4.19)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stems</td>
<td>69</td>
<td>4</td>
</tr>
<tr>
<td>Mean Spacing (m)</td>
<td>3.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Canopy top wind speed (km/h)</td>
<td>36</td>
<td>54</td>
</tr>
</tbody>
</table>

The same simulations were run for the Dispersed Retention treatment to demonstrate the sensitivity to wind direction and show how trees which are sheltered by the upwind timber edge do not get damaged demonstrating sensitivity to wind direction (Figures 4.20 and 4.21). Also note that nearly all the trees away from the edge in the opening were windthrown.
Figure 4.20. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of 101 km/h of southeast wind in WindFIRM/ForestGALES_BC for Dispersed Retention treatment.

Figure 4.21. Harvested (yellow), windthrown trees (red) and live standing trees (green) after simulation of 86 km/h of northwest wind in WindFIRM/ForestGALES_BC for Dispersed Retention treatment.
An overlay of simulated windthrow for 86 km/h northwest and 101 km/h southeast winds was used to compare the distribution and penetration of modelled windthrow with edge survey results (Figure 4.22).

Figure 4.22. Overlay of edge windthrow survey and simulated windthrow for 86 km/h northwest and 101 km/h southeast winds in the Dispersed Retention treatment.

The number of isolated trees is accentuated in the Dispersed Retention treatment when compared to the Aggregate Retention. The amount of simulated damage in the Dispersed Retention appears much higher within the opening when compared to the percent windthrow in the field plots (Figure 4.23). As noted, nearly all the trees away from the sheltering influence of the edge were windthrown whereas the plots show a wider variation of damage.
The graphical displays of simulated windthrow in the Aggregate Retention (Figure 4.17) and Dispersed Retention (Figure 4.22) treatments indicate that more trees are windthrown within the opening when compared to the distribution of windthrow among plots for the respective treatments (Figures 4.18 and 4.23). However, the edge surveys only recorded the area of windthrow penetration and did not include plots in the buffer zone around the treatment units to quantify windthrow in these areas at the tree level. Therefore, treatment level comparisons between simulated and actual windthrow assumed the simulation encompassed the harvested block and a zone around the edge and that the field plot data represents windthrown stems per hectare across the same area within and around the block. Based on this assumption, the distribution of damage across the treatments is different between simulated windthrow and actual windthrow from the field plots (Table 4.11).
Table 4.11. Windthrow simulation results (stems/ha) for Aggregate Retention (AR), Dispersed Retention (DR) and Commercial Thinning (CT) treatments using only TASS-simulated trees, for a 101 km/h above canopy southeast wind.

<table>
<thead>
<tr>
<th></th>
<th>AR</th>
<th>DR</th>
<th>CT</th>
<th>Total</th>
<th>T(_{\text{calculated}})</th>
<th>T(_{\text{critical}})</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td>16</td>
<td>23</td>
<td>1</td>
<td>40</td>
<td>32.0</td>
<td>5.991</td>
<td>(T_{\text{calc}} &gt; T_{\text{crit}}) : Reject H(_0)</td>
</tr>
<tr>
<td>Actual</td>
<td>53</td>
<td>32</td>
<td>71</td>
<td>158</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(T_{\text{critical}}\) at the 95% confidence level.

Contingency tables were used to compare simulated and actual windthrow (stems/ha) for each class variable including treatment and species (Table 4.12). There was also a difference between simulated and actual windthrow by species in the Aggregate Retention treatment (\(\alpha = 0.05\)). The Chi-Square test is not an appropriate test for contingency tables that have cells with expected counts less or equal to 5 (Conover 1980), and was therefore not used for Retention and Commercial Thinning treatments. However, it appears that WindFIRM/ForestGALES_BC under-represented windthrow at the simulated wind speed (101 km/h). The predictions were closer for the Dispersed Retention treatment but still lower compared to actual windthrow.
Table 4.12. Summary results (windthrown stems per hectare) for species in each treatment due to a 101 km/h southeast wind.

<table>
<thead>
<tr>
<th></th>
<th>$Fd$</th>
<th>$Cw$</th>
<th>$Hw$</th>
<th>Total</th>
<th>$t_{calculated}$</th>
<th>$t_{critical}$</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aggregate Retention</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted</td>
<td>15</td>
<td>0</td>
<td>1</td>
<td>16</td>
<td>10.0</td>
<td>5.991</td>
<td>$t_{calc} &gt; t_{crit}$ : Reject $H_0$</td>
</tr>
<tr>
<td>Actual</td>
<td>42</td>
<td>12</td>
<td>15</td>
<td>54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>42</td>
<td>12</td>
<td>16</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dispersed Retention</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted</td>
<td>20</td>
<td>2</td>
<td>2</td>
<td>24</td>
<td>3.6</td>
<td>5.991</td>
<td>*See note</td>
</tr>
<tr>
<td>Actual</td>
<td>31</td>
<td>1</td>
<td>0</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>51</td>
<td>3</td>
<td>2</td>
<td>56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Commercial Thinning</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.8</td>
<td>5.991</td>
<td>*See note</td>
</tr>
<tr>
<td>Actual</td>
<td>39</td>
<td>25</td>
<td>7</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>40</td>
<td>25</td>
<td>7</td>
<td>72</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The approximate value of $\alpha$ is a good estimation of the true value of $\alpha$ if the expected number of observations in each cell is large. If any of the number of expected observations is small (i.e. < 5) then the approximation is poor. The Dispersed Retention had one expected observation which was small and Commercial Thinning had multiple expected values of less than one.

** $t_{calc}$ at the 0.05 significance level.

$Fd$ = Douglas-fir, $Cw$ = western redcedar, $Hw$ = western hemlock.

WindFIRM/ForestGALES_BC simulations in the Commercial Thinning yielded very low levels of windthrow which were difficult to detect in the images. However, there was enough simulated damage to use cumulative frequency distributions to assess differences in the recorded windthrow in field plots and simulated windthrow in the simulations.

Cumulative frequency distributions were used to compare simulated and actual windthrow with respect to the continuous variables height, DBH and height to DBH ratio (Figures 4.24 – 4.26). The distribution functions for five simulated wind speeds in the range of interest (86 – 115 km/h) were included to test sensitivity to wind speed. Where there was a visible separation among the simulated windthrow distribution functions, for different wind speeds,
the trend was that the simulated cumulative frequency distributions moved closer to the actual windthrow distribution function with increasing wind speed. The statistical analyses were based on simulations with a wind input of 101 km/h from the southeast (135 degrees).

Figure 4.24. Cumulative proportional frequency distributions of recorded windthrow (◊, solid line) from field plots at STEMS and simulated windthrow (⋯) at windspeeds of 86 (+), 94 (●), 101 (x), 108 (□), and 115 (Δ) km/h from the southeast in ForestGALES_BC/WindFIRM (with respect to height).
Figure 4.25. Cumulative proportional frequency distributions of recorded windthrow (◊, solid line) from field plots at STEMS and simulated windthrow (⋯) at windspeeds of 86 (+), 94 (☆), 101 (x), 108 (□) and 115 (Δ) km/h from the southeast in ForestGALES_BC/WindFIRM (with respect to DBH).
Figure 4.26. Cumulative proportional frequency distributions of recorded windthrow (◊, solid line) from field plots at STEMS and simulated windthrow (····) at windspeeds of 86 (+), 94 (*), 101 (x), 108 (□) and 115 (Δ) km/h from the southeast in ForestGALES_BC/WindFIRM (with respect to height to diameter ratio).

Differences in the distribution functions were statistically evaluated based on the Kolmogorov-Smirnov test which is a measure of greatest distance between two functions.
The null hypothesis states that cumulative distribution function is the same for the simulation as it is for the field plots for all $x$’s in the function (Table 4.13).

Table 4.13. Summary of Kolmogorov-Smirnov test results.

<table>
<thead>
<tr>
<th>N</th>
<th>$t_{\text{calculated}}$</th>
<th>$t_{\text{critical}}$</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aggregate Retention</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>5</td>
<td>0.378</td>
<td>0.563</td>
</tr>
<tr>
<td>DBH</td>
<td>7</td>
<td>0.427</td>
<td>0.483</td>
</tr>
<tr>
<td>Height : DBH</td>
<td>8</td>
<td>0.607</td>
<td>0.454</td>
</tr>
<tr>
<td><strong>Dispersed Retention</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>4</td>
<td>0.092</td>
<td>0.624</td>
</tr>
<tr>
<td>DBH</td>
<td>7</td>
<td>0.266</td>
<td>0.483</td>
</tr>
<tr>
<td>Height : DBH</td>
<td>7</td>
<td>0.476</td>
<td>0.483</td>
</tr>
<tr>
<td><strong>Commercial Thinning</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>6</td>
<td>0.238</td>
<td>0.519</td>
</tr>
<tr>
<td>DBH</td>
<td>10</td>
<td>0.738</td>
<td>0.409</td>
</tr>
<tr>
<td>Height : DBH</td>
<td>9</td>
<td>0.881</td>
<td>0.430</td>
</tr>
</tbody>
</table>

* $t_{\text{critical}}$ at the 0.05 significance level.

4.3.4. Validation and sensitivity analyses using field tree-lists

As noted earlier, there was some variation in the accuracy of the representation of plot trees using TASS-simulated trees. More simulated windthrow occurred in tree-lists populated with TASS-simulated trees than those populated with actual tree-lists from the plot data. Therefore, further comparisons were used to explain differences in windthrow levels. Means for selected plots were calculated and compared between TASS-simulated trees and actual trees (Table 4.14). The mean DBH for TASS-simulated trees was similar to mean DBH from the plot data at two locations (Plots 10 and 11) and the mean height of TASS-simulated trees was similar to the mean height from Plot 25. TASS-simulated trees have smaller DBH’s and larger heights than field plot trees where there were differences (t-test; $\alpha = 0.05$) between the means of TASS-simulated versus field plot tree-lists. The mean height-to-DBH ratio for
TASS-simulated trees was significantly different than the mean height-to-DBH ratio in all field plot trees.

Table 4.14. Summary of differences and similarities between the plot trees (STEMS) and TASS-simulated trees for all trees in Plots 10, 11 and 25.

