

1538447216 PREDICTING WINDTHROW IN RIPARIAN ZONES
IN INSULAR NEWFOUNDLAND

by

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ABSTRACT

After logging, remnant timber in riparian zones is vulnerable to wind damage, potentially impacting riparian zone functionality. The goal of this study was to identify the extent of wind damage in riparian zones on the island of Newfoundland, and to develop a predictive windthrow model and risk map using tree, neighbourhood, and stand-level variables. Measurements on 1814 windthrown trees were taken from 138 plots in 52 riparian zones. Riparian zones experienced 0-76% of trees windthrown. Nearly 80% of windthrown trees were located on outer riparian edges, suggesting that the internal structure remained functional. Important tree level variables included tree diameter and height to live crown, but stand-level variables were the most significant in explaining 60% or more of the windthrow observations. Specifically, damage increased with increasing fetch (the sum of the open distance limited to 300m for all eight cardinal directions, $p = 0.021$) and increasing local exposure or direx60 (the sum of the eight cardinal directions open to a distance of 60 meters, $p = 0.001$). Damage also increased with decreasing topex500, a measure of the topographic modification of local wind speeds (sum of the angle to skyline for eight cardinal directions within 500m, $p = 0.037$). Damage was not related to cut block shape ($p = 0.536$), structure ($p = 0.174$), or area ($p = 0.869$). The best-fitted regression models for the inner and outer riparian zones were then used for the purpose of windthrow risk mapping, for riparian zones in particular, and forest retention cutting in general.

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1.0 INTRODUCTION

In recent years, Newfoundland foresters have noted heavy losses of timber in newly created riparian edges due to wind damage, and this has raised questions concerns about the viability of riparian zone functioning (Figure 1). Therefore, a Newfoundland and Labrador Riparian Zone Working Group (NLRZWG) comprising of Corner Brook Pulp and Paper, Newfoundland and Labrador Department of Natural Resources, Western Newfoundland Model Forest, and the Forest Engineering Research Institute of Canada was formed to determine how to examine the situation and associated risks, and to make recommendations regarding riparian zone management and operations. Among several activities, NLRZWG initiated a study to develop a predictive model of windthrow for riparian zones in Newfoundland. The goal was to identify those variables that best predict and map wind-throw risks, thereby allowing NLRZWG to develop ways and means to minimize such risks.

In general, forest damage from wind has become increasingly important as forest management in Newfoundland and elsewhere steadily moves towards increased levels of harvest expectations from forested lands, while having to deal with highly fairly fragmented forest landscapes subject to various management objectives at the same time. As a result, forested landscapes are increasingly becoming more and more convoluted and dotted (fragmented), with many regenerating forest patches of decreasing size (Ruel, 1995) and remnant stands remaining among these patches and in the form of buffer strips along lakes, streams and roads. All remnant stands are, in principle, highly prone to wind damage (Canham et al., 2001), and the impact of this damage has many economic and ecological consequences. For example, wind damage to remaining forest stands

represents a significant economic timber loss, but also affects wildlife habitat, becomes a source for initiation of insect infestations and diseases, enhances sediment losses to streams, and reduces the overall functioning of riparian corridors (Ravn, 1985; Schroeder and Eidmann, 1993; Quine et al., 1995).

Newfoundland's complex partly rocky and forested terrain, interspersed with numerous bogs, streams, lakes, rivers and shorelines, is particularly prone to wind damage on account of frequent storm events. This, combined with a high annual rate of precipitation, ensures that forests soils are often saturated. The forest vegetation is dominated by balsam fir (*Abies balsamea* (L.) Mill.) and black spruce (*Picea mariana* (Mill.) B.S.P.). The current forest landscape is interspersed by clear cuts that often amalgamate because of a lack of green-up delays. Hence, the size of a cutblock made in one year is often increased by an adjacent cut during the next year, leaving very large areas exposed to wind and storms in some cases.

This study presents an attempt to numerically examine and model the influence of tree, neighbourhood, and stand-level variables on the percentage of windthrow in riparian zones. In order to do so, the study involves direct field observations, conducted along riparian zones, and analyzing these observations systematically with attributes attained through the use of a GIS. The general intent is to generate a model for riparian windthrow that may find practical use in forest operations planning and silvicultural design.



Figure 1. Two different riparian zones showing uncompromised riparian structure (top photo) and compromised riparian structure due to severe wind damage (bottom photo).

1.1 SPECIFIC RESEARCH OBJECTIVES

To assess the vulnerability of riparian zones to windthrow, a study was conducted in the summer of 2006. The objectives of this study were:

1. to determine the extent of wind damage in insular Newfoundland riparian zones,
2. to determine the relative influence of predictor variables (tree, neighbourhood, and stand level),
3. to construct a windthrow model for Newfoundland riparian zones, and
4. to develop a windthrow risk map for riparian zones in Newfoundland.

1.2 LITERATURE REVIEW

Winds play an important role in determining the structure of forests in both tropical and temperate regions (Everham and Brokaw, 1996) and are a significant natural cause of windthrow damage to forests in North America (Mitchell, 1995; Mitchell, 1998; Dunham and Cameron, 2000). Numerous tree and stand characteristics affect susceptibility to windthrow. These refer to tree and stand characteristics, antecedent insect damage and disease conditions, harvest (treatment) patterns, soil conditions, topography and wind exposure.

Windthrow of healthy trees include factors such as tree species composition, stand age, diameter at breast height, height, height to live crown, crown position, and size (Dunham and Cameron, 2000; Mitchell et al., 2001; Achim et al., 2005). Some stand characteristics have been found to be more significant than others. For example, results relating windthrow to diameter at breast height have been inconsistent, with some studies

finding no relationship (Huggard et al., 1999; Dunham and Cameron, 2000) and others reporting positive and/or negative relationships (Stoekler and Arbogast, 1955; Richter, 1996). However, tree height (Mitchell et al., 2001; Achim et al., 2005) and height to diameter ratio (Jull and Sagar, 2001; Mason, 2002) have consistently been found to strongly influence windthrow.

In the boreal forests of Quebec, a study of riparian zone windthrow showed that balsam fir accounted for 19.6% of the number of stems damaged, in comparison to 5.3%, 11.1% and 4.0% for white spruce (*Picea glauca* (Moench) Voss), black spruce, and white birch (*Betula papyrifera* Marsh), respectively (Ruel et al., 2001). Significant differences have also been found in the amount of windthrow between conifer species. Balsam fir dominated stands experienced 12% more mortality by area than spruce dominated stands following a windstorm in 1994 (Ruel, 2000).

Balsam fir is thought to be more prone to windthrow than black spruce because of its susceptibility to insect damage and wind damage (Pham et al., 2004). Insect damage often leads to the weakening of trees and reduced root systems leaving them prone to disease. In spruce budworm (*Choristoneura fumiferana* [Clem.]) outbreaks in New Brunswick, tree mortality shifted from spruce budworm-caused mortality during an outbreak to wind induced mortality after the outbreak (Taylor and MacLean, 2007). Insect pests and rot are prevalent in forests of Newfoundland. Armillaria root rot, caused by *Armillaria ostoyae*, is the most common root disease of boreal forest conifers, attacking stressed trees causing primarily growth loss and tree mortality (Mallett, 1992). Root and butt/stem rots have been found to be associated with high frequencies of

windthrow and associated with failure mode (uprooting, stem snap, and / or crown snap) because of their effects on root anchorage and butt/bole strength (Schaetzl et al. 1989).

Treatment factors found to affect susceptibility to windthrow include applied silviculture treatment, adjacent stand treatments, and time since treatment (Jalkanen and Mattila, 2000; Beese, 2001; Mitchell et al., 2001; Ruel et al., 2003). With regards to time since harvest, Mitchell et al. (2001) found 20-30% of edge segments sampled had wind damage within the first 5 years since harvest, Beese (2001) found most damage occurred in the first year, while Holmes (1985) found no relationship.

Topographic exposure is an important component in windthrow studies. The topographical exposure index (topex) used in these studies is the sum of the maximum angle to the horizon in the eight cardinal directions (Miller, 1985). A positive value indicates a sheltered area while a negative value indicates an exposed area. Distance-limited topex is a modification of this measure, where the distance searched for the horizon is limited, therefore enabling the ability to discern between hilltops and plateaus (Ruel et al., 2002). Aspect and slope can also influence vulnerability to windthrow, as edges facing the predominant winds are often at a higher damage risk (Scott and Mitchell, 2005). Tree fall directions are generally thought to mimic predominant winds, as found in New Brunswick (Taylor and MacLean, 2007). However, other studies have found riparian tree-fall directionality was not directly related to wind direction (Sobota et al., 2006). Hairston-Strang and Adams (1998) and Welty et al. (2002) found that riparian trees have a strong general tendency to fall directly toward the stream regardless of predominant winds. In several studies, windthrown trees were found to reflect pathways of dominant storm winds (Steinblums et al., 1984; Andrus and Froelich, 1992; Ott 1997).

Related to topography is the soil moisture factor in windthrow studies. For example, Mitchell et al. (2001) found that trees were more susceptible to windthrow on moist soils than on wet or dry soil. Huggard et al. (1999) found trees were susceptible on wet sites. In a study undertaken in the Bowater watershed in central Nova Scotia, Connors (2005) found an almost linear relationship between decreasing depth to water and uprooted trees. Failure mode can also be related to soil moisture. Beher (1921) found that the probability of stem breakage was higher on dry sites, and that the probability of uprooting would be higher on wet sites.

Shelter is an important variable in assessing windthrow risk to forest edges. Fetch is defined as the uninterrupted distance that wind travels before hitting an edge. Fetch and modifications of it provide good measure of shelter. A modification of fetch, called Direx, sums the number of directions in which the fetch reaches a specified distance. Damage to edges where openings were in only two directions for Direx100 (100 m) was less than 20% and was 60% for edges open in four directions (Lanquaye, 2003). Scott and Mitchell (2005) in a patch retention study found that windthrow increased with increases in an index of fetch, measured as distance multiplied by removal level. In this case, proportion of damage was less than 10% for distances of 150 m and over 30% in areas with openings of 750 m.

In recent years, tools have been developed to predict wind-caused forest damage (Scott and Mitchell, 2005; Mickovski et al., 2005). These tools are based on observational or empirical approaches (Ruth and Yoder, 1953; Harris, 1989; Stathers et al. 1994), or mechanistic approaches (Achim et al., 2005). Empirical windthrow risk models are statistical models that relate the magnitude of wind damage to various

environmental and management attributes from multiple field sampling locations (Scott and Mitchell, 2005). These models are ideal for complex terrain, variable soil and stand conditions and for stands with high incidence of stem and root decay (Valinger and Friedman, 1997) and model inputs and outputs differ between sites for which they were constructed because of variation in biophysical or management attributes (Mitchell, 2003; Scott and Mitchell, 2005). Mechanistic models such as ForestGales and HWIND (Gardiner et al., 2000; Ruel, 2000) help gauge the risk of damage for certain forest areas. Mechanistic modeling involves determination of critical wind speeds needed for overturning or breaking a tree and then determining the likelihood of that wind speed occurring. Mechanistic models are best for structurally uniform, single-species stands, and are not suitable for use in areas characterized by variable tree size and height, severe wind regimes, and complex terrain.