<table>
<thead>
<tr>
<th>Plot 10 (n=17 trees)</th>
<th>Mean Height (m)</th>
<th>Mean DBH (cm)</th>
<th>Mean Ht/DBH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot Data (STEMS)</td>
<td>20.8 a</td>
<td>26.9</td>
<td>80.7 a</td>
</tr>
<tr>
<td>Sim. Data (TASS)</td>
<td>29.0 b</td>
<td>22.4</td>
<td>131.9 b</td>
</tr>
<tr>
<td>Plot 25 (n=23 trees)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plot Data (STEMS)</td>
<td>30.6</td>
<td>38.3 a</td>
<td>84.1 a</td>
</tr>
<tr>
<td>Sim. Data (TASS)</td>
<td>28.7</td>
<td>24.3 b</td>
<td>120.1 b</td>
</tr>
<tr>
<td>Plot 11 (n=49 trees)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plot Data (STEMS)</td>
<td>23.4 a</td>
<td>28.6</td>
<td>87.3 a</td>
</tr>
<tr>
<td>Sim. Data (TASS)</td>
<td>29.3 b</td>
<td>25.1</td>
<td>120.7 b</td>
</tr>
</tbody>
</table>

* Different letters indicate significant differences between plot and TASS-simulated tree data.

All the TASS-simulated trees in Plot 10 were windthrown for an above canopy wind of 101 km/h from the southeast whereas the field plot data shows that 42% were windthrown at this location. WindFIRM/ForestGALES_BC allows the user to condition the wind field and wind profiles at the grid cell level using the TASS-simulated trees, substitute in real trees for any location of interest and overlay the results. To test this process, the TASS-simulated trees were replaced with actual trees from STEMS field plot data in the textfile which was re-run through the model to compare windthrow results for TASS-simulated trees and field plot trees at that location only (Figure 4.27).
The same substitution was done at Plot 25 to compare windthrow of TASS-simulated trees and field plot trees at the same wind speed from the same direction (Figure 4.28). More TASS-simulated trees were windthrown than the replacement trees from the field plot in the windthrow model simulation. In reality, 53% of the trees at Plot 25 were windthrown at this location. Text files of tree-lists’ dendrometric data were listed with damage status and compared in table format for TASS-simulated and real tree replacements (Appendix 2).
The orientation of some windthrown trees in the field plots indicated the damaging wind originated out of the northwest (Figure 4.10). All the windthrown trees in Plot 11 were oriented in an east to southeast direction. Therefore, the model was run with a northwest wind (315 degrees) at several wind speeds up to 115 km/h until some damage occurred in the plot location (Figure 4.29). The grid cell at the plot location required a higher than expected wind speed (115 km/h vs. 86 km/h) from the northwest to produce damage.
Another factor that was analyzed in the simulations was the effect of crown modification in the Dispersed Retention treatment. Most of the trees in the Dispersed Retention treatment were windthrown in the simulations while the plot data indicates a higher level of survival. Therefore, tree-lists were modified in select grid cells where most or all of the trees were windthrown in the initial simulation. Since crown length is the input variable which determines the crown frontal area in WindFIRM/ForestGALES_BC, crown length was reduced up to 50% for all the trees in the selected grid cells to emulate the spiral pruning treatment, which removed 30 to 50% of the crown area, that was carried out on 15 to 20 stems per hectare of retained trees at STEMS (de Montigny 2004). The amount of crown removed in the model is, in reality, much higher than 50%. However, because the crown
length is the only variable available for adjustment, the crown removal occurs in the lower
crown where the wind speeds are lower. The model was re-run after the crown modifications
and fewer trees were windthrown (Table 4.15); however the level of predicted damage is still
higher than actual damage. Specific tree-level pre and post-pruning conditions and the
related change in tree status were also compared for each grid cell in tabular form (Appendix
3).

Table 4.15. Simulation of 101 km/h southeast wind in Dispersed Retention treatment with insets
showing results from grid cells where one-third of the crown length was removed for all trees.

<table>
<thead>
<tr>
<th>Nearest Plot</th>
<th>Total Trees</th>
<th>Windthrown Trees</th>
<th>Grid Cell #</th>
<th>Total Trees Pre-pruning</th>
<th>Windthrown Trees Pre-pruning</th>
<th>Total Trees Post-pruning</th>
<th>Windthrown Trees Post-pruning</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-20</td>
<td>5</td>
<td>2</td>
<td>150</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3-19</td>
<td>4</td>
<td>0</td>
<td>293</td>
<td>11</td>
<td>7</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3-3</td>
<td>6</td>
<td>4</td>
<td>393</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3-11</td>
<td>6</td>
<td>4</td>
<td>563</td>
<td>16</td>
<td>16</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

4.4 Discussion

The direction of damaging winds was consistent with the synoptic conditions which generate
high wind speeds on the east coast of southern Vancouver Island. During the winter months
a continual flow of extra-tropical low pressure systems move east from the Pacific Ocean
across western North America (Environment Canada 1992). Strong southeast winds at the
leading edge of these weather systems flow unobstructed over the water of Georgia Strait
(Figure 4.4). Where there is a large surface pressure gradient between the low pressure
centre and a high pressure system following it, strong northwesterly winds may develop in its
wake. However, there is a significant mountain range to the west which partially shelters the
STEMS area from northwesterly winds.
WindFIRM/ForestGALES_BC has important advancements in the capacity of mechanistic windthrow models to represent real-world complexity in site and stand conditions, and to more realistically represent the process of damage propagation in stands during strong wind events. The model is capable of simulating windthrow in irregular openings and retention patterns, using spatial tree-lists. If desired, the dendrometrics of individual trees can be edited within the tree-list to customize species mixes, heights and diameters and match them to trees measured in field plots. Crown dimensions can also be modified in the tree-list to account for the effects of pruning on crown frontal area reduction. Options are available in WindFIRM/ForestGALES_BC to create new harvest areas and apply partial harvest and retention treatments. It is also possible to thin stands from above or below to user-specified thresholds (i.e. thin 50% of basal area by taking out smallest trees). Shapefiles and text files of input data or simulation results can also be created for use in spatial or tabular analysis.

Simulation results for STEMS show that WindFIRM/ForestGALES_BC is sensitive to wind speed and direction, and can characterize wind damage within and adjacent to partially harvested or clearcut treatment units. The pattern of simulated windthrow around the edges of the treatment units at STEMS appears reasonable compared to the pattern of actual windthrow that was mapped in the edge surveys in the field. The addition of field plots in a buffer zone around each treatment would improve the veracity of future model validations by providing tree level data to quantify tree loss rates around the opening. The simulations highlight the reality that the creation of harvest openings in the canopy increases wind loading and potential for windthrow of trees outside of the treatment unit as well as within the unit. Running a simulation of a proposed silviculture system experiment would help
researchers predict potential windthrow outcomes, and design efficient experimental protocols for monitoring these outcomes within, and at the edges of treatment units.

It was noticed that, with the exception of the Commercial Thinning treatment, more trees were predicted to blow down within the openings than was observed in the field plots. However, it could be that fewer were predicted to blow down around the edges than in the field based on the area of damage from the edge surveys. This could be confirmed with field plots in the buffer zones around the treatments which record windthrow at the tree level. Future validation could also include simulations to reflect that cumulative damage may have occurred from several windstorms over many years.

At the highest speed tested (115 km/h), simulated windthrow within the block is greater than what the field plots indicate in the aggregate and Dispersed Retention treatments. For example, most of the trees in the Dispersed Retention blew down in the simulation except for those in the immediate shelter of an upwind edge. However, the plot data in the Dispersed Retention shows a wider range in the percent of windthrow across the treatment unit. There were also some patches within the Aggregate Retention unit that showed more simulated windthrow than what the field plots indicated. There are at least two reasons for this. The first reason is that boundary edges which cut across grid cells create a scenario where the model calculates artificially high spacing distances (Figure 4.19).

It is possible to represent the edge at the grid cell resolution (i.e. 25m X 25m) but that obscures the true nature of the boundary edge. Therefore, the preferred path was to retain the more accurate treatment layouts. In future model refinements, it will be necessary to add new
algorithms to resolve this issue in partially populated grid cells along treatment unit edges. One limit to implementing these new algorithms will be computational speed. In the STEMS scenarios, there were up to 70,000 trees in each simulation and thousands of these could require secondary calculations in partially populated grid cells. Most simulations took approximately 5 minutes to run.

A second major reason for more simulated windthrow than recorded windthrow in the openings is differences in the dendrometrics of TASS and actual (STEMS) trees used in the tree-lists. The stand and stock tables used to compare TASS-simulated trees and plot trees showed a general similarity with respect to the distribution of stems and volumes across the DBH classes. However, there were more small trees and large trees in the field plots than were present in the TASS-derived tree-list for STEMS. Therefore, it appears the distributions of TASS-simulated trees do not capture the tails of the actual size class distribution at STEMS and over-represents the middle classes to compensate. This could be resolved by randomly substituting small and large trees into the TASS-simulated tree-list to more closely reflect the actual stand. Currently this is a manual process. The plot-level accuracy of the windthrow predictions improved after making these substitutions (Table 4.15). The comparisons made between plot trees and TASS-simulated trees at these plot locations revealed that TASS-simulated trees had larger height-to-diameter ratios than the plot trees of similar diameter which would also explain the higher simulated windthrow in the opening. The model predictions are consistent with empirical studies which find that trees with larger height-to-diameter ratios are more susceptible to windthrow and that as retention increases the proportion of windthrow decreases (Burton 2001, Rollerson et al. 2009). It is likely that the larger height to diameter ratios masked any sensitivity to the range
in fetch values in the openings, especially for more isolated trees in the Dispersed Retention. In simulations using lower wind speeds, the proportion of windthrown stems was inversely related to the amount of within block retention (Figure 4.10). The implication of this is that adjustments to the model are required to reflect more sensitivity to opening sizes with lower fetch values.

The ability to substitute TASS-simulated trees with real trees is a powerful feature in WindFIRM/ForestGALES_BC which gives it the capacity to enhance the representation of real stands. This could be automated if individual trees were stem-mapped in plots and listed with x and y coordinates. Another important feature of the model is the ability to modify crown lengths to account for crown modification treatments which are common in BC (Rowan et al. 2003). Model accuracy was improved in the plots where crown lengths were reduced to represent post-harvest spiral pruning in the Dispersed Retention treatment (Table 4.15; Appendix 3). Currently, this crown-length reduction is manual process which could be applied more efficiently if it were automated in the model.

Cumulative frequency distributions were used to compare simulated windthrow and actual windthrow from the plots for tree size and form variables (height, DBH, height-to-diameter ratio). Tree height shows the best fit between predictions and outcomes across all treatments. Among the different treatments, the Dispersed Retention showed the best fit with respect to height (Figure 4.24). The Aggregate Retention cumulative frequency distribution function for the simulated windthrow was slightly different than for the field plot data where a higher proportion of shorter trees were damaged. This is due to the fact although smaller trees were retained in the aggregates in the field experiment, very few short trees are present in the
TASS-derived tree-lists. The Dispersed Retention and Commercial Thinning treatments do not show this discrepancy, presumably because most of the shorter trees were harvested. Snow press was recorded at STEMS for regeneration but was not specified as a damage agent for residual trees. Snow damage is a potential source of damage and differentially affects smaller and more slender trees on some BC sites (Huggard et al. 1999). It is uncertain whether the smaller trees at STEMS failed due to windthrow or snow press, but periodic wet snow events do occur in coastal BC (Karl et al. 1993). Despite these differences, the model is accurate in characterizing the relative susceptibility of trees of different tree height classes across a range of retention treatments (Table 4.13).

The shapes of the cumulative distribution functions for simulated and recorded windthrow with respect to diameter were similar, but windthrow commenced in lower diameter classes for TASS-simulated trees (Figure 4.25). Consequently, the model predicts that trees in the lower diameter classes are more susceptible to windthrow than the field plot data indicate. This could be because smaller diameter trees in the TASS-simulated tree-lists were, on mean, taller than field plot trees with a similar diameter (Table 4.7). However, given the similarity in the shapes of the functions, it may be possible to calibrate the model to reflect the differences in TASS-simulated and plot trees. The only treatment which showed a significant difference in the distribution functions was the Commercial Thinning treatment (Table 4.13). This may be due to a combination of the presence of more large trees in the field plot data than the TASS-simulated data and the individual tree selection process in the Commercial Thinning treatment which increased the relative proportion of large trees.
Cumulative distributions by height to diameter ratio showed the poorest fit using the Kolmogorov-Smirnov test (Table 4.13). The hypothesis that the cumulative distribution functions were significantly different in the Dispersed Retention treatment could not be rejected but it was a borderline result. The graphs of the functions show more windthrown trees with lower height to diameter ratios in the recorded data than in the simulations. This makes sense given that the mean height to diameter ratio of TASS-simulated trees was significantly larger than plot trees in the selected locations used for substitution (Table 4.14). Trees with lower height to diameter ratios were not windthrown in the TASS-simulated tree-lists simply because fewer trees existed with those dimensions.

It is also important to consider how tree size distributions affect the calculation of the vertical wind speed profile. The most important variable to correctly capture is tree height because it controls the zero-plane displacement where the wind profile changes from an exponential to a logarithmic relationship. The mean height of TASS-simulated trees was approximately 3 to 5 metres taller than field plot trees (Table 4.7). The implications of this are that the exponential part of the wind profile extends higher resulting in lower wind speeds with height. Another important variable that comes from the TASS-simulated tree-list is the mean spacing. The wind speed decreases with increased stand density as noted in Chapter 1. The stand table comparison shows that TASS-simulated stands have more stems per hectare than actual stands. While it is true that there are some high numbers of trees in the smallest diameter classes in the field plots, these trees are generally in the understory and do not have much impact on the wind profile.
It was also noted that as the wind speed was increased, the cumulative distribution function for simulated windthrow moved closer that of recorded windthrow. The spread was most pronounced in the treatment units where more discrimination was used to select trees for retention in the field. For example, leave trees in the Dispersed Retention and Commercial Thinning were selected specifically to minimize windthrow, so trees with better than mean slenderness ratios, free of defects and growing on good microsites were selected (de Montigny 2004). The automated harvest functions in WindFIRM/ForestGALES_BC provide less control over selection of trees based on attributes, and the real-world variability in tree attributes is not represented in the TASS-derived tree-lists. Simulation results are more accurate for the Aggregate Retention where there is no discrimination regarding leave trees and the retained trees represent the stand profile within the retained aggregates. Replacement of TASS-simulated trees with trees that better represent the size and form attributes of actual plot trees improved predictions. Presumably it would further improve predictions if the substitution occurred across the entire treatment unit and adjacent stands, rather than just at the plot-level.

Predicted windthrow was significantly less than recorded windthrow for at least one treatment unit given 101 km/h wind speed from the southeast (Table 4.11). Predicted windthrow by species was also lower than the recorded outcomes (Table 4.12). Higher input wind speeds could have been chosen to create more damage but this would not have been consistent with what is expected for the area. Even though the maximum peak wind speed recorded at Comox airport was 115 km/h it was assumed, for analysis purposes, the peak wind speed at the STEMS site was closer to the mean of the top ten wind events at Comox given that it is not as close to the open water of the Strait of Georgia.
There was a greater discrepancy between the predicted and observed levels of windthrow in the Dispersed Retention and Commercial Thinning treatments compared to the Aggregate Retention treatment. Another potential source of this error is the fetch function used to adjust the wind loading. The model is not very sensitive to the low fetch values in the Commercial Thinning treatment. The relationship between upwind retention conditions and experienced wind loading is complicated (Clark and Mitchell 2007). The VRFetch function in WindFIRM/ForestGALES_BC is based on the assumption that wind loading (as indicated by the proportion of stems windthrown) increases linearly with increasing fetch up to some threshold value of fetch. It is true that a function related to the proportion of windthrow is distinct from one related to mean wind loading. In fact, the empirical equation in ForestGALES_BC underestimates the effects of VRFetch on the ratio of maximum to mean moment by as much as 50% (Mitchell and Byrne 2009). However, it was considered a good starting point and an effective placeholder until equations that calculate crown loading instead of proportion of damage with respect to fetch can be incorporated into the model. The higher number of retained trees also reduce the within stand wind speed when compared to the wider spaced Dispersed Retention treatment. Tree-to-tree collisions where one tree knocks over its neighbour are not reflected in the model (Schelhaas et al. 2007). Resistance equations for western redcedar and western hemlock are based on tree winching data from a coastal site in the same biogeoclimatic zone. The drag and resistance equations for western redcedar and western hemlock used in WindFIRM/ForestGALES_BC are supported by very low root mean square errors and high correlation coefficients (Byrne 2005). However, the resistance function of the primary species at STEMS, Douglas-fir, is based on tree winching data for juvenile trees in the interior of BC. It is possible that the resistance equation used for Douglas-fir is not transferrable to a coastal site. Other sources of variability that are not
calculated in the model include the effects of local soil conditions and rooting strength. Data from studies related to rooting and soil strength along with the rooting characteristics on sloped and flat terrain can be incorporated into future versions of WindFIRM/ForestGALES_BC (Nicoll et al. 2006). Adjustment factors in the literature related to important factors such as variable terrain, soil and rooting conditions in British Columbia will be a reasonable place to start if they can be provided as spatial layers.

A new method of calculating local windiness due to local topographic effects will also improve the veracity of the model. DAMS (Detailed Aspect Method of Scoring) is used to characterize local windiness in the UK (Quine and White 1993). However, BC requires a system that can account for the sheltering effects of steep and highly variable topography in combination with the new ability to simulate the effects of wind from variable directions. This can be partially accomplished through the use of numeric weather model predictions to condition local above canopy wind speeds (Mitchell et al. 2008); however, the resolution of these numerical weather predictions needs to be fine enough to account for local terrain complexity. A system analogous to the DAMS system could be used to estimate local wind speeds at a higher resolution than what is provided by numerical weather prediction models.

This is an early validation of WindFIRM/ForestGALES_BC which is intended to demonstrate the capacity and flexibility of the model, determine the direction and magnitude of future calibrations and highlight knowledge gaps to guide future research needs. New data and technological advances (e.g. computing power) will serve to greatly enhance the accuracy of WindFIRM/ForestGALES_BC predictions. Silviculture systems trials such as STEMS are well suited for validation because they offer large sets of field plot data and
represent a range of treatments and stand conditions. These data could be improved by the inclusion of local weather data, and more plot data around the perimeter of the treatment units. Since WindFIRM/ForestGALES_BC works with spatial tree-lists, stem mapping in the field plots would also be useful data to have for future validations. More representation of small trees and dominant trees in the TASS generated tree-list would also contribute to the veracity of the model simulations. Any future changes to WindFIRM/ForestGALES_BC should be accompanied by ongoing validation of results and sensitivity analyses of function parameters.

The nature of the field data from STEMS makes a thorough validation problematic at this time. For example, quantitative data was only recorded for plot locations within each treatment unit when it is clear that treatment induced windthrow extended beyond the treatment unit boundaries. For example, there is no quantitative windthrow data from plots in the clearcut treatment (Table 4.3) where it is clear that treatment induced windthrow has occurred around the edges (Figure 4.11). While some qualitative edge surveys were completed, the data collected were insufficient to compare modelled and actual tree-level windthrow along cutblock edges. Despite these limitations, qualitative comparisons between the simulated windthrow maps and mapped areas of windthrow from the edge surveys and proportion of damage in each plot were useful in assessing the accuracy of the location and extent of windthrow which could be useful in forest management planning. It was also possible to verify the capacity of the model to be sensitive to wind direction and compare simulated and actual windthrow results to determine over or under prediction and to inform the direction and magnitude of future model development.
4.5 Conclusions

WindFIRM/ForestGALES_BC is a significant step in the evolution of mechanistic windthrow prediction models. Previously developed models are non-spatial and cannot calculate differences in individual tree loading across stands with irregular spatial distributions of harvested trees and variable retention levels within openings. No existing models simulate the propagation of damage during high wind events or make it possible to account for tree-to-tree interactions up to and during failure. This spatial capacity has enabled the simulation of windthrow at the tree level for a wide range of irregular retention levels and patterns which are characteristic of variable retention silvicultural prescriptions.

The use of STEMS data enabled the comparison of modelled windthrow predictions to plot data from one such example of the vertical and horizontal structural complexity which is inherent in variable retention block layouts. The results suggest that the model under-represents windthrow at both the treatment and species level. However, the damage trends are consistent with changes to input wind speed and the progression of damage through the tree-lists follows the expected patterns with respect to individual tree attributes. Future validation datasets which include plots in the buffer zones around treatments in combination with model revisions which were recommended in Chapter 3 will further enhance the accuracy of the model.