2.0 METHODS

2.1 DESCRIPTION OF STUDY AREA

This study was conducted in riparian zones in two regions of insular Newfoundland and Labrador: (1) the western region, characterized by balsam fir and complex terrain (Figure 2); and (2) the central region, dominated by black spruce on primarily flat terrain (Figure 3). These two regions were studied because of differences in climate, geology, topography, and forest types. Initially a comparison between areas was sought and while some comparisons are suggested, due to the harvesting history, the majority of riparian zones surveyed were in western Newfoundland. This area has seen higher levels of harvesting and as a result more riparian zones were available for study.

The western Newfoundland study area is comprised of more than one million hectares, extending from Codroy Valley in the south to Bonne Bay in the north and from the west coast inland, including much of the Long Range Mountains. The area is characterized by high amounts of precipitation (1186mm) resulting from an interaction between winds coming off the Gulf of St. Lawrence and the mountainous terrain (Online http://www.env.gov.nl.ca/parks/library/pdf/Ecoregions/Island_1b_corner_brook%20-202007.pdf, accessed September 10, 2007). This results an annual snowfall and rainfall of 414 cm and 771 mm, respectively. The Long Range Mountains serve to protect areas from cold northeasterly winds, affording the region the longest frost-free periods on the island. Mean monthly temperature ranges from -6.8 to 17.4 degrees Celsius with a mean daily temperature of 5.2 degrees Celsius (Figure 4). The climate is relatively humid and the region experiences warm summers and cold winters providing the most favorable growing conditions on the island.

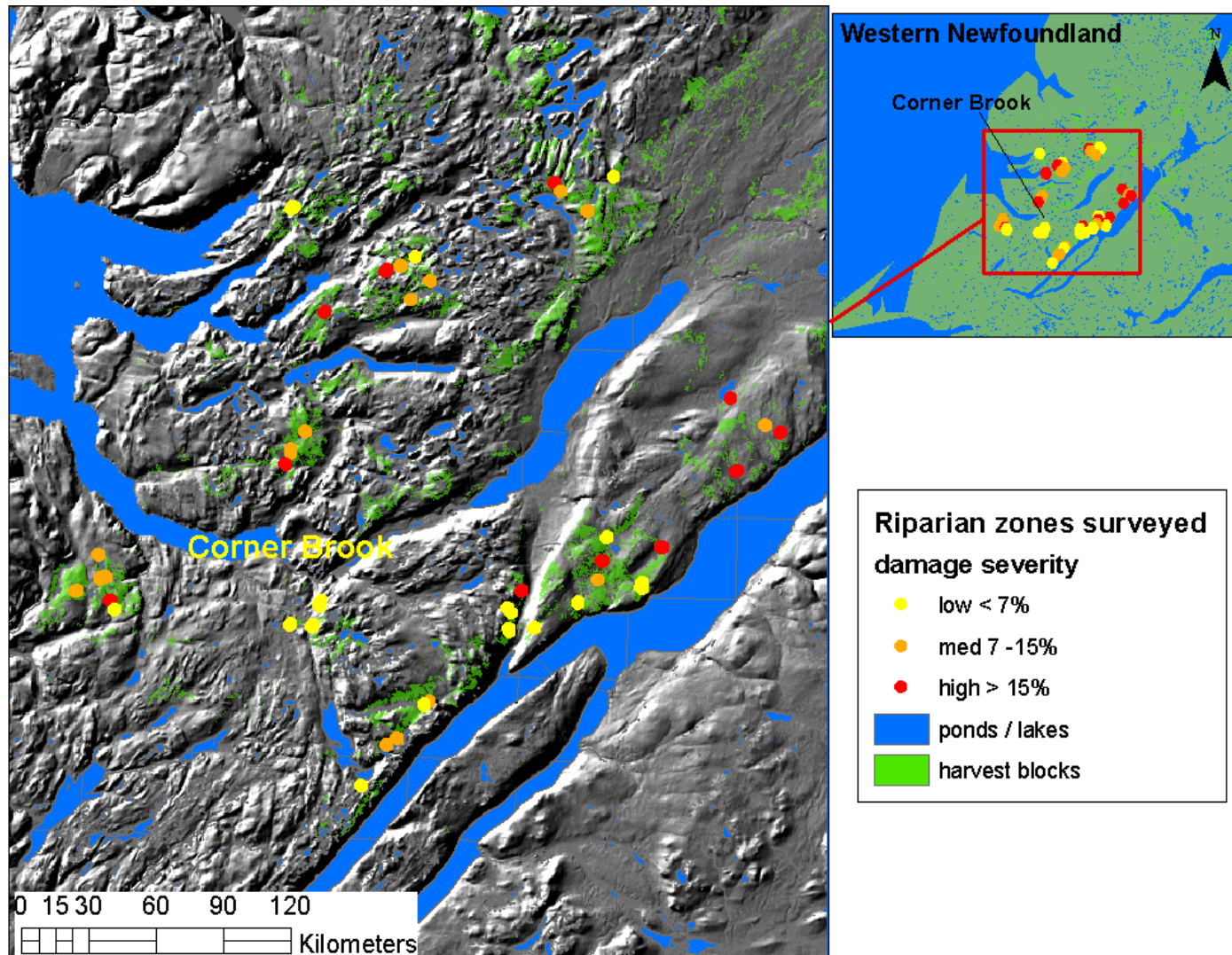


Figure 2. Map of western Newfoundland showing riparian zones surveyed and associated damage severity.

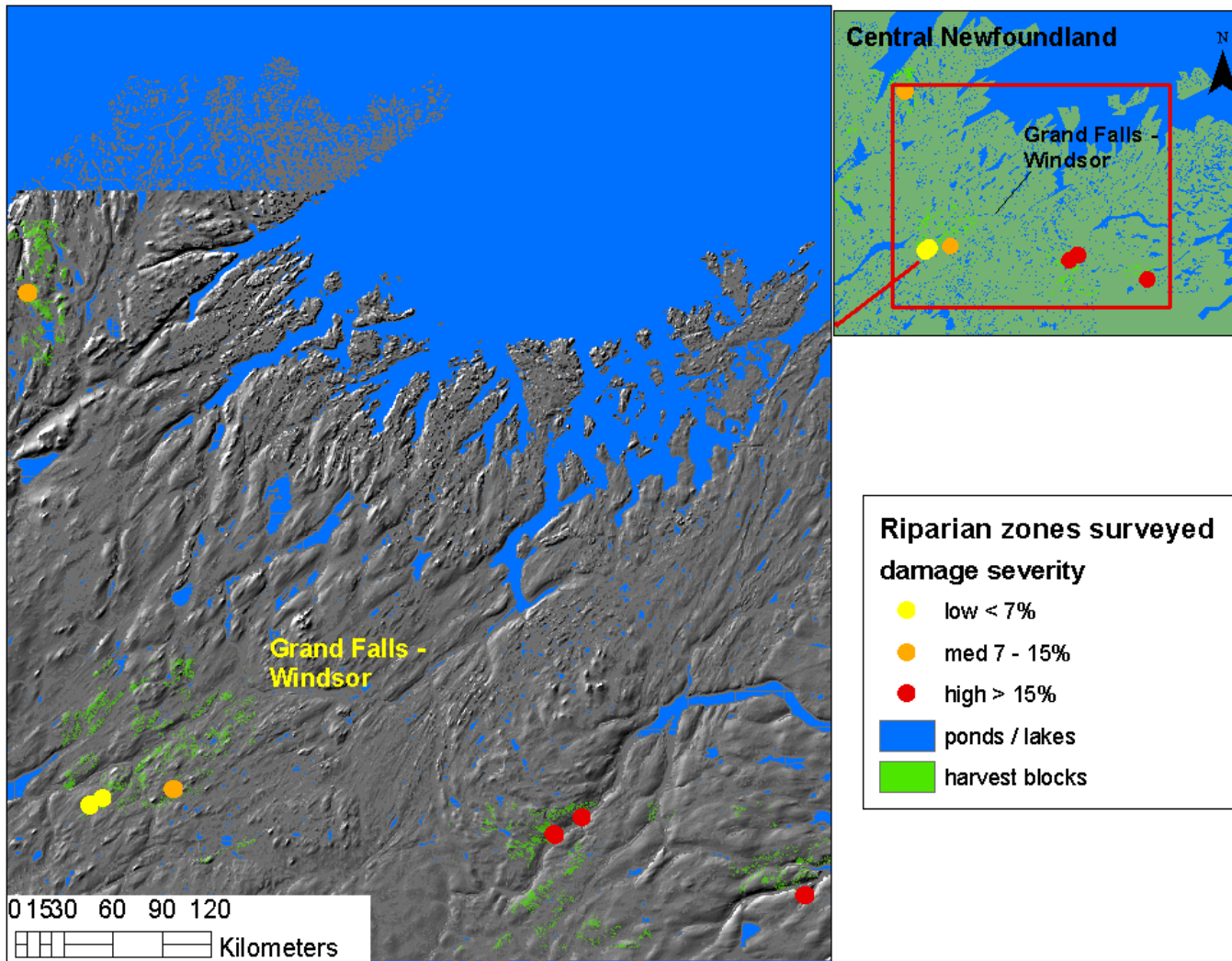


Figure 3. Map of central Newfoundland showing riparian zones surveyed and associated damage severity.

Maximum wind gusts mainly come from south-south west, and average 89 km/hr in September to a maximum of 133 km/hr in January (Environment Canada, 2007). Winds are generally from the southwest with the exception in March and April, when winds come mainly from the northeast (Figure 4).

A number of factors influence forest dynamics in this area. Major forest disturbances result from insects, primarily spruce budworm, balsam fir sawfly (*Neodiprion abietis* [Harr.]), and hemlock looper (*Lambdina fiscellaria fiscellaria* [Guen]), followed by root rots and wind damage. As a result of the natural disturbance patterns, balsam fir dominates, and although black spruce is found, pure black spruce stands are sporadic, concentrated only in rocky outcrops and poorly drained locations (Damman, 1983). The common forest type is Dryopteris-Balsam Fir forest and western Newfoundland supports some of the most productive stands in Newfoundland (Online http://www.nr.gov.nl.ca/forestry/maps/west_eco.stm, accessed September 10, 2007). White birch is found commonly throughout the area, and white spruce stands are found sporadically.