WindFIRM/ForestGALES_BC enables the user to customize tree-lists to specific block layouts and display windthrow results in the form of tables, images and shapefiles. The validation exercise for the STEMS experiment illustrates how this could be used in forest
management planning. Multiple scenarios can be simulated to aid in cutblock layout design and the implications of exposure to increasing wind speeds, or multiple wind directions can be evaluated. Like any model of a complex process, WindFIRM/ForestGALES_BC is neither complete nor correct in all respects. The addition of directional windiness functions to adjust for topographic exposure relative to the wind direction and resistance functions which account for site variability related to soils and root structure will further improve predictions. The model has been restructured to incorporate spatial datasets for soils, terrain and wind attributes as these data become available and functions are developed. The next level of future validations could also address cumulative windthrow caused by multiple wind storms once proposed improvements to the model are made.
5.0 Conclusions and Recommendations

Three research questions were set out at the beginning of this dissertation.

1. What spatial and temporal variations of tree, stand and meteorological attributes are required to represent the spatial variation of windthrow and the propagation of windthrow at the tree level in mixed species and multi-storied stands?

2. How can other models (e.g. growth and yield models) and readily available spatial datasets such as tree lists, cutblock boundaries, post-harvest retention levels, topography and wind flow be assembled, normalized and integrated with a tree level mechanistic model?

3. How well does the improved model work for real stand conditions encountered in BC?

The improvements to ForestGALES completed in this research fall into two categories: changes that improve the capacity of the model to represent wind damage processes in stands with complex structures and harvesting treatments; and changes in the program that make it easier to add or modify existing functions and parameterize new scenarios.

WindFIRM/ForestGALES_BC is coded in Python, an open source object-oriented programming language. The logic behind dividing model functions into several objects is to facilitate unit testing and sensitivity analyses of model components before they are re-integrated. These changes were made to directly address the first objective of this research
which was to improve the model structure to test changes to model equations independently from the overall model (i.e. unit test), determine the effects of input variables on windthrow outcomes, help identify knowledge gaps and more easily integrate new equations related to these gaps. The structure of ForestGALES_BC has been designed to easily incorporate new functions that quantify the effects of such factors as decay, stem irregularities on individual trees or the effects of standing dead trees and irregular stands on the wind profile as the data become available from any future wind tunnel or tree winching studies. In the absence of wind profile data for irregular stands, the equations used for regular stands were retained in ForestGALES_BC. Differences in the vertical wind speed profile affect the centre of pressure which is important in the windthrow process. For example, a less dense stand would cause the centre of pressure to drop. However, the empirical equation used to calculate VRFetch partially captures this process.

The changes made to equations in ForestGALES_BC related to dendrometrics enable the model to account for differences in crown and stem attributes between species which affect the wind profile, stem bending and resistance and loading equations. Coupled with new equations that calculate the effects of exposure and gust factors, these changes in critical wind speed outputs which were more realistic compared to empirical studies. This meets the second objective of this research which was to improve windthrow predictions with respect to tree size, gap and gust factor variables.

ForestGALES_BC was changed to calculate the failure of individual trees given an above-canopy input wind speed. Coupled with the integration of spatial tree lists and the ability to alter these tree lists to reflect complex layout scenarios, this enabled the model to simulate
the wind loading effects of wind direction, upwind gaps and the position of individual trees within the canopy. This represents a major step in mechanistic model development and addresses the third and fourth objectives of this research which were to spatially represent mechanistic windthrow results for multiple individual trees and model spatial differences in windthrow across a landscape which are sensitive to wind direction, upwind stand characteristics and individual tree attributes.

WindFIRM/ForestGALES_BC can also be run as an executable in the growth and yield model TASS. This development permits the quantification of wind disturbance on tree level growth and yield simulations which was the fifth objective of this research. Windthrow processes which such as windthrow propagation were also successfully simulated which satisfies the sixth research objective. This was made possible through the use of spatial tree lists to model the effects of adjacency and shelter on the stability of neighbouring trees.

Even though simulated windthrow underestimated actual windthrow at the absolute scale, the “patchiness” of windthrow was represented across the stand as shown by WindFIRM/ForestGALES_BC damage output displayed by shapefiles. Clearly there is more work to do to successfully validate simulated damage with actual damage from field plots. However, the model still enables the analysis of the relative effects of a wide range of forest scenarios and crown modification treatments. Therefore, the seventh objective was partially met in that the model is not yet an absolute predictive tool but can serve forest managers in other ways to assess the relative risk of windthrow. It also serves as a useful tool to identify knowledge gaps and research needs which was the eighth objective.
WindFIRM/ForestGALES_BC is a significant step in the evolution of mechanistic models which calculate stability in forests at the individual tree level. Previous models were non-spatial and could not calculate differences in individual tree loading with vertical position in the canopy and across stands with irregular openings and retention levels within openings. In terms of decision-support, the features available in WindFIRM/ForestGALES_BC enable the user to customize tree lists to specific block layouts and display windthrow results in the form of tables, images and shapefiles. This has important implications to management planning where multiple scenarios may be simulated and compared to aid in cutblock layout design. Specifically, it has been integrated with TASS which TIPSY uses to produce growth and yield projections which presents the opportunity to use the coupled model to explore stand dynamics.

WindFIRM/ForestGALES_BC is a good model framework for integration of new research results. The modular design and use of an open-source programming language allows researchers to add and test model sensitivity to key input variables, new stand or treatment scenarios and identify knowledge gaps. The model was designed to accommodate new stand or treatment scenarios or knowledge by separating important functions into independent but integrated objects to make unit testing easier. This structure will make WindFIRM/ForestGALES_BC a useful research tool to examine the effects of wind and tree interactions in complex terrain and site conditions. While it already serves as a good relative measure of windthrow predictions, the model can improve as a predictive tool with more research to collect data required to improve functions related to local wind velocity and direction in very complex terrain. Mechanical or mechanistic functions related to the mechanics of soil and root interactions would also fill an important knowledge gap related to
the resistance of trees over a range of sites and soil moisture conditions (i.e. wind and high rainfall events). Another important topic is how trees acclimate to changes in the wind regime due to either changes in exposure or changes in peak wind return periods due to climate change. Adjustment factors which quantify the influence of tree sway dynamics and collisions on the applied load will also be very informative.

In summary, there are many components of the windthrow process which are not yet quantified. The advantage of mechanistic models such as WindFIRM/ForestGALES_BC is that they are useful tools for simulations of possible future scenarios. The model structure has been designed with these future scenarios in mind so that when data and functions are available they can be easily programmed into the model. This will also help guide future experiments and provide a framework to organize and prioritize the data requirements. The most critical limiting factor related to increasing the complexity of this model, apart from the expense and logistics of running future experiments, is the computing capacity required to run functions on individual trees within the tree lists. Innovative techniques such as cluster or cloud computing along with ongoing technological improvements should satisfy this requirement.
Bibliography


Bergeron, C. 2004a. ForestGALES regression coefficient additions for black spruce. in, Vancouver.


D'Anjou, B. 2002. Roberts Creek study forest: Harvesting, windthrow and conifer regeneration within alternative silvicultural systems in Douglas-fir dominated forests on the Sunshine Coast. BC Ministry of Forests - Research Branch, Nanaimo, BC.


Green, R. N., and K. Klinka. 1994. A Field Guide to Site Identification and Interpretation for the Vancouver Forest Region. 28, Province of British Columbia; Ministry of Forests, Victoria, BC.


Polsson, K. 2007. Personal communication. BC Ministry of Forests and Range, Victoria, BC.


Appendix 1 – Computer and Software Set-up
Requirements for Operating WindFIRM

A. Remote operation of WindFIRM

The easiest way to run tree lists using the latest version of WindFIRM is to connect remotely to Tim Shannon’s Linux computer at UBC Forestry (computer name: ducky.forestry.ubc.ca). Two executables will need to be downloaded to the local computer to run WindFIRM remotely.


2. Download WinSCP from the following website. http://winscp.net/eng/download.php

Save these programs and run them to open their respective interfaces. It may be most convenient to save these to your desktop then you can simply double-click on their icons to run the programs.

PuTTY

PuTTY.exe is used run WindFIRM on ducky.forestry.ubc.ca from a remote computer. Double-click on the PuTTY.exe icon and you will see the following window pop-up.

Type ducky.forestry.ubc.ca in the Host Name box, and then click Open.

The following window will appear where you will be prompted to login with a username and password (tsuga103). Hit return and it will show that you are now connected to
If you are logging on for the first time with a new username and password, you must type, `getPython.py windfirm`, at the prompt. This needs to be done only once. Then change the directory to where the tree list you would like to run is located (e.g. `cd Data/Juan1`). Note that the directories and file names are case sensitive.

Then run WindFIRM by entering `windfirm.py` in the directory that contains the `tree-list.txt` file you would like to run. The following window will appear. Enter 1 to run the spatial version of ForestGALES_BC and hit return.
Note that it is possible to run the Python version of the original ForestGALES but this version is non-spatial and pre-dates the current one being run in the UK. After selecting ForestGALES_BC the following window appears. You can enter 1 to edit the configuration file (eg. windspeed and direction) and then 5 to do a single run of GALES on a tree list. You can also enter 24 to run GALES in batch mode for a series of scenarios. Currently, batch settings need to be adjusted in the code but work is underway to set up the batch configuration by editing a text file. Once a run is complete post script images (select 11 then hit return) or shapefiles (select 23 then hit return) which graphically represent the output can be generated.
NB – It is easiest to edit the configuration files using WinSCP (next section) not PuTTY.

**WinSCP**

WindSCP is a ftp program which allows users to access and edit files in both the local computer and the remote computer using the same window. You can also copy files from one computer to the other with a simple click and drag. Double-click on the WinSCP icon and the following window appears.
Computer names can also be saved as shown above which speeds up the process of logging in. Click Login and the following window appears.

Enter your password and the following WinSCP interface opens.
The left side of the window is the user’s local computer and the right side is the remote computer (eg. ducky.forestry.ubc.ca). Files are easily transferred by clicking and dragging. All the data and configuration files required by WindFIRM are located in the data directory (eg. in this case: /home/kbyrne/Data/Juan1).

As mentioned, it is easiest to edit the configuration files in the WinSCP environment and use PuTTY only to run the model and generate graphic output and reports. Images (eg. post script images) of the model output are automatically copied to the images directory in the user’s profile (eg. in this case: /home/kbyrne/Data/Juan1/OUT/images). Stand damage reports are copied to the reports directory (eg. in this case /home/kbyrne/Data/Juan1/OUT/reports). Note, reports are copied immediately after a run whereas images must first be generated in the PuTTY interface (eg. enter 11 for post script image of model results) before they are copied to the images directory.

It is easiest to have both the PuTTY and WinSCP interfaces open at the same time while running WindFIRM simulations using the remote method. This makes it quicker to edit and save the configuration file between runs in PuTTY. Note, you may be prompted for your password again before saving the configuration file.

If model results (eg. textfiles, jpegs and shapefiles) do not appear immediately after a run in the WinSCP directories select Remote then Refresh from the main menu. If you have problems viewing jpegs in the remote computer just copy the files into the local computer and open them with your usual viewer.

It is VERY IMPORTANT that the input tree list file is in the data directory (eg in this case: /home/kbyrne/Data/Juan1) is named tree-list.txt. If you wish to run different tree lists it is best to create a new subdirectory for each tree list you wish to run and copy all ancillary files (other than tree-list.txt) from the source data directory. Then run windfirm.py from each
subdirectory representing different tree lists. Each subdirectory would then have a unique tree-list.txt file representing each tree list. The format of the text file (as viewed in most text editors) is also important and must have the following fields as indicated in the following image.

<table>
<thead>
<tr>
<th>ID</th>
<th>AGE</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>SPECIES</th>
<th>HEIGHT</th>
<th>DIBBH</th>
<th>DOBBH</th>
<th>DBCB</th>
<th>DOBCB</th>
<th>DBCC</th>
<th>DOBCB</th>
<th>BA</th>
<th>VOLUME</th>
<th>CRWAREA</th>
<th>CRWLNGT</th>
<th>FOLIARV</th>
<th>SPACING</th>
<th>PFALL</th>
<th>CELL_ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>60</td>
<td>84.1</td>
<td>372.9</td>
<td>0</td>
<td>Fdc</td>
<td>28.7</td>
<td>0</td>
<td>22</td>
<td>7.2</td>
<td>7.8</td>
<td>5.5</td>
<td>5.9</td>
<td>0</td>
<td>0.43</td>
<td>7.1</td>
<td>5.4</td>
<td>9.6</td>
<td>999</td>
<td>0</td>
<td>340</td>
</tr>
<tr>
<td>11</td>
<td>60</td>
<td>133.1</td>
<td>372.9</td>
<td>0</td>
<td>Fdc</td>
<td>30.6</td>
<td>0</td>
<td>25.6</td>
<td>10.7</td>
<td>11.5</td>
<td>8.6</td>
<td>9.3</td>
<td>0.1</td>
<td>0.6</td>
<td>12.1</td>
<td>8.4</td>
<td>17.9</td>
<td>999</td>
<td>0</td>
<td>342</td>
</tr>
<tr>
<td>13</td>
<td>60</td>
<td>216.6</td>
<td>372.9</td>
<td>0</td>
<td>Fdc</td>
<td>31.2</td>
<td>0</td>
<td>31.5</td>
<td>13.4</td>
<td>14.4</td>
<td>10.9</td>
<td>11.7</td>
<td>0.1</td>
<td>0.94</td>
<td>17.4</td>
<td>8.3</td>
<td>26.4</td>
<td>999</td>
<td>0</td>
<td>345</td>
</tr>
<tr>
<td>18</td>
<td>60</td>
<td>331.9</td>
<td>372.9</td>
<td>0</td>
<td>Fdc</td>
<td>28.7</td>
<td>0</td>
<td>18.7</td>
<td>6</td>
<td>6.4</td>
<td>4.1</td>
<td>4.4</td>
<td>0</td>
<td>0.31</td>
<td>5</td>
<td>4.3</td>
<td>6.9</td>
<td>999</td>
<td>0</td>
<td>350</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
<td>349.6</td>
<td>372.9</td>
<td>0</td>
<td>Fdc</td>
<td>28</td>
<td>0</td>
<td>29.1</td>
<td>10.3</td>
<td>11</td>
<td>7.8</td>
<td>8.4</td>
<td>0.1</td>
<td>0.72</td>
<td>12.4</td>
<td>6.4</td>
<td>16.5</td>
<td>999</td>
<td>0</td>
<td>350</td>
</tr>
<tr>
<td>21</td>
<td>60</td>
<td>375.4</td>
<td>372.9</td>
<td>0</td>
<td>Fdc</td>
<td>29.5</td>
<td>0</td>
<td>25.3</td>
<td>8.8</td>
<td>9.5</td>
<td>6.9</td>
<td>7.4</td>
<td>0.1</td>
<td>0.58</td>
<td>9.6</td>
<td>5.7</td>
<td>13.7</td>
<td>999</td>
<td>0</td>
<td>352</td>
</tr>
<tr>
<td>27</td>
<td>60</td>
<td>447.6</td>
<td>372.9</td>
<td>0</td>
<td>Fdc</td>
<td>31.9</td>
<td>0</td>
<td>27</td>
<td>11</td>
<td>11.8</td>
<td>9.1</td>
<td>9.8</td>
<td>0.1</td>
<td>0.69</td>
<td>11.6</td>
<td>8.3</td>
<td>18</td>
<td>999</td>
<td>0</td>
<td>354</td>
</tr>
<tr>
<td>30</td>
<td>60</td>
<td>458.9</td>
<td>372.9</td>
<td>0</td>
<td>Fdc</td>
<td>27.2</td>
<td>0</td>
<td>19.5</td>
<td>5.4</td>
<td>5.8</td>
<td>3.8</td>
<td>4</td>
<td>0</td>
<td>0.33</td>
<td>4.6</td>
<td>3.9</td>
<td>5.8</td>
<td>999</td>
<td>0</td>
<td>355</td>
</tr>
<tr>
<td>37</td>
<td>60</td>
<td>17.9</td>
<td>372.6</td>
<td>0</td>
<td>Fdc</td>
<td>31.9</td>
<td>0</td>
<td>33.8</td>
<td>16</td>
<td>17.2</td>
<td>13.3</td>
<td>14.3</td>
<td>0.1</td>
<td>1.07</td>
<td>22.8</td>
<td>10.6</td>
<td>35.2</td>
<td>999</td>
<td>0</td>
<td>337</td>
</tr>
<tr>
<td>54</td>
<td>60</td>
<td>330.6</td>
<td>372.6</td>
<td>0</td>
<td>Fdc</td>
<td>26.7</td>
<td>0</td>
<td>16.3</td>
<td>3.5</td>
<td>3.8</td>
<td>2.3</td>
<td>2.5</td>
<td>0</td>
<td>0.22</td>
<td>2.4</td>
<td>3</td>
<td>7.9</td>
<td>999</td>
<td>0</td>
<td>350</td>
</tr>
<tr>
<td>63</td>
<td>60</td>
<td>431.6</td>
<td>372.6</td>
<td>0</td>
<td>Fdc</td>
<td>32.1</td>
<td>0</td>
<td>37.6</td>
<td>17.2</td>
<td>18.5</td>
<td>14.3</td>
<td>15.4</td>
<td>0.1</td>
<td>1.34</td>
<td>24</td>
<td>10</td>
<td>37.4</td>
<td>999</td>
<td>0</td>
<td>354</td>
</tr>
<tr>
<td>64</td>
<td>60</td>
<td>433.9</td>
<td>372.6</td>
<td>0</td>
<td>Fdc</td>
<td>30.4</td>
<td>0</td>
<td>25.6</td>
<td>9.8</td>
<td>10.5</td>
<td>7.9</td>
<td>8.5</td>
<td>0.1</td>
<td>0.61</td>
<td>10.4</td>
<td>7</td>
<td>15.1</td>
<td>999</td>
<td>0</td>
<td>354</td>
</tr>
</tbody>
</table>

The fields that require real data necessary to run the model are:

- ID
- X
- Y
- HEIGHT
- DOBBH (diameter outside bark at breast height)
- CRWLNGT (crown length)
- PFALL
- CELL_ID

WindFIRM assigns CELL_ID according to each tree’s X and Y coordinates and PFALL (probability of failure) will change with each run of the model. The other fields are not currently being used by the model but they have been retained in the text file format as placeholders for additions of other spatial windthrow factors in the future (eg. soils, moisture, distance from edge, exposure relative to wind direction, etc.).

Running WindFIRM remotely ensures the most recent version is being used and also requires the least amount of software to be installed on the local computer. WindFIRM can be run independently on a local computer but requires more set-up (see next section).
B. Independent operation of WindFIRM on a local computer

WindFIRM and ForestGALES_BC can also be run on any computer independently. However, there is a list of software and extensions which must be downloaded and then referenced in the environment variables on the local computer. All of the software required to run WindFIRM/ForestGALES_BC (in DOS console mode) is open-source and freely available online as listed below.

<table>
<thead>
<tr>
<th>Program</th>
<th>Version</th>
<th>Web Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Python</td>
<td>2.4</td>
<td><a href="http://www.python.org">http://www.python.org</a></td>
</tr>
<tr>
<td>Ghostview</td>
<td>gsv49w32 and gsv49w64</td>
<td><a href="http://pages.cs.wisc.edu/~ghost/">http://pages.cs.wisc.edu/~ghost/</a></td>
</tr>
<tr>
<td>ImageMagick</td>
<td>6.3.7-1-Q16-windows-dll</td>
<td><a href="http://www.imagemagick.org">http://www.imagemagick.org</a></td>
</tr>
<tr>
<td>shapelib</td>
<td>pyshapelib-0.3.win32-py2.4.exe</td>
<td><a href="http://shapelib.maptools.org/">http://shapelib.maptools.org/</a></td>
</tr>
<tr>
<td>gdalwin32</td>
<td>gdalwind32</td>
<td><a href="http://download.osgeo.org/gdal/win32/1.4.2/">http://download.osgeo.org/gdal/win32/1.4.2/</a></td>
</tr>
</tbody>
</table>

* A utility used to convert Python code into an executable.