Covering nearly 28,000 km², the central Newfoundland region encompasses the central and northeastern third of the island, which has the most continental climate of anywhere in insular Newfoundland (Online http://www.env.gov.nl.ca/parks/library/pdf/Ecoregions/Island_2c_portage_pond%20-%202007.pdf, accessed September 10, 2007). The climate results in the highest summer and lowest winter temperatures for the island, with an annual mean temperature of 4.6 degrees Celsius and a monthly mean range of from -7.1 to 17.5 degrees Celsius. Annual precipitation is 1034mm of which snowfall and rainfall comprise 297cm and 735mm, respectively (Figure 4). The most frequent wind

directions are west and southwest, and no monthly average winds come from the northeast. Maximum wind gusts range from 105 km/hr in June to 172 km/hr in January (Figure 5) (Environment Canada, 2007).

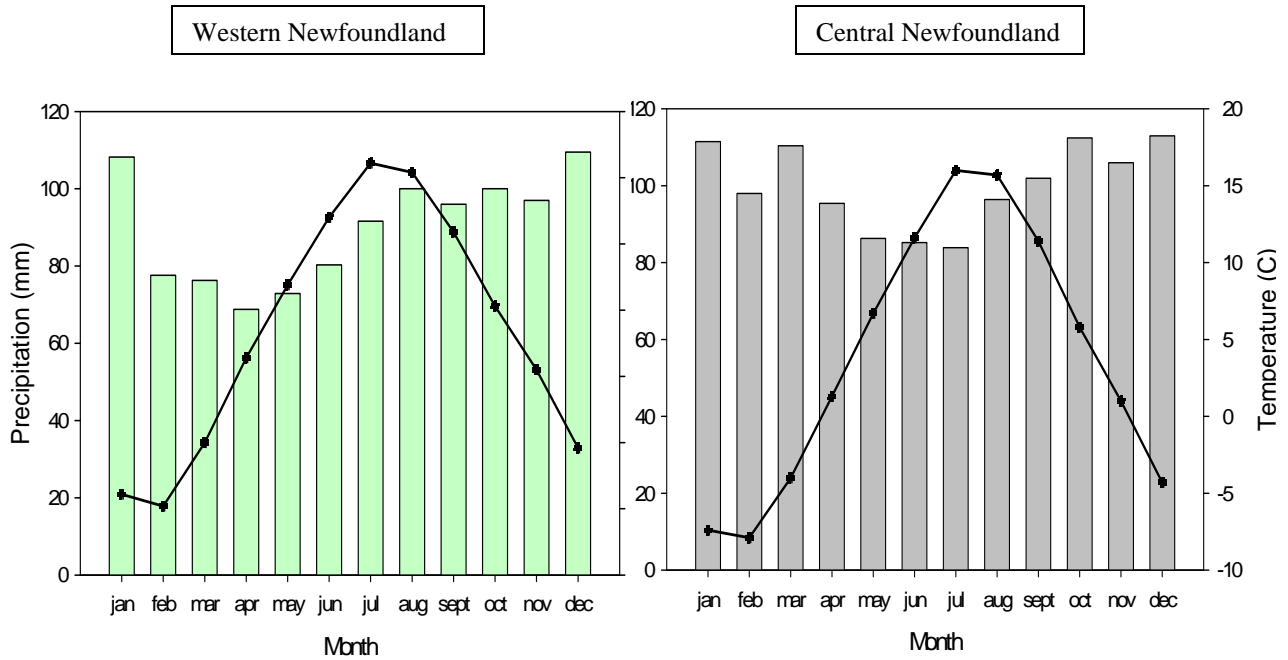


Figure 4. Average monthly precipitation and temperature for western and central Newfoundland.

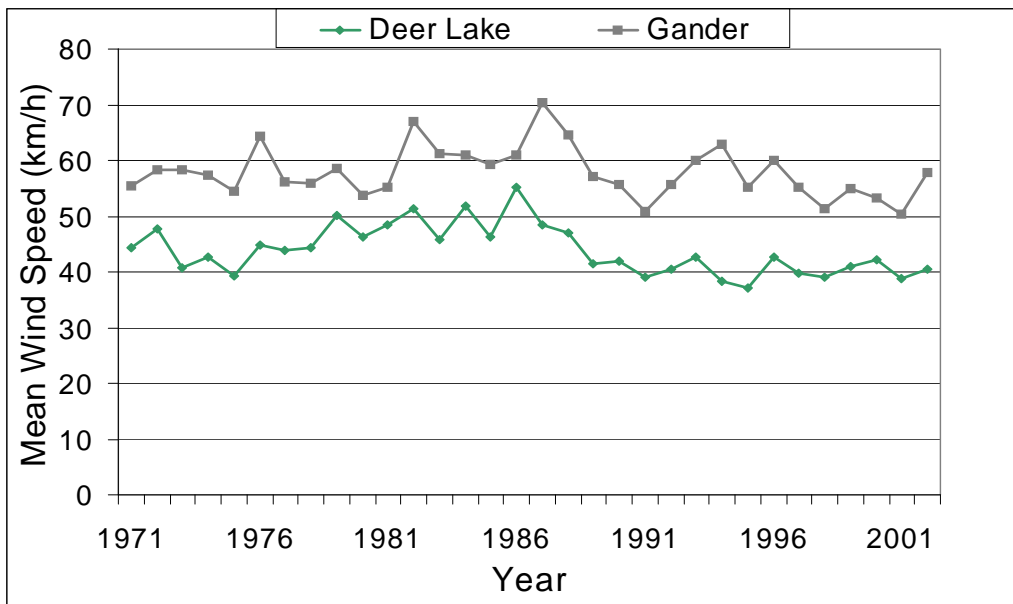


Figure 5. Average annual wind speed for western and central Newfoundland for 1971 to 2001.

Due to warm summers, extended periods without precipitation, and high evapotranspiration rates, soils in the northern part of this region exhibit actual soil-moisture deficiency. Characteristic forests are of coniferous and mixedwood stands. Fires have played a major role in this region's natural history, which has converted much of the balsam fir-feather moss forest to pure black spruce forest (Online http://www.nr.gov.nl.ca/forestry/maps/central_eco.stm, Accessed on September 10, 2007)

2.2 METHODOLOGY

Using the Newfoundland and Labrador Department of Natural Resources (NLDNR) database, 1:50,000 and 1:250,000 scale maps of operating areas were produced and all riparian zones were identified on maps. The maps were not accurately depicting the state of riparian zones (some were harvested, some were not present at all) so the majority of riparian zones had to be identified through field reconnaissance. All riparian zones that could be found in the field (the entire population was not surveyed), regardless of the time since harvest were surveyed. The only requirements was that riparian zones were of sufficient size (>100m in length) and composed of merchantable trees.

2.2.1 Field Data

Tree-level data were collected from two continuous strip plots (each 4 m wide) oriented parallel to the riparian edge (Figure 6). One plot was placed 2 m in from the riparian zone-clearcut edge and the second plot was placed 2 m from the riparian zone-stream bank interface. Plot length was subject to topographic, forest structure, and/or cut

block design features and ranged from 100 m to 500 m in length. In each plot, individual tree measurements were collected for all standing and windthrown trees of merchantable size (> 8 cm dbh). Tree species, condition (live or dead), and DBH (cm), were collected for all standing trees. For each windthrown tree, the species, DBH, condition, height (m), height to crown (m), crown base width (m), and location of failure (root, stem, and crown) was measured. As well, each windthrown tree was examined for the presence of rot including brown cubic rot, white string, and root rot. The direction of windthrow (°) and Global Positioning System (G.P.S.) coordinates were recorded for each windthrown tree. Stand density (stems/ha) was calculated for each plot using the individual tree data.

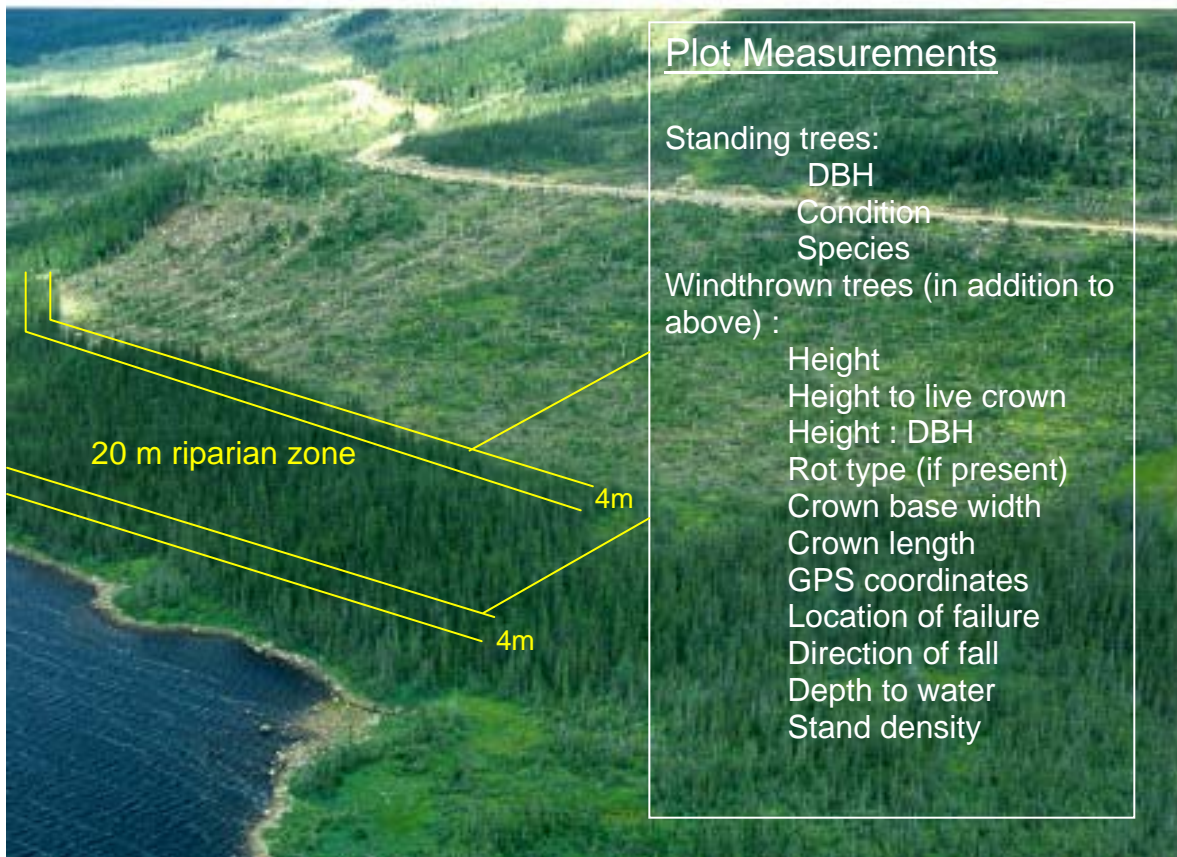


Figure 6. Picture displaying plot layout and field measurements taken in each plot.