The following steps describe how to download WindFIRM and where to install it on the local computer.

1. **Go to following ftp site** and enter credentials as follows to access directory:
   [ftp://atlas.forestry.ubc.ca](ftp://atlas.forestry.ubc.ca)
   - USERNAME: atlas1
   - PASSWORD: atlas-1
   - DIRECTORY: /ATLAS/outgoing/tshannon/Programs/windfirm.zip

2. **Create directories** on your local computer as follows:
   C:\Coord\Py

3. **Get ‘windfirm.zip’** from the ftp site and place it into C:\Coord\Py. If in console mode this is done by going to that directory (C:\Coord\Py) and typing ‘get windfirm.zip’.

4. **Unzip ‘windfirm.zip’** in the ‘C:\Coord\Py’ directory.

The following image shows all the folders and files which are required by WindFIRM in the C:\Coord\Py directory.
WindFIRM also requires a directory with palette files (C:\Coord\Data\Palettes) to produce the maps and images of model outputs. This directory may need to be sent as a separate zip file.
The components of the ForestGALES_BC portion of the model are shown in the following image in the `C:\Coord\Py\UNITS\Wind\Gales_BC_KenV1` directory.

WindFIRM (windfirm.py) needs to be run in whichever directory the tree list (`tree-list.txt`) is stored. There are also many ancillary files that need to be in the same directory as the tree list file. Since WindFIRM is designed to run on a file called `tree-list.txt`, it is easiest to organize tree lists representing different forests in uniquely named subdirectories of the `C:\Coord\DATA` directory.

For example, the following image shows how three different tree lists representing the STEMS (Silviculture Treatments for Ecosystem Management in the Sayward) research site are organized into `LO1`, `LO2` and `LO3` subdirectories of the `C:\Coord\DATA\STEMS` directory. The `tree-list.txt` file has the same name in each subdirectory but the data are different to represent the unique forest. All the other ancillary files are identical in each subdirectory.

In this example the `C:\Coord\DATA\STEMS\LO2` directory shows the `tree-list.txt` file and all the other ancillary file names in the right pane which are required to run WindFIRM on a tree list.
To run WindFIRM on a tree list, open a DOS console as shown below. As an example, the image shows how WindFIRM would be set up to run on the tree list in C:\Coord\DATA\STEMS\LO2. After changing the directory type windfirm.py at the prompt and hit return.
This will bring up the first menu of the WindFIRM/ForestGALES_BC interface as shown in the following image.

Beyond this point, running WindFIRM works exactly the same as using the remote computer.

*IMPORTANT*
WindFIRM will not run properly on the local computer until the environment variables are set. Enter the system properties window either by right-clicking on Computer then Properties or clicking Control Panel, System then the Advanced tab. The following window will appear.

Click on Environment Variables to get the following window.

Click New in the Environment Variables window and the following window will appear.
Two variable names and their associated values will be entered at this stage.

1. The first variable to be entered is **path**.

   In the box next to Variable Name enter: path

   In the box next to Variable Value enter the following:

   \[
   \text{C:\Python24;C:\Coord\Py;C:\Program Files\Atlantis\OpenEV 1.80;C:\Program Files\Ghostgum\gsview;C:\Program Files\Imagemagick-6.2.5-Q16;C:\Coord\gdalwin32-1.4.2\bin}
   \]

   **NB** – the above path refers to locations of where the necessary programs and files are located on my computer. These paths may vary depending on where they are stored on your computer.

   Click OK in the New User Variable window.

2. The second variable to be entered is **pythonpath**.

   Click New in the Environment Variables window again.

   In the box next to Variable Name enter: pythonpath

   In the box next to Variable Value enter the following:

   "C:\python24;C:\python24\Lib;C:\Coord\Py;C:\Program Files\Atlantis\OpenEV 1.80\python"

   **NB** – again the above path refers to locations of where the necessary programs and files are located on my computer. These paths may vary depending on where they are stored on your computer.
### Appendix 2 – Tree-lists for Plot and Simulation Comparisons

Table A2.1. Tree-list comparison for plot and simulated trees in Plot 10 (Aggregate Retention treatment).

<table>
<thead>
<tr>
<th>Species</th>
<th>Ht</th>
<th>DBH</th>
<th>Status</th>
<th>Species</th>
<th>Ht</th>
<th>DBH</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cwc</td>
<td>24.8</td>
<td>54.1</td>
<td>0</td>
<td>Fdc</td>
<td>28.2</td>
<td>19.7</td>
<td>101</td>
</tr>
<tr>
<td>Cwc</td>
<td>20.1</td>
<td>33.2</td>
<td>0</td>
<td>Fdc</td>
<td>28.8</td>
<td>24.2</td>
<td>101</td>
</tr>
<tr>
<td>Cwc</td>
<td>20.1</td>
<td>25.9</td>
<td>0</td>
<td>Fdc</td>
<td>30.6</td>
<td>28.7</td>
<td>101</td>
</tr>
<tr>
<td>Cwc</td>
<td>6.5</td>
<td>11.9</td>
<td>0</td>
<td>Fdc</td>
<td>32.3</td>
<td>26.3</td>
<td>101</td>
</tr>
<tr>
<td>Cwc</td>
<td>29.9</td>
<td>41.2</td>
<td>0</td>
<td>Fdc</td>
<td>26.2</td>
<td>24.2</td>
<td>101</td>
</tr>
<tr>
<td>Cwc</td>
<td>7.9</td>
<td>15.0</td>
<td>0</td>
<td>Fdc</td>
<td>28.8</td>
<td>19.4</td>
<td>101</td>
</tr>
<tr>
<td>Fdc</td>
<td>19.9</td>
<td>25.5</td>
<td>0</td>
<td>Fdc</td>
<td>27.0</td>
<td>18.6</td>
<td>101</td>
</tr>
<tr>
<td>Fdc</td>
<td>28.3</td>
<td>32.4</td>
<td>101</td>
<td>Fdc</td>
<td>29.6</td>
<td>22.7</td>
<td>101</td>
</tr>
<tr>
<td>Fdc</td>
<td>19.9</td>
<td>20.1</td>
<td>0</td>
<td>Fdc</td>
<td>27.5</td>
<td>18.1</td>
<td>101</td>
</tr>
<tr>
<td>Fdc</td>
<td>19.9</td>
<td>19.1</td>
<td>0</td>
<td>Fdc</td>
<td>27.6</td>
<td>20.3</td>
<td>101</td>
</tr>
<tr>
<td>Fdc</td>
<td>21.0</td>
<td>18.2</td>
<td>0</td>
<td>Fdc</td>
<td>28.2</td>
<td>18.8</td>
<td>101</td>
</tr>
<tr>
<td>Fdc</td>
<td>21.0</td>
<td>19.1</td>
<td>0</td>
<td>Fdc</td>
<td>29.6</td>
<td>23.7</td>
<td>101</td>
</tr>
<tr>
<td>Fdc</td>
<td>21.0</td>
<td>26.2</td>
<td>0</td>
<td>Fdc</td>
<td>26.9</td>
<td>17.4</td>
<td>101</td>
</tr>
<tr>
<td>Fdc</td>
<td>21.0</td>
<td>21.0</td>
<td>101</td>
<td>Fdc</td>
<td>31.7</td>
<td>29.0</td>
<td>101</td>
</tr>
<tr>
<td>Fdc</td>
<td>25.5</td>
<td>34.7</td>
<td>0</td>
<td>Fdc</td>
<td>29.5</td>
<td>19.2</td>
<td>101</td>
</tr>
<tr>
<td>Fdc</td>
<td>25.5</td>
<td>27.0</td>
<td>101</td>
<td>Cwc</td>
<td>29.9</td>
<td>25.3</td>
<td>101</td>
</tr>
<tr>
<td>Hwc</td>
<td>21.9</td>
<td>33.5</td>
<td>0</td>
<td>Cwc</td>
<td>29.8</td>
<td>25.0</td>
<td>101</td>
</tr>
</tbody>
</table>

* Tree status for windthrown trees (101) and live standing trees (0)
Cwc = western redcedar, Fdc = Douglas-fir, Hwc = western hemlock
Ht (m), DBH (cm).
Table A2.2. Tree-list comparison for plot and simulated trees in Plot 25 (Aggregate Retention treatment).

<table>
<thead>
<tr>
<th>Species</th>
<th>Plot trees</th>
<th>Simulated trees</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ht</td>
<td>DBH</td>
</tr>
<tr>
<td>Cwc</td>
<td>22.1</td>
<td>31.1</td>
</tr>
<tr>
<td>Fdc</td>
<td>39.5</td>
<td>56.5</td>
</tr>
<tr>
<td>Fdc</td>
<td>37.2</td>
<td>49.4</td>
</tr>
<tr>
<td>Fdc</td>
<td>34.1</td>
<td>50.3</td>
</tr>
<tr>
<td>Fdc</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Fdc</td>
<td>40.9</td>
<td>62.4</td>
</tr>
<tr>
<td>Fdc</td>
<td>24.8</td>
<td>19.6</td>
</tr>
<tr>
<td>Fdc</td>
<td>28</td>
<td>27.1</td>
</tr>
<tr>
<td>Fdc</td>
<td>43.7</td>
<td>63.4</td>
</tr>
<tr>
<td>Fdc</td>
<td>30.5</td>
<td>42.3</td>
</tr>
<tr>
<td>Fdc</td>
<td>37.9</td>
<td>39.4</td>
</tr>
<tr>
<td>Fdc</td>
<td>34.4</td>
<td>38.8</td>
</tr>
<tr>
<td>Fdc</td>
<td>39.9</td>
<td>63.7</td>
</tr>
<tr>
<td>Fdc</td>
<td>24.6</td>
<td>20.7</td>
</tr>
<tr>
<td>Fdc</td>
<td>24.6</td>
<td>27.1</td>
</tr>
<tr>
<td>Fdc</td>
<td>40.9</td>
<td>56.4</td>
</tr>
<tr>
<td>Fdc</td>
<td>28.7</td>
<td>30</td>
</tr>
<tr>
<td>Fdc</td>
<td>29.1</td>
<td>35.4</td>
</tr>
<tr>
<td>Fdc</td>
<td>28.7</td>
<td>30</td>
</tr>
<tr>
<td>Hwc</td>
<td>24.6</td>
<td>30.8</td>
</tr>
<tr>
<td>Hwc</td>
<td>24.6</td>
<td>25.2</td>
</tr>
<tr>
<td>Hwc</td>
<td>28.6</td>
<td>39</td>
</tr>
<tr>
<td>Hwc</td>
<td>8.4</td>
<td>13.8</td>
</tr>
</tbody>
</table>

* Tree status for windthrown trees (101) and live standing trees (0)
Cwc = western redcedar, Fdc = Douglas-fir, Hwc = western hemlock
Ht (m), DBH (cm).
Table A2.3. Tree-list comparison for plot and simulated trees in Plot 11 (Aggregate Retention treatment).