2.2.2 GIS Data Compilation

Neighbourhood and stand-level variables were assessed using ArcGIS ESRI® ArcMap™ 9.2 (ESRI Inc, 2006). GIS coverage was obtained from the NLDNR and provided forest cover; including stand variables such as stratum, height (m), age (yrs), site class (good, medium, poor), and crown closure (%), as well as cut block location, area and year harvested and finally streams and lakes inventory.

A flow-channel, wet-areas and depth-to-water map was constructed by way of flow direction and flow accumulation algorithms from the NASA SRTM DEM data for Newfoundland, as described by Meng et al. (2005). An example of this map is shown in Figure 7.

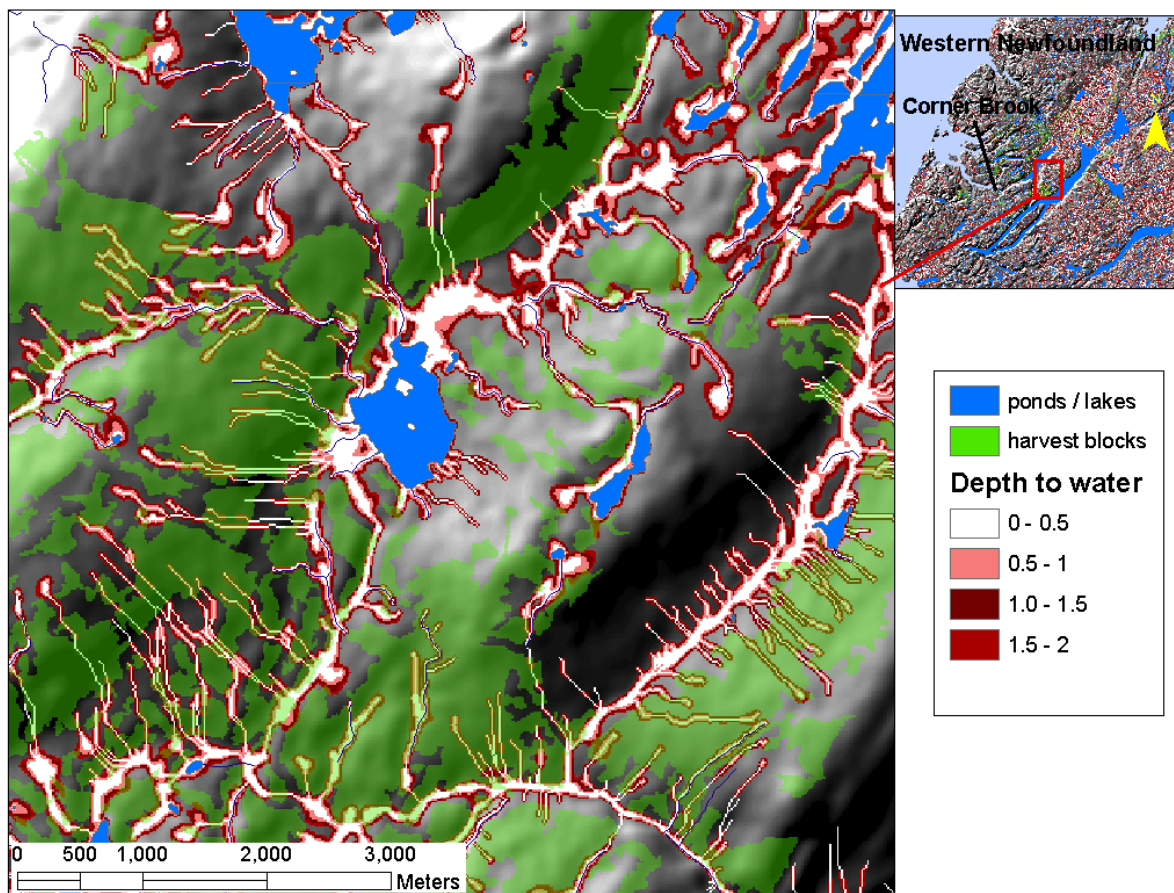


Figure 7. Wet areas map for section in western Newfoundland.

The same DEM was used to derive the distance-limited topex map (Online University of British Columbia Windthrow Research Group, Faculty.forestry.ubc.ca/mitchell/windthrow.htm, accessed June 7, 2007). Distance limited topex is a measure of the topographic modification of local wind speeds. It is the sum of angle to skyline in eight cardinal directions within a specified distance (Quine and White, 1994) (Figure 8). This study calculated the Topex index from 500 to 2000m was assessed. Topex-2000 m has been shown to be a good predictor of damage and wind speeds (Hannah et al., 1995; Mitchell, 2001).

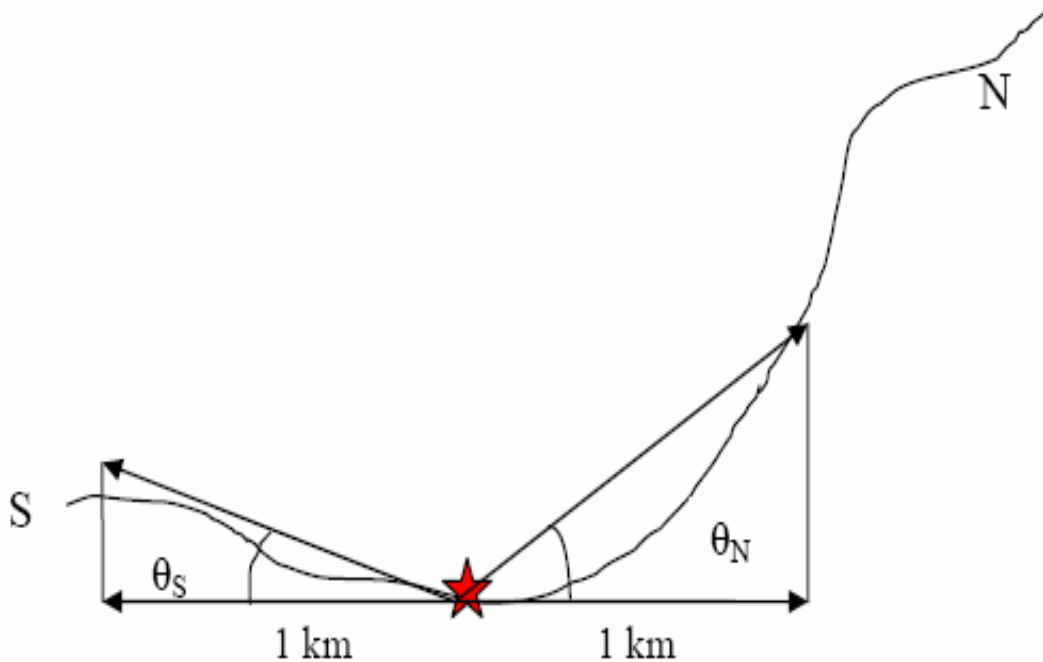


Figure 8. Illustration of topex at 1km for a north (N) to south (S) transect located in a valley bottom (Ruel et al., 2002)

Fetch, another exposure variable, is defined as the uninterrupted distance wind can travel before contacting a forest edge. A fetch index map was developed for the existing harvest block layer, using a script that estimates total uninterrupted distance for each grid

cell up to 300 m for each of eight cardinal directions (Figures 9). The maximum fetch value for a given cell is 2400m (8 x 300m). A fetch distance of 300 m was used in this study, equal to 10 tree heights in length, beyond which little change in wind speed profile would be expected in a conventional opening (Scott and Mitchell, 2005).

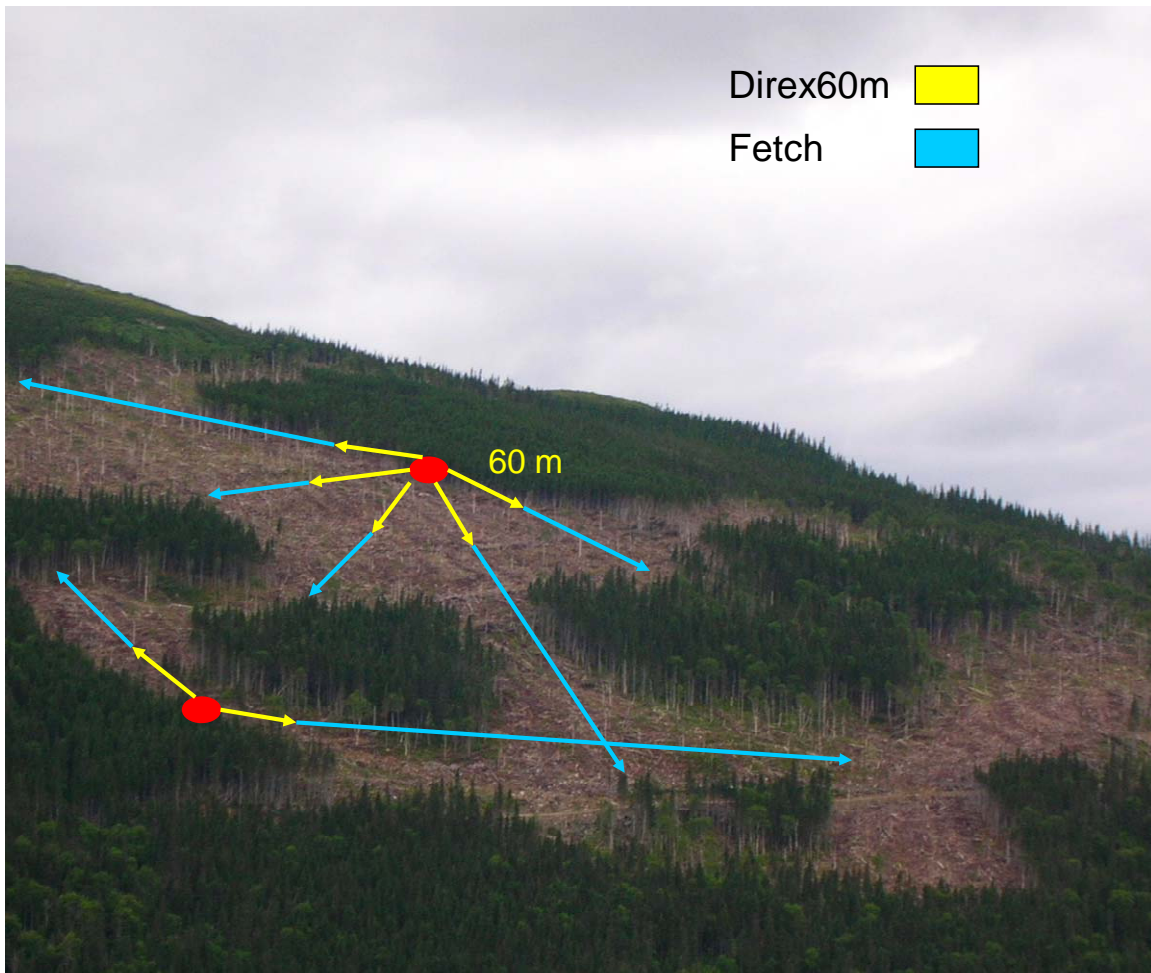


Figure 9. Illustration of direx and fetch. The cut edge in the top right has a direx of 5 versus a direx of 2 for the bottom left edge. Fetch is limited to 300m and is the sum of the distance for all cardinal directions open, with a maximum value of 2400 m.