<table>
<thead>
<tr>
<th>Species</th>
<th>Plot trees</th>
<th></th>
<th></th>
<th>Simulated trees</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ht</td>
<td>DBH</td>
<td>Status</td>
<td>Species</td>
<td>Ht</td>
<td>DBH</td>
</tr>
<tr>
<td>Cwc</td>
<td>13.8</td>
<td>7.1</td>
<td>0</td>
<td>Fdc</td>
<td>30.2</td>
<td>22.7</td>
</tr>
<tr>
<td>Cwc</td>
<td>13.8</td>
<td>20.1</td>
<td>0</td>
<td>Fdc</td>
<td>28.4</td>
<td>22.8</td>
</tr>
<tr>
<td>Cwc</td>
<td>13.8</td>
<td>15.9</td>
<td>0</td>
<td>Fdc</td>
<td>31.8</td>
<td>26.8</td>
</tr>
<tr>
<td>Cwc</td>
<td>21.3</td>
<td>33.4</td>
<td>0</td>
<td>Fdc</td>
<td>30.1</td>
<td>21.9</td>
</tr>
<tr>
<td>Cwc</td>
<td>6.5</td>
<td>8.8</td>
<td>0</td>
<td>Fdc</td>
<td>32.1</td>
<td>29.2</td>
</tr>
<tr>
<td>Cwc</td>
<td>21.3</td>
<td>27.1</td>
<td>0</td>
<td>Fdc</td>
<td>29.8</td>
<td>29.1</td>
</tr>
<tr>
<td>Cwc</td>
<td>13.8</td>
<td>16</td>
<td>0</td>
<td>Fdc</td>
<td>32.5</td>
<td>36</td>
</tr>
<tr>
<td>Cwc</td>
<td>13.8</td>
<td>19.1</td>
<td>0</td>
<td>Fdc</td>
<td>33.1</td>
<td>31.2</td>
</tr>
<tr>
<td>Cwc</td>
<td>21.3</td>
<td>21.9</td>
<td>0</td>
<td>Fdc</td>
<td>31.1</td>
<td>35.5</td>
</tr>
<tr>
<td>Cwc</td>
<td>6.7</td>
<td>8.4</td>
<td>0</td>
<td>Fdc</td>
<td>28.1</td>
<td>20.7</td>
</tr>
<tr>
<td>Cwc</td>
<td>22.9</td>
<td>33.2</td>
<td>0</td>
<td>Fdc</td>
<td>28.8</td>
<td>22.1</td>
</tr>
<tr>
<td>Fdc</td>
<td>24.2</td>
<td>27</td>
<td>0</td>
<td>Fdc</td>
<td>28.1</td>
<td>20.2</td>
</tr>
<tr>
<td>Fdc</td>
<td>29</td>
<td>38.4</td>
<td>0</td>
<td>Fdc</td>
<td>27.5</td>
<td>22.3</td>
</tr>
<tr>
<td>Fdc</td>
<td>27.8</td>
<td>36.5</td>
<td>0</td>
<td>Fdc</td>
<td>27.6</td>
<td>19.9</td>
</tr>
<tr>
<td>Fdc</td>
<td>24.2</td>
<td>26.6</td>
<td>0</td>
<td>Fdc</td>
<td>29.9</td>
<td>26.8</td>
</tr>
<tr>
<td>Fdc</td>
<td>28</td>
<td>39.4</td>
<td>0</td>
<td>Fdc</td>
<td>30.3</td>
<td>28.6</td>
</tr>
<tr>
<td>Fdc</td>
<td>26.5</td>
<td>27.1</td>
<td>0</td>
<td>Fdc</td>
<td>28</td>
<td>19.7</td>
</tr>
<tr>
<td>Fdc</td>
<td>29.1</td>
<td>37</td>
<td>0</td>
<td>Fdc</td>
<td>25.2</td>
<td>18.4</td>
</tr>
<tr>
<td>Fdc</td>
<td>21.6</td>
<td>28.1</td>
<td>0</td>
<td>Fdc</td>
<td>25.9</td>
<td>16.5</td>
</tr>
<tr>
<td>Fdc</td>
<td>13.8</td>
<td>20.1</td>
<td>0</td>
<td>Fdc</td>
<td>30</td>
<td>28.9</td>
</tr>
<tr>
<td>Fdc</td>
<td>21.3</td>
<td>27.2</td>
<td>0</td>
<td>Fdc</td>
<td>31.6</td>
<td>30.1</td>
</tr>
<tr>
<td>Fdc</td>
<td>26.3</td>
<td>28.8</td>
<td>0</td>
<td>Fdc</td>
<td>27.7</td>
<td>19.2</td>
</tr>
<tr>
<td>Fdc</td>
<td>27.7</td>
<td>35.2</td>
<td>0</td>
<td>Fdc</td>
<td>30.9</td>
<td>28.1</td>
</tr>
<tr>
<td>Fdc</td>
<td>32.9</td>
<td>38.1</td>
<td>0</td>
<td>Fdc</td>
<td>32.4</td>
<td>38.6</td>
</tr>
<tr>
<td>Fdc</td>
<td>26.9</td>
<td>36.2</td>
<td>0</td>
<td>Fdc</td>
<td>28.3</td>
<td>26.3</td>
</tr>
<tr>
<td>Fdc</td>
<td>26.1</td>
<td>26.2</td>
<td>0</td>
<td>Fdc</td>
<td>30</td>
<td>25.9</td>
</tr>
<tr>
<td>Fdc</td>
<td>17.9</td>
<td>15.2</td>
<td>0</td>
<td>Fdc</td>
<td>27.5</td>
<td>21.9</td>
</tr>
<tr>
<td>Fdc</td>
<td>25.8</td>
<td>29.4</td>
<td>0</td>
<td>Fdc</td>
<td>31.1</td>
<td>26.3</td>
</tr>
<tr>
<td>Fdc</td>
<td>26.8</td>
<td>31.4</td>
<td>0</td>
<td>Fdc</td>
<td>30.9</td>
<td>23.4</td>
</tr>
<tr>
<td>Fdc</td>
<td>28.3</td>
<td>41.9</td>
<td>0</td>
<td>Fdc</td>
<td>28.3</td>
<td>20.7</td>
</tr>
<tr>
<td>Fdc</td>
<td>24.7</td>
<td>29.5</td>
<td>0</td>
<td>Fdc</td>
<td>30.7</td>
<td>25.4</td>
</tr>
<tr>
<td>Fdc</td>
<td>23.2</td>
<td>63.4</td>
<td>0</td>
<td>Fdc</td>
<td>29.8</td>
<td>27.6</td>
</tr>
<tr>
<td>Fdc</td>
<td>22.2</td>
<td>30.9</td>
<td>0</td>
<td>Fdc</td>
<td>28.6</td>
<td>19.3</td>
</tr>
<tr>
<td>Fdc</td>
<td>18.3</td>
<td>11.7</td>
<td>101</td>
<td>Fdc</td>
<td>29.4</td>
<td>20.3</td>
</tr>
<tr>
<td>Fdc</td>
<td>29.8</td>
<td>39.2</td>
<td>0</td>
<td>Fdc</td>
<td>28.7</td>
<td>21.9</td>
</tr>
<tr>
<td>Fdc</td>
<td>29.3</td>
<td>39.2</td>
<td>0</td>
<td>Fdc</td>
<td>28.1</td>
<td>19.2</td>
</tr>
<tr>
<td>Fdc</td>
<td>32.5</td>
<td>54.4</td>
<td>0</td>
<td>Fdc</td>
<td>30.8</td>
<td>33.1</td>
</tr>
<tr>
<td>Fdc</td>
<td>29.7</td>
<td>35.3</td>
<td>0</td>
<td>Fdc</td>
<td>28.4</td>
<td>28.3</td>
</tr>
<tr>
<td>Fdc</td>
<td>26.5</td>
<td>26.4</td>
<td>0</td>
<td>Fdc</td>
<td>27.4</td>
<td>27.5</td>
</tr>
<tr>
<td>Fdc</td>
<td>36.2</td>
<td>46.2</td>
<td>0</td>
<td>Fdc</td>
<td>28.9</td>
<td>22.6</td>
</tr>
<tr>
<td>Fdc</td>
<td>18.9</td>
<td>16.6</td>
<td>0</td>
<td>Hwc</td>
<td>26.9</td>
<td>17.5</td>
</tr>
<tr>
<td>Fdc</td>
<td>24</td>
<td>25.9</td>
<td>0</td>
<td>Hwc</td>
<td>24.5</td>
<td>14.7</td>
</tr>
<tr>
<td>Fdc</td>
<td>30.7</td>
<td>40.6</td>
<td>0</td>
<td>Hwc</td>
<td>30</td>
<td>28.4</td>
</tr>
<tr>
<td>Fdc</td>
<td>25.1</td>
<td>29</td>
<td>0</td>
<td>Hwc</td>
<td>26.2</td>
<td>22.7</td>
</tr>
<tr>
<td>Hwc</td>
<td>27.2</td>
<td>23</td>
<td>0</td>
<td>Hwc</td>
<td>28.4</td>
<td>22.4</td>
</tr>
<tr>
<td>Hwc</td>
<td>4.4</td>
<td>5.5</td>
<td>101</td>
<td>Hwc</td>
<td>28.9</td>
<td>28.2</td>
</tr>
<tr>
<td>Hwc</td>
<td>30.7</td>
<td>33.2</td>
<td>0</td>
<td>Hwc</td>
<td>29.2</td>
<td>27</td>
</tr>
<tr>
<td>Hwc</td>
<td>30.7</td>
<td>26</td>
<td>0</td>
<td>Cwc</td>
<td>32.7</td>
<td>37.1</td>
</tr>
<tr>
<td>Hwc</td>
<td>30.5</td>
<td>26</td>
<td>0</td>
<td>Cwc</td>
<td>29.2</td>
<td>25.7</td>
</tr>
</tbody>
</table>

* Tree status for windthrown trees (101) and live standing trees (0)
Cwc = western redcedar, Fdc = Douglas-fir, Hwc = western hemlock
Ht (m), DBH (cm).
Appendix 3 – Tree-list Comparisons for Pruned and Non-pruned Pixels in the Aggregate Retention Treatment

Table A3.1. Tree-list comparison for the status of pruned and non-pruned trees in Pixel 150.

<table>
<thead>
<tr>
<th>ID</th>
<th>SPECIES</th>
<th>HEIGHT</th>
<th>DOBBH</th>
<th>CRWLNGT</th>
<th>PFALL</th>
<th>CRWLNGT</th>
<th>PFALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>86637</td>
<td>Fdc</td>
<td>30.6</td>
<td>32.3</td>
<td>14.6</td>
<td>101</td>
<td>9.7</td>
<td>101</td>
</tr>
<tr>
<td>89836</td>
<td>Fdc</td>
<td>30.7</td>
<td>31</td>
<td>13.2</td>
<td>101</td>
<td>8.8</td>
<td>101</td>
</tr>
<tr>
<td>89888</td>
<td>Fdc</td>
<td>29.4</td>
<td>29.1</td>
<td>11.2</td>
<td>101</td>
<td>7.5</td>
<td>101</td>
</tr>
<tr>
<td>122389</td>
<td>Hwc</td>
<td>35.6</td>
<td>32.3</td>
<td>12.1</td>
<td>101</td>
<td>8.1</td>
<td>101</td>
</tr>
<tr>
<td>122531</td>
<td>Hwc</td>
<td>32.9</td>
<td>31.6</td>
<td>8</td>
<td>101</td>
<td>5.3</td>
<td>0</td>
</tr>
<tr>
<td>136636</td>
<td>Cwc</td>
<td>27.6</td>
<td>35.9</td>
<td>16.8</td>
<td>101</td>
<td>11.2</td>
<td>101</td>
</tr>
</tbody>
</table>

* Tree status (PFALL) for windthrown trees (101) and live standing trees (0)
** Crown length (CRWLNGT)

Cwc = western redcedar, Fdc = Douglas-fir, Hwc = western hemlock
Ht (m), DBH (cm).

Table A3.2. Tree-list comparison for the status of pruned and non-pruned trees in Pixel 293.

<table>
<thead>
<tr>
<th>ID</th>
<th>SPECIES</th>
<th>HEIGHT</th>
<th>DOBBH</th>
<th>CRWLNGT</th>
<th>PFALL</th>
<th>CRWLNGT</th>
<th>PFALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>63745</td>
<td>Fdc</td>
<td>26.7</td>
<td>20.6</td>
<td>4.8</td>
<td>101</td>
<td>3.2</td>
<td>0</td>
</tr>
<tr>
<td>63911</td>
<td>Fdc</td>
<td>28.5</td>
<td>23.8</td>
<td>8.2</td>
<td>101</td>
<td>5.4</td>
<td>101</td>
</tr>
<tr>
<td>64150</td>
<td>Fdc</td>
<td>27.1</td>
<td>21.3</td>
<td>3.8</td>
<td>101</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td>64627</td>
<td>Fdc</td>
<td>25.9</td>
<td>16.3</td>
<td>2.5</td>
<td>0</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td>64877</td>
<td>Fdc</td>
<td>28.4</td>
<td>27.2</td>
<td>7.7</td>
<td>101</td>
<td>7.7</td>
<td>101</td>
</tr>
<tr>
<td>65342</td>
<td>Fdc</td>
<td>30</td>
<td>28.1</td>
<td>9.2</td>
<td>101</td>
<td>6.1</td>
<td>101</td>
</tr>
<tr>
<td>65596</td>
<td>Fdc</td>
<td>32.6</td>
<td>39.5</td>
<td>16</td>
<td>101</td>
<td>10.7</td>
<td>101</td>
</tr>
<tr>
<td>119568</td>
<td>Hwc</td>
<td>33.6</td>
<td>36.8</td>
<td>13.1</td>
<td>0</td>
<td>13.1</td>
<td>0</td>
</tr>
<tr>
<td>119663</td>
<td>Hwc</td>
<td>24.7</td>
<td>12.1</td>
<td>0.3</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>133432</td>
<td>Cwc</td>
<td>31.4</td>
<td>38.1</td>
<td>15.5</td>
<td>101</td>
<td>10.3</td>
<td>0</td>
</tr>
<tr>
<td>133539</td>
<td>Cwc</td>
<td>30.2</td>
<td>30.6</td>
<td>10.5</td>
<td>101</td>
<td>4.6</td>
<td>0</td>
</tr>
</tbody>
</table>

* Tree status (PFALL) for windthrown trees (101) and live standing trees (0)
** Crown length (CRWLNGT)

Cwc = western redcedar, Fdc = Douglas-fir, Hwc = western hemlock
Ht (m), DBH (cm).

Table A3.3. Tree-list comparison for the status of pruned and non-pruned trees in Pixel 393.

<table>
<thead>
<tr>
<th>ID</th>
<th>SPECIES</th>
<th>HEIGHT</th>
<th>DOBBH</th>
<th>CRWLNGT</th>
<th>PFALL</th>
<th>CRWLNGT</th>
<th>PFALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>57417</td>
<td>Fdc</td>
<td>31.8</td>
<td>32.7</td>
<td>12.1</td>
<td>101</td>
<td>5.4</td>
<td>101</td>
</tr>
<tr>
<td>118508</td>
<td>Hwc</td>
<td>33.6</td>
<td>34.3</td>
<td>11.9</td>
<td>101</td>
<td>5.2</td>
<td>0</td>
</tr>
<tr>
<td>132305</td>
<td>Cwc</td>
<td>29</td>
<td>30.2</td>
<td>12.3</td>
<td>101</td>
<td>5.4</td>
<td>0</td>
</tr>
<tr>
<td>132491</td>
<td>Cwc</td>
<td>30.9</td>
<td>34.9</td>
<td>15.2</td>
<td>101</td>
<td>6.7</td>
<td>0</td>
</tr>
<tr>
<td>132748</td>
<td>Cwc</td>
<td>30.2</td>
<td>30.6</td>
<td>10.5</td>
<td>101</td>
<td>4.6</td>
<td>0</td>
</tr>
</tbody>
</table>

* Tree status (PFALL) for windthrown trees (101) and live standing trees (0)
** Crown length (CRWLNGT)

Cwc = western redcedar, Fdc = Douglas-fir, Hwc = western hemlock
Ht (m), DBH (cm).
<table>
<thead>
<tr>
<th>ID</th>
<th>SPECIES</th>
<th>HEIGHT</th>
<th>DOBBH</th>
<th>CRWLNGT</th>
<th>PFALL</th>
<th>CRWLNGT</th>
<th>PFALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>26353</td>
<td>Fdc</td>
<td>26.5</td>
<td>19.9</td>
<td>4.3</td>
<td>101</td>
<td>1.8</td>
<td>0</td>
</tr>
<tr>
<td>26354</td>
<td>Fdc</td>
<td>32.4</td>
<td>31</td>
<td>13.5</td>
<td>101</td>
<td>6</td>
<td>101</td>
</tr>
<tr>
<td>26665</td>
<td>Fdc</td>
<td>26.8</td>
<td>19.2</td>
<td>4.5</td>
<td>101</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>26875</td>
<td>Fdc</td>
<td>26.1</td>
<td>18.1</td>
<td>5.1</td>
<td>101</td>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td>26940</td>
<td>Fdc</td>
<td>27.6</td>
<td>17.4</td>
<td>5.2</td>
<td>101</td>
<td>2.2</td>
<td>101</td>
</tr>
<tr>
<td>27217</td>
<td>Fdc</td>
<td>27.4</td>
<td>23.5</td>
<td>6.8</td>
<td>101</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>27548</td>
<td>Fdc</td>
<td>28.1</td>
<td>22.8</td>
<td>6</td>
<td>101</td>
<td>2.6</td>
<td>0</td>
</tr>
<tr>
<td>27833</td>
<td>Fdc</td>
<td>32.1</td>
<td>31</td>
<td>10.9</td>
<td>101</td>
<td>4.8</td>
<td>101</td>
</tr>
<tr>
<td>31439</td>
<td>Fdc</td>
<td>30.6</td>
<td>30.5</td>
<td>10.5</td>
<td>101</td>
<td>4.6</td>
<td>101</td>
</tr>
<tr>
<td>115007</td>
<td>Hwc</td>
<td>28.3</td>
<td>23.4</td>
<td>6.5</td>
<td>101</td>
<td>2.8</td>
<td>0</td>
</tr>
<tr>
<td>115038</td>
<td>Hwc</td>
<td>28.4</td>
<td>20.6</td>
<td>5.5</td>
<td>101</td>
<td>3.6</td>
<td>101</td>
</tr>
<tr>
<td>115068</td>
<td>Hwc</td>
<td>31.9</td>
<td>28.7</td>
<td>10.5</td>
<td>101</td>
<td>4.6</td>
<td>0</td>
</tr>
<tr>
<td>115437</td>
<td>Hwc</td>
<td>33.2</td>
<td>30.6</td>
<td>9.7</td>
<td>101</td>
<td>4.2</td>
<td>0</td>
</tr>
<tr>
<td>115476</td>
<td>Hwc</td>
<td>32.2</td>
<td>32.3</td>
<td>9.7</td>
<td>101</td>
<td>4.3</td>
<td>0</td>
</tr>
<tr>
<td>129341</td>
<td>Cwc</td>
<td>30.6</td>
<td>36.6</td>
<td>14.4</td>
<td>101</td>
<td>6.4</td>
<td>0</td>
</tr>
<tr>
<td>129349</td>
<td>Cwc</td>
<td>29.4</td>
<td>29.9</td>
<td>8.5</td>
<td>101</td>
<td>3.7</td>
<td>0</td>
</tr>
</tbody>
</table>

* Tree status (PFALL) for windthrown trees (101) and live standing trees (0)
** Crown length (CRWLNGT)