Another index of exposure that is related to fetch is direx. Direx is a local exposure index and has only recently been studied as a predictor of windthrow seems valid (Lanquaye, 2003; Scott and Mitchell, 2005). DIREX is determined similar to fetch. A

map is constructed using ArcGIS spatial analyst extension, harvest block coverage, and a script that calculates the total number of eight cardinal directions where opening length is greater than a set distance. In this case, distances of 20, 40, 60, and 100 m were examined. These different lengths (20, 40, and 60) were chosen based on previous work that has suggested that wind loading on windward facing edges drops after a length of three tree lengths (Gardiner, 1997; Novak et al., 2000). The 100 m distance was chosen because of the larger openings associated with the size of cutblocks in the area.

A variety of cut block features were determined using ArcGIS, including cut block size (ha), shape (straight or irregular edge), and structure (contiguous or patchy). In Newfoundland, cut blocks tend to increase with each year. Therefore, rather than relying on the size of the most recent and immediate cut associated with the riparian zone, cut block size was calculated as the sum adjacent cuts less than 5 years old. The shape of the block is related to the cut block edges. Blocks with two or more straight edges were termed straight-edged and those with less than two straight edges were termed irregular. Only those edges that were in the immediate area of the riparian zone were used in determining the block shape. The structure of the cut block was determined to either be patchy or contiguous based on patchy blocks consisting of islands, other riparian zones, and or other forested stands intertwined within the cut block. Contiguous blocks were those that had no obstacle boundaries and were completely wide open areas.

Newfoundland forests have a history of insect defoliation. The NLDNR provided shapefiles of damage classes, by year, associated with hemlock looper and balsam fir sawfly. These classes include none, light, moderate, severe, and severe with mortality. The defoliation of both insects was combined and used to compute the total number of

years with defoliation damage, time since first defoliation event, time since last defoliation event, as well as the cumulative defoliation damage for each riparian zone. The cumulative defoliation was determined using the percent damage associated with each defoliation class in each year.

In this study, wind damage was quantified as the percentage of stems windthrown. This method of quantification was chosen as it is the usual method of measure for windthrow in Newfoundland. Using a percentage of stems also helps visualize the damage as compared to other measures such as volume (m^3/ha) or basal area (m^2/ha) windthrown. Where damage is classed as low (<7%), medium (15%), or high (>15%) these damage classes are based on previous observations that the author and the NLRZWG feel are acceptable levels of damage for each classification.

2.2.3 Data Analysis

Windthrow data are analyzed by plot, except for differences in relation to tree characteristics, tree failure mode, and rot type, which are on an individual tree basis. An independent samples t-test was used to test the significance of differences between means of two cases such as species and tree characteristics and differences between block characteristics and exposure variables. Data were analyzed both as continuous data as well as classified data. To test for significant differences among tree, neighbourhood, and stand level characteristic classes, a one-way analysis of variance was used. For both the t-test and ANOVA a Levene's statistic was used to test for homogeneity of variance. To test relationships between single continuous variables and percent windthrow, simple regressions were constructed. The main windthrow models are multiple regressions and

terms that reduced the overall deviance ($p < 0.05$) were retained. Pearson's correlation was used to test for significant relationships between variables used in modeling, and where two variables were highly correlated, only one was fit in the model. Three models were constructed, one for inner plots and outer plots separately, and then one for both plots combined. Independent samples t-test and ANOVAs were performed using SPSS[®] 12.0 for Windows (SPSS Inc., Chicago, 2006). Simple and multiple regression analysis were performed using StatView[®] 5.0 for windows (SAS Institute Inc., 1998).

2.2.4 Windthrow Risk Map Construction

Construction of a windthrow risk map was accomplished using an ArcGIS ESRI[®] ArcMap[™] 9.2 (ESRI Inc, 2006). The model parameters that best predict wind damage are entered into the map calculator, which calculates the predicted probability of damage for each cell. Since the dependant variable of the model is the log of percent windthrow, the regression formula is transformed by placing it to the power of 10. A full step-by-step procedure for map construction, including all the significant inputs based on the windthrow models can be found in appendix I and is discussed further in the results section.

3.0 RESULTS

3.1 GENERAL CHARACTERISTICS

Fifty two riparian zones were surveyed, and a total of 18,666 trees were sampled, 1814 of which were windthrown. Some riparian zones had adjacent cuts associated with one side of the riparian zone, while others had two sides bordered by adjacent cuts. Seven riparian zones were surveyed in central Newfoundland and 45 in western Newfoundland, accounting for 18 plots or 247 windthrown trees and 120 plots or 1567 windthrown trees, respectively. Riparian zones surveyed were located in a variety of tree, neighbourhood, and stand-level conditions (Table 1). Damage ranged from 0-76% with plots on average suffering 12% of stems windthrown. There was no difference in damage severity between central and western regions ($p = 0.702$), although there was a small sample size in central Newfoundland.

3.1 TREE LEVEL VARIABLES

The common mode of failure was uprooting (76%), with the remainder of trees failing at the stem (22%) and at the crown (2%). Stem snap accounted for 33% and 19% in central and western regions respectively (Table 2). Balsam fir and white spruce failed more frequently at the roots than black spruce, which was more prone to stem snap. Almost half (47%) of wind damaged trees were subject to rot. Root rot, brown cubicle and white string, was present in 24%, 19%, and 4% of windthrown trees respectively. The type and percentage of rot differed by region. Central Newfoundland had higher

amounts of brown cubicle rot, related to more trees failing at the stem, while western Newfoundland had higher amounts of root rot, associated with uprooting.

Table 1. Summary of tree, neighbourhood, and stand-level variables.

Variable	Mean	Std. Dev.	Min	Max
Windthrown trees (n = 1814)				
Height (m)	12.9	2.9	4.5	23.2
Dbh (cm)	17.4	5.6	8.0	44.0
Height:dbh	0.7	0.1	0.3	1.5
Height to live crown (m)	8.1	2.5	1.0	17.0
Crown length (m)	7.2	4.6	0.4	22.1
Crown base width (m)	2.3	0.9	0.6	7.6
Neighbourhood				
Cut Age (yrs)	4	2	1	10
Direx20	2.3	3.6	0	8
Direx40	2.4	2.5	0	8
Direx60	3.2	2.1	0	8
Direx100	1.5	1.8	0	8
Stand				
Density (stems/ha)	1871	605	388	4140
Stand volume (m ³ /ha)	119	35	63	191
Cut area (ha)	78	63	2	303
Slope (%)	12.3	11.6	0.5	41.8
Topex500	18.9	15.3	-0.8	73.3
Topex2000	25.0	15.3	1.8	71.2
Elevation (m)	253.7	75.5	52	422
Simple Fetch (m)	104.4	39.6	0	190

Table 2. Percentage of stems windthrown by failure type, species, and region.

	Uprooting	Stem Snap	Crown Snap
Balsam fir	79	19	2
Black spruce	71	27	2
White spruce	82	16	2
Total	76	22	2
Region			
Central	64	33	3
Western	79	19	1

Windthrow differed between species. Balsam fir was more commonly windthrown (13%) than black spruce (9%) and white spruce (9%) (Table 3). Hardwood species were the least likely to be windthrown. The two dominant species differed in tree height: black spruce = 13.2m, balsam fir = 12.1m, $p = <0.001$. There were also differences in crown length ($p = <0.001$) and crown base width ($p = <0.001$) between the two species. Balsam fir had longer, wider crowns. No differences were found between height to diameter ratio ($p = 0.691$) and height to live crown ($p = 0.865$), but the diameter of windthrown fir was larger than that of spruce, with a mean of 17.9 cm and 16.2 cm, respectively ($p = < 0.001$).

Table 3. Number of damaged, undamaged, and percent damaged of trees by species.

Species	# Undamaged	# Damaged	Percentage Windthrown
Balsam fir	9663	1224	13
Black spruce	6168	537	9.0
White spruce	468	42	9.0
White Birch	542	5	0.09

Tree diameter differed between windthrown and standing trees ($p = < 0.001$): mean diameters were 17.5cm and 14.1cm, respectively. Diameter distributions for windthrown trees contained a higher percentage of large trees than that of standing trees (Figure 10). Highly damaged plots contained a greater percentage of large diameter stems, and the percentage of large diameter stems decreased with decreasing damage severity. Each damage class had distinct population of diameters. Low damage plots had high percentage of 8 to 12 cm diameter stems, while medium-damage plots contained a higher percentage of 14 cm to 24 cm diameter stems. High- damage plots generally had a higher percentage of 18 to 40 cm diameter stems.

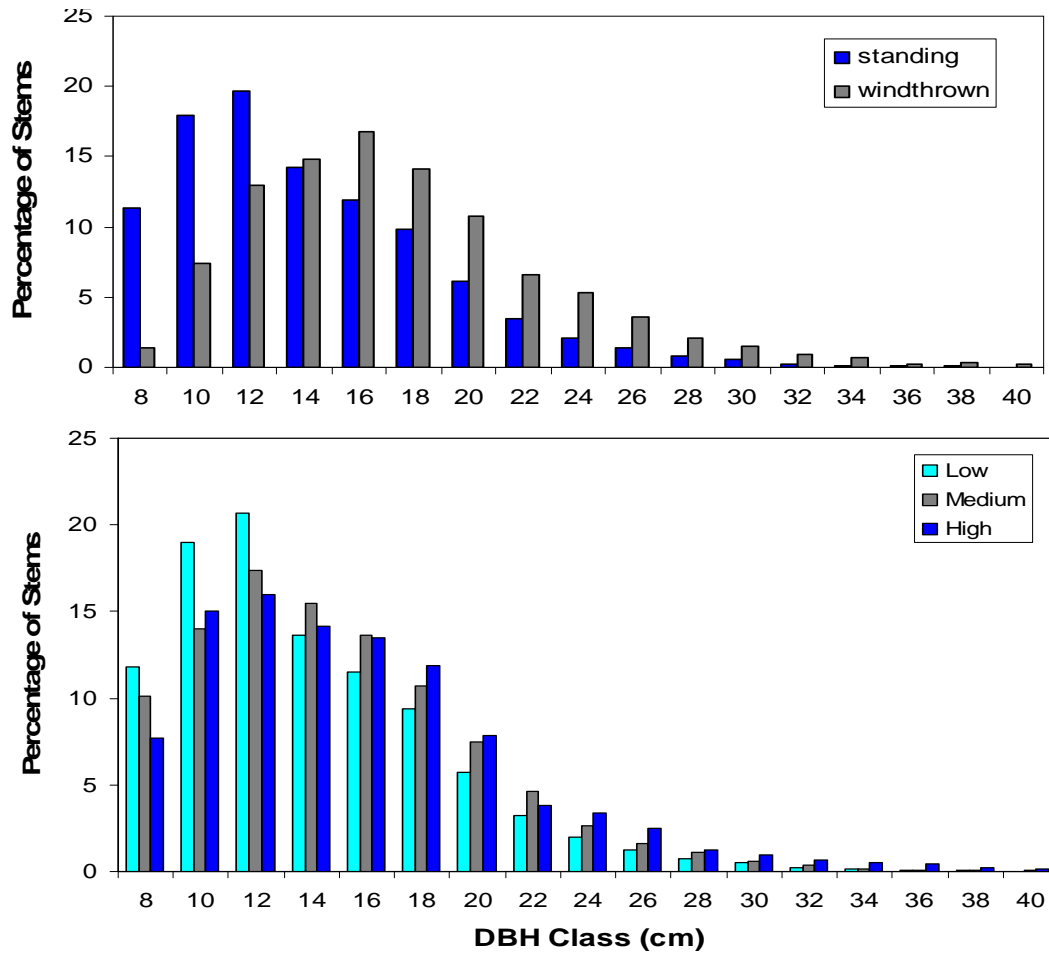


Figure 10. Diameter distribution comparison between windthrown and standing trees and between damage severity.

No other relationships were found between percent windthrow and tree characteristics or classed tree characteristics. Percentage windthrow was not related to height to diameter ratios of windthrown trees ($r^2 = 0.02$, $p = 0.607$) or classed height to diameter ratios ($p = 0.659$). Damage increased with increasing height to live crown ($r^2 = 0.04$, $p = 0.02$) but there was no significant difference between height to live crown classes ($p = 0.333$). Plots with height to live crown measurements of less than seven meters averaged 11% of stems windthrown, and increased with increasing height to live crown to 14.7% and 16.3% for height to live crowns of nine meters and greater than nine

meters respectively. Damage was not related to crown base width ($r^2 = 0.02$, $p = 0.152$), plots had a mean damage of 9.3% where windthrown trees had crown base widths of less than 1m which increased to 14.7% and 16% damage for 2m and greater than 2m crown base widths. While no significant difference was found between classes ($p = 0.254$) the variability in damage did increase with increasing crown base width.

Wind damage increased with decreasing stand density ($r^2 = 0.257$, $p = < 0.001$) and differences existed between stand density classes ($p = < 0.001$). Damage decreased from 21.3% in plots with less than 1500 stems/ha to 3.8% in plots with greater than 2500 stems/ha (Figure 11). Stand density did not differ between inner and outer plots ($p = 0.822$).

An initial wet areas map showed damage was negatively correlated with the depth to water and was significantly different between other variables such as failure location and rot. It became apparent, however, that the official stream inventory was not accurate, and a number of existing streams were missing in this inventory. Riparian zones that were surveyed and associated with streams were then digitized, and a new wet-areas map was constructed (Table 4). The new wet-areas map also provides information regarding the connectivity of the various often isolated stream segments that are part of the official stream inventory (Fig. 12).

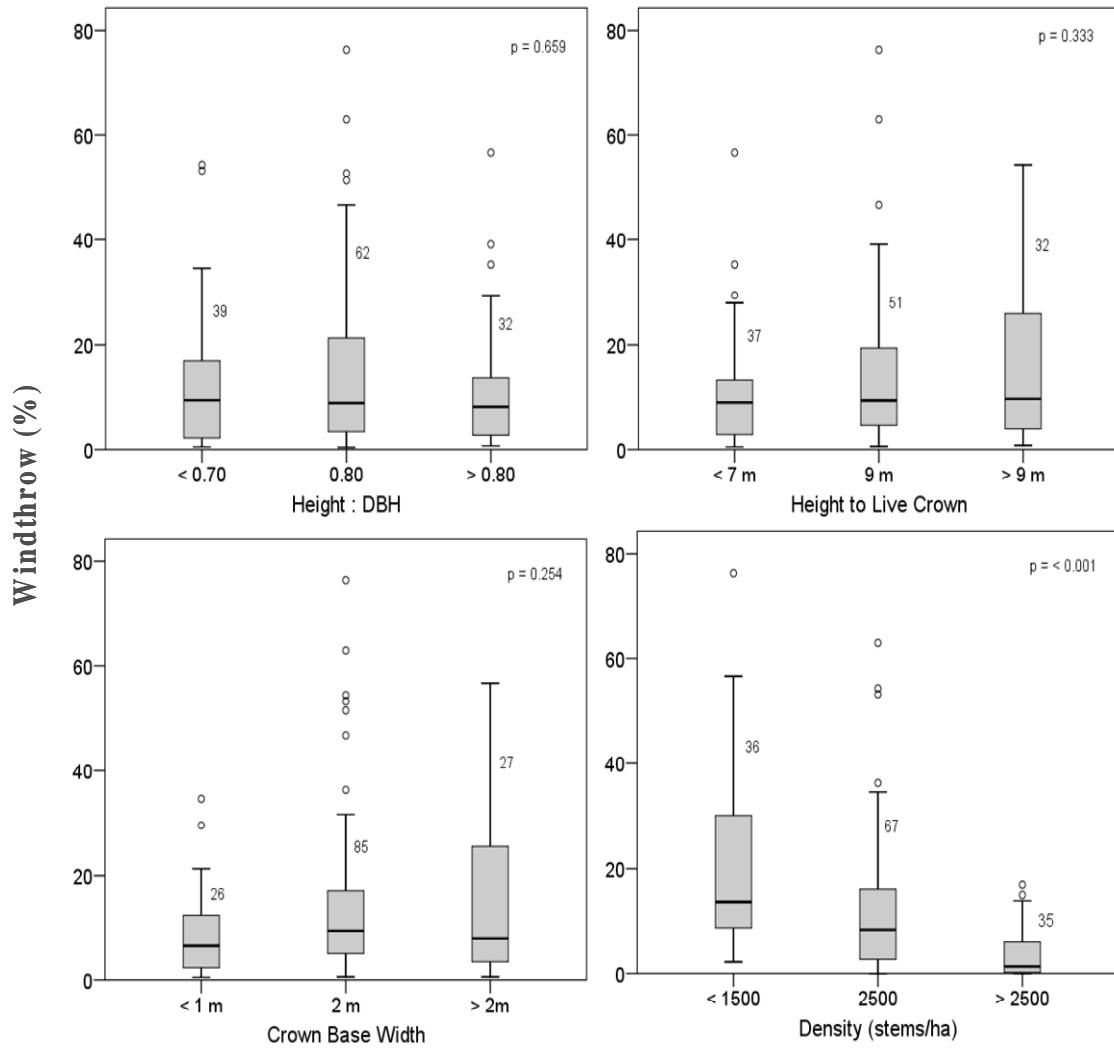


Figure 11. Box plots for windthrow (%) by height to diameter ratio, height to live crown, crown base width, and stand density.

Table 4. Percent conformance between inventoried streams and lakes and predicted wet areas.

Water type	# of plots	Inventory conformance (%)	Wet areas Mapping conformance(%)
Ponds / Lakes	18	100	100
Streams	120	70	100

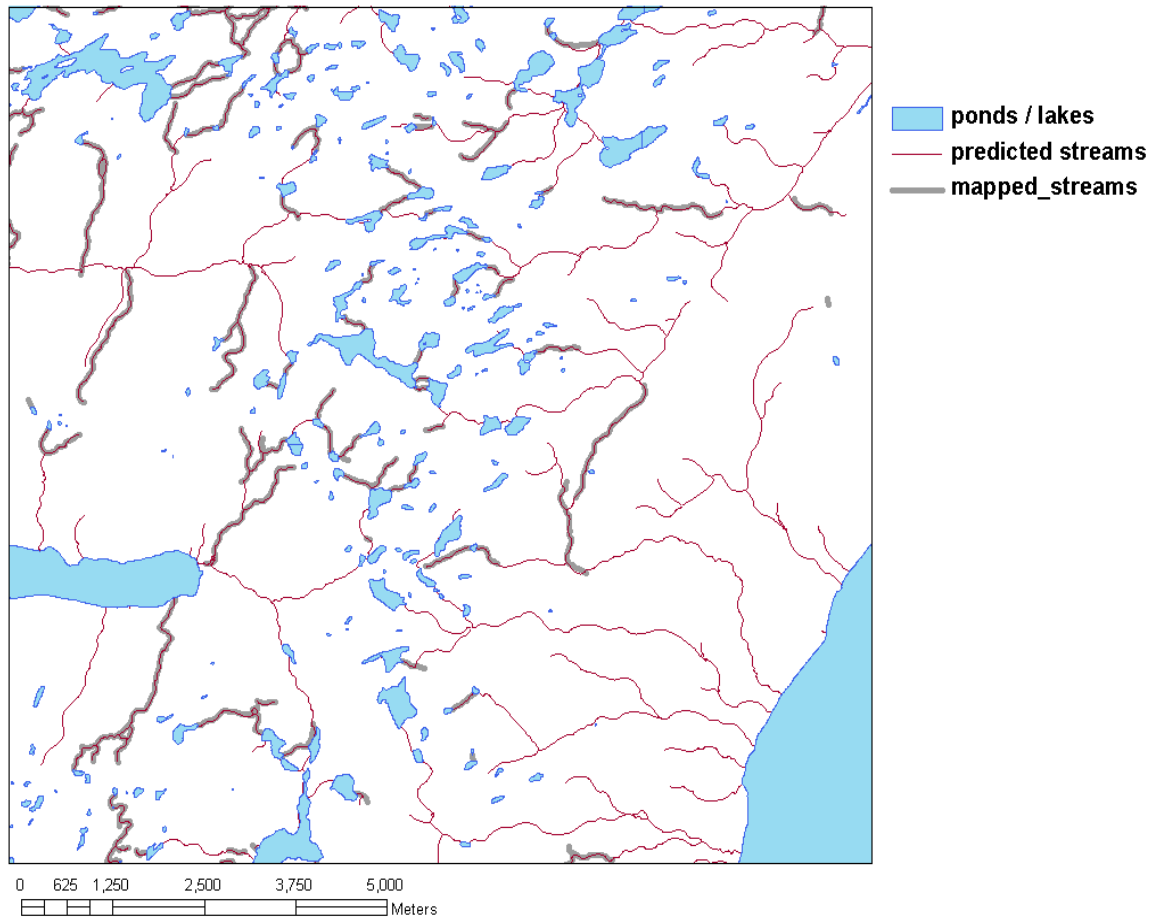


Figure 12. Map section showing mapped inventoried streams (dark lines) and predicted streams.

Differences in depths to water were found between species, with black spruce failing in wetter areas than balsam fir ($p < 0.001$). The depth to water was significantly different between inner and outer plots ($p < 0.001$). Regression analysis did not reveal a significant relationship between windthrow and depth to water when looking at outer and inner plots separately. Wind damage, however, was related to depth to water for the combined data ($r^2 = 0.043$, $p = 0.015$), such that the extent of damage increased with increasing depth to water. This result is only indirectly related to the depth to water variable, because the wind-exposed trees of the outer zone would naturally be located on higher ground than the trees in the inner zone (average depth to water along out zone =

2.8 m, = 1.2 m for the inner zone). Also, higher stand densities were generally in higher depths to water thereby further negating the detection of a simple cause and effect relationship between shallow depth to water and increased windthrow frequencies (Figure 13). Also, no relationship was found between depth-to-water and rot type or failure mode.

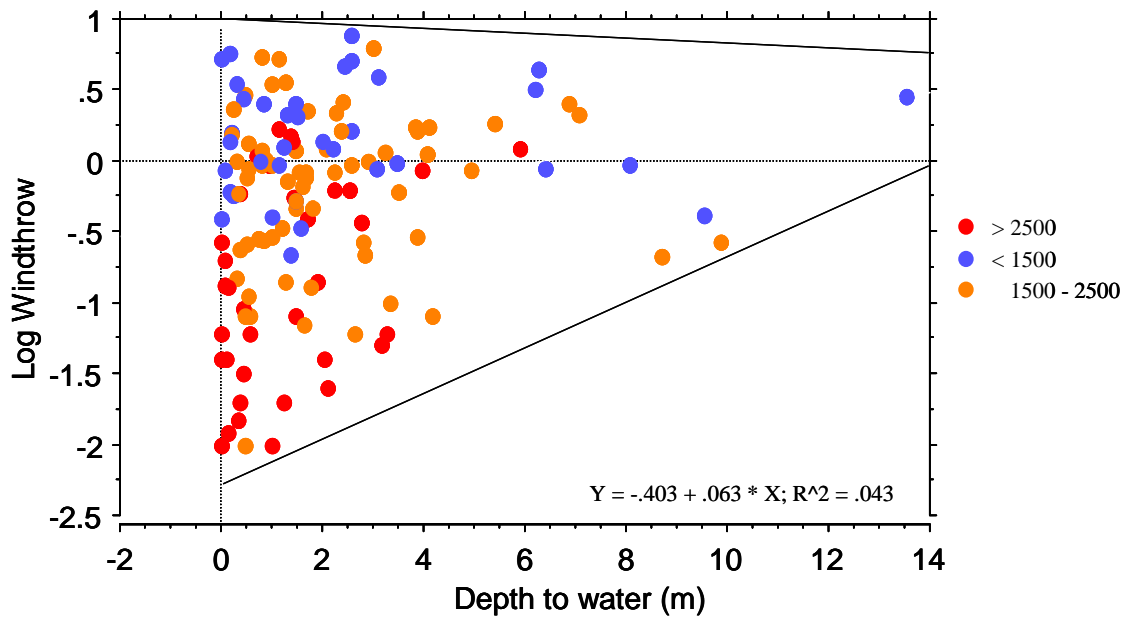


Figure 13. Simple regression plot for log windthrow and depth to water, split by stand density class.

3.2 NEIGHBOURHOOD / STAND LEVEL VARIABLES

Exposure indices were the most significant predictors of windthrow in riparian zones. Among the direx indices, direx60 was the best overall windthrow predictor, and topex500 was a better predictor than topex2000 (Table 4). The variability and severity of damage increased with increasing Direx60 values ($r^2 = 0.155$, $p = 0.001$), and with

decreasing topex500 values ($r^2 = 0.032$ $p = 0.037$). Direx60 and direx100 were the only direx indices significantly related to windthrow.

Table 5. Significance and predictive power of direx* and topex variables.

Exposure Variable	R ²	p value
Direx20	0.002	0.694
Direx40	0.002	0.736
Direx60	0.155	0.001
Direx100	0.082	0.018
Topex500	0.032	0.037
Topex2000	0.006	0.380

* Direx regressions include outer plots only.

Topex500 was not different between inner and outer plots ($p = 0.89$). Topex500 values ranged from 1 to 67 and damage was higher in more exposed plots where topex500 values were less than 20 (average = 15.0%), then in more sheltered plots with topex500 values greater than 20 (average = 10.0%). Damage also increased with increasing fetch ($r^2 = 0.04$, $p = 0.021$). Damage increased in extent and variability as fetch values increase from 50 m of open cut (averaged 8.1%) to 150 m of open cut (averaging 14.3%).

There was no difference in damage associated with cut block characteristics such as cut block area ($p = 0.869$): damage to plots was similar in cuts less than 30 ha and cuts greater than 90 ha in size. Windthrow was similar with plots associated with irregular or straight cut block edges ($p = 0.536$). Plots in irregular cut blocks experienced an average wind damage of 13.4% while those in straight edged cut blocks experienced an average damage of 11.7% (Figure 14). Exposure related to the block shape, quantified with topex500 had a small effect ($p = 0.06$), with plots in irregular-edge blocks being slightly more exposed and subject to slightly more windthrow than plots in straight-edge blocks. Exposure related to block shape, quantified by fetch value (amount of openness around

the plot) was not different ($p = 0.086$) between irregular and straight-edge blocks. Similarly the amount of openness around the plot within a set distance as quantified by *direx60* was not different between the two block shapes ($p = 0.856$).

Windthrow was not different between block structure, contiguous or patchy (average = 14.0% and 10.3%, respectively, $p = 0.174$), even though there was differences between the two block structures and exposure indices. *Topex500* was significantly lower between contiguous and patchy cuts (average = 16 and 28, respectively, $p = < 0.001$), indicating that plots in contiguous cuts are more topographically exposed. Also, plots associated with contiguous cuts were significantly more exposed as it relates to fetch values ($p = < 0.001$) and *direx60* values ($p = < 0.009$), as the amount of openness is higher around plots in contiguous cuts.

Windthrow varied with respect to tree position in relation to the predominant wind directions: damage was higher and more variable with plots facing windward than leeward (average = 17.0 and 8.6%, respectively, $p = 0.001$). No relationship was found between damage and aspect ($r^2 = 0.004$, $p = 0.440$). Plots associated with adjacent cuts on both sides of the riparian zone experienced no greater damage than those that were associated with only one cut face ($p = 0.970$). It should be noted, however, that damage is therefore double in riparian zones.

The affect of exposure is most noticeable comparing wind damage to outer and inner plots. Damage to outer plots (78% of fallen trees) was significantly higher than in inner plots ($p = < 0.001$). The mean windthrow for outer plots was 18% versus 6% for inner plots. Generally the direction of fall was into the riparian zone regardless of the direction the riparian zone faces. Over 70% of all windthrown trees fell into the riparian zone,

while only 20% of trees fell out towards the cut over. Less than 10% fell at an angle or parallel to the riparian zone.

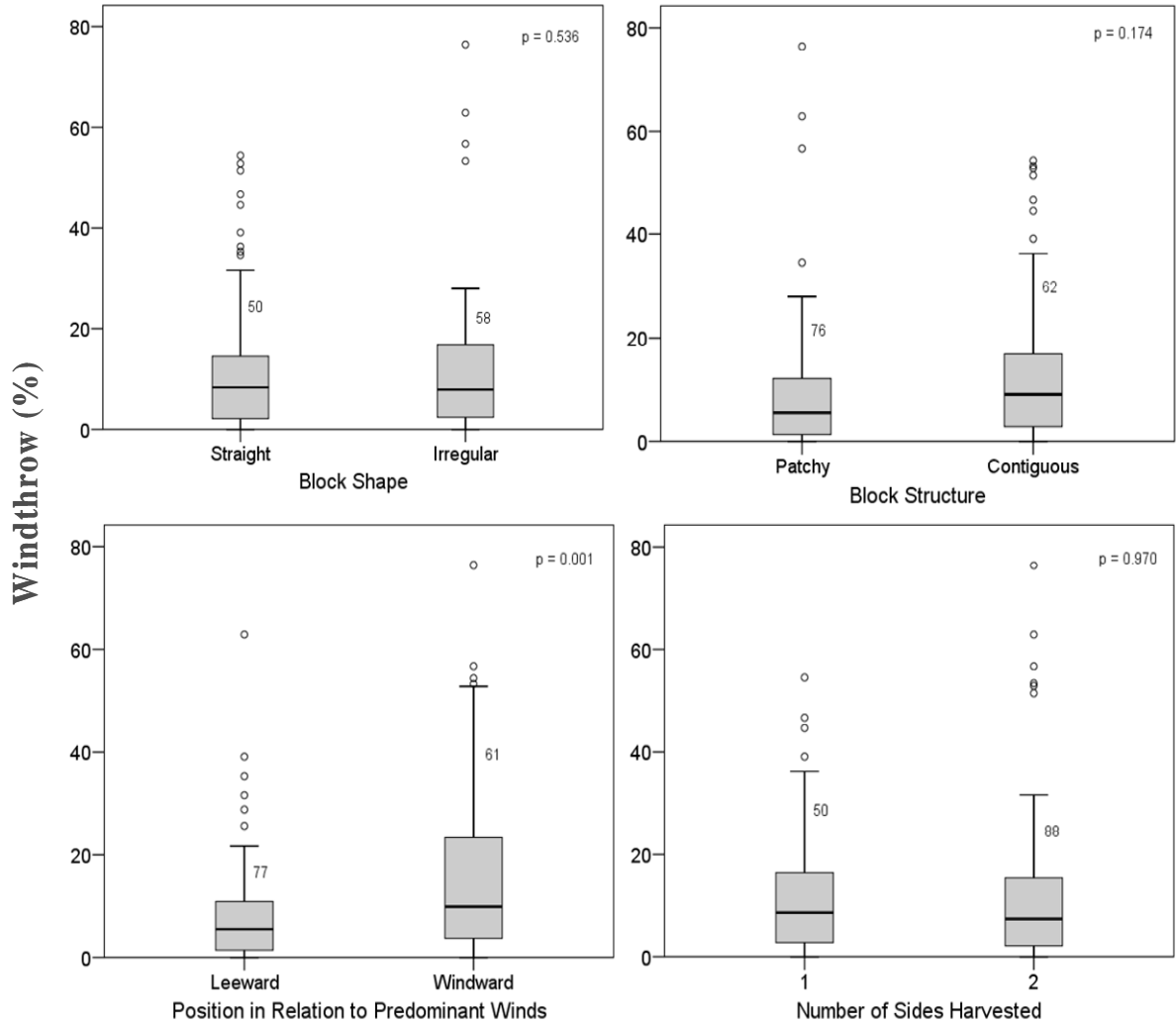


Figure 14. Box plots for windthrow (%) by cutblock shape and structure, position in relation to predominant winds, and number of sides harvested.

3.3 WINDTHROW MULTIPLE REGRESSION MODELS

Several correlations exist among the tree-level variables (Table 5). For example, the diameter of windthrown trees was positively correlated with crown base width, and

highly correlated with the diameter of standing trees. The diameter of windthrown and standing trees were both positively correlated to the height of the windthrown trees. The height of windthrown trees was also closely related to other characteristics including the height to live crown, crown length, crown base width, and slope.

A number of neighbourhood and stand-level variables were moderately correlated with one another (Table 6). For example, stand density was negatively correlated with the diameter of windthrown and standing trees, and with the crown length of windthrown trees.

Table 6. Pearson's correlations for variables used in multiple regression analysis*

Variable 1	Variable 2	*Correlation Coefficient
Windthrow dbh (cm)	Windthrow crown base width (m)	0.646
Windthrow dbh (cm)	Dbh standing trees (cm)	0.669**
Dbh standing trees (cm)	Slope (%)	0.500
Density (stems/ha)	Dbh windthrow (cm)	-0.470
Density (stems/ha)	Dbh standing trees (cm)	-0.545
Density (stems/ha)	Windthrow crown length (m)	-0.400
Height of windthrown trees (m)	Windthrow height to live crown (m)	0.641
Height of windthrown trees (m)	Windthrow dbh (cm)	0.812
Height of windthrown trees (m)	Windthrow crown length (m)	0.480
Height of windthrown trees (m)	Windthrow crown base width (m)	0.523
Height of windthrown trees (m)	Slope (%)	0.525
Height of windthrown trees (m)	Dbh standing trees (cm)	0.683

*Correlations significant at the 0.01 level

** Average dbh on plot basis

With the dependant variable of log windthrow percentage, four models were constructed: outer zone only, inner zone only, and two different models with inner and outer zone combined. The two combined models included one with direx60 and another replacing direx60 with plot (Table 7). No tree-level variables were selected for in the

models and were the first variables removed. Neighbourhood and stand level variables were the most predictive variables. Two variables retained relate to exposure of the riparian zone. Direx60 was an important input for both model 2 and model 3 and topex500 was important for model 1, model 3, and model 4. In model 1 windthrow increased as topex500 decreased or exposure increased. In model 2 windthrow increased as direx60 increased, i.e., as the number of cardinal directions a riparian zone faces increases). In Model 3 and 4, similar relationships exist.

Table 7. Multiple regression models for outer, inner, and all plots combined.

Variables	Coefficients			
	Inner Model (Model 1)	Outer Model (Model 2)	Combined Model (Model 3)	Combined Model (Model 4)
Intercept	1.068	0.096	0.663	2.066
Density	- 0.00074	- 0.00029	- 0.00068	- 0.00068
Direx60	-----	0.142	0.166	-----
Topex500	- 0.0089	-----	- 0.0089	- 0.0089
Plot	-----	-----	-----	- 0.6921
<i>Model building data</i>	<i>n =70</i>	<i>n =67</i>	<i>n =137</i>	<i>n =137</i>
P value	< 0.001	< 0.001	< 0.001	< 0.001
F value	74.730	17.630	83.510	80.33
R ²	0.690	0.355	0.653	0.644

Depth to water was initially retained in models but stand density replaced this variable as the better and more consistent predictor variable for all four model situations: In all cases, windthrow increases as stand density decreases. Density was closely related to other tree level characteristics and as such likely takes tree level variables into account within the model.

Model 1, built with inner plot data only, explained the most variability ($r^2 = 0.690$, $p = <0.001$) than the other three models. Model 3, built with data from all plots, explained almost as much of the data variations ($r^2 = 0.653$, $p = <0.001$) as model 1. Model 2, built on the outer plot data only, explained the least amount of the data variations ($r^2 = 0.355$, $p = <0.001$). Model 3 accounts for inner and outer plots with the input of direx60, which is highly correlated with plot. All inner plots have direx60 values of zero, considering inner plots are surrounded by forest and are not open in any direction. Model 4 was constructed with direx60 being replaced with plot. This model explained slightly less variation in the data. Direx60 improved model predictability and is more advantageous operationally since it takes into account the shelter afforded outer riparian edges.

In general, the topex500 (Figure 15) and direx60 (Figure 16) exposure indices were determined to be the most important variables to account for the various blow-down observations. The fetch index (Figure 17) was also related to these observations, but did not add to the model performance when used as an additional variable. To a large extent, this is due to the similarity between the fetch and the direc60 maps, with the latter showing more and sharper details than the former (compare Figure 16 with Figure 17).

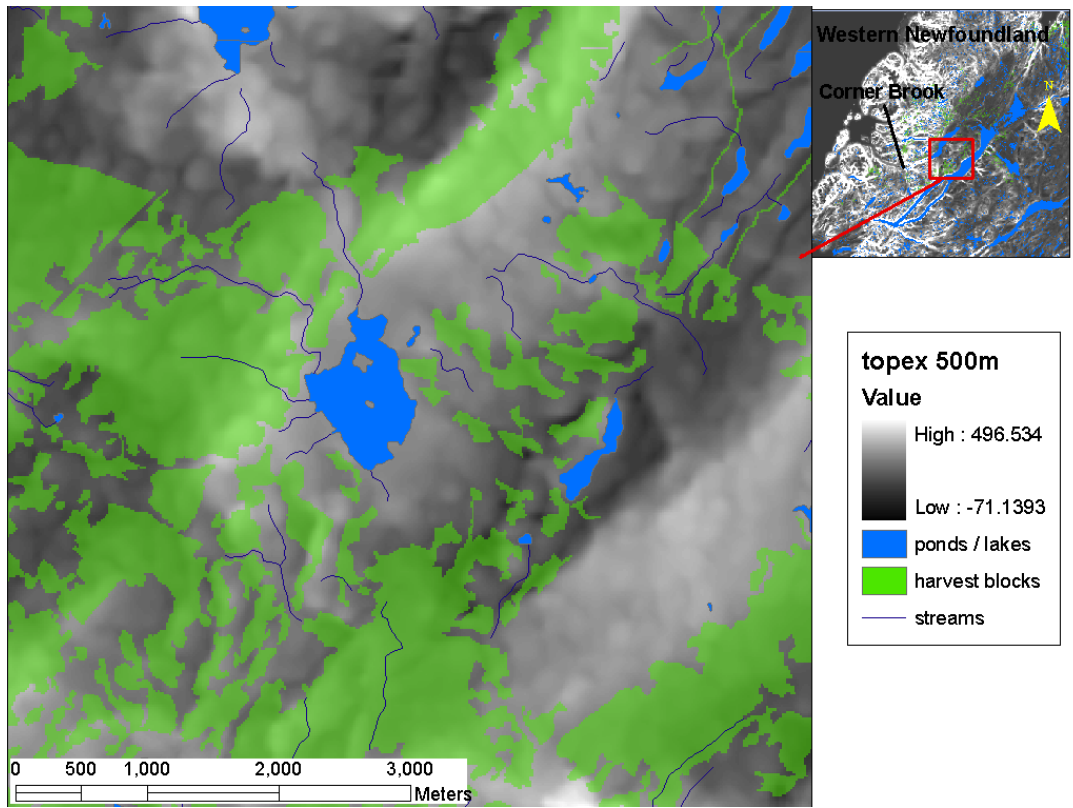


Figure 15. Topex500m map for a section in western Newfoundland.

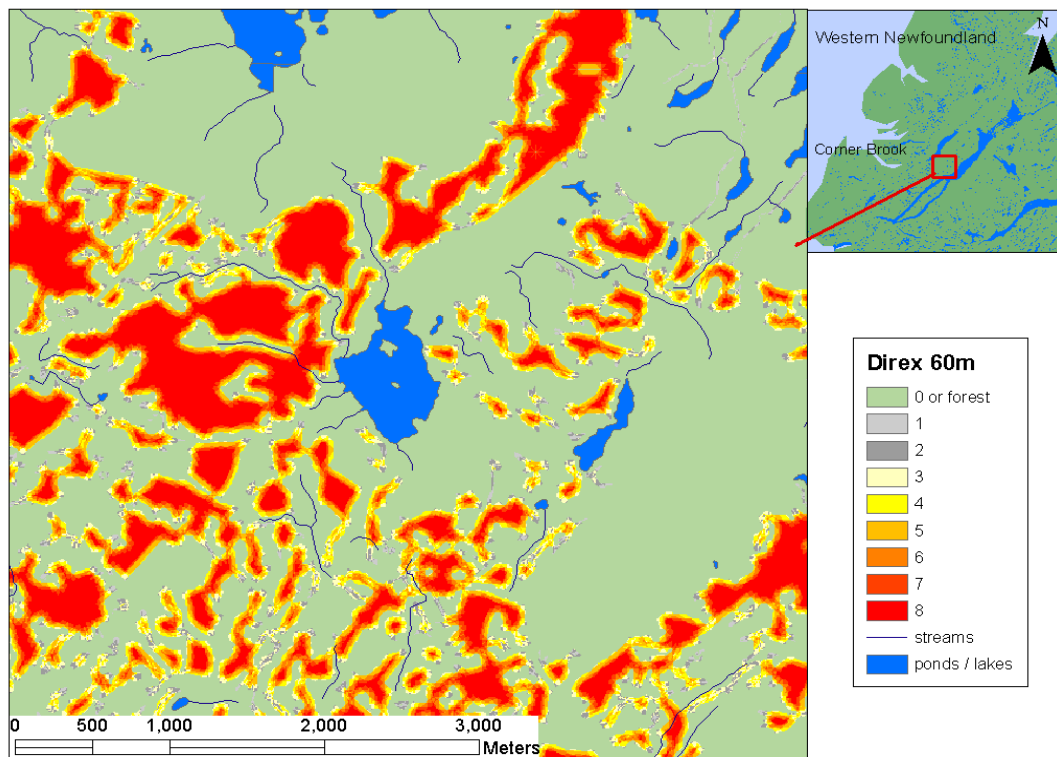


Figure 16. Direx60m map for a section in western Newfoundland.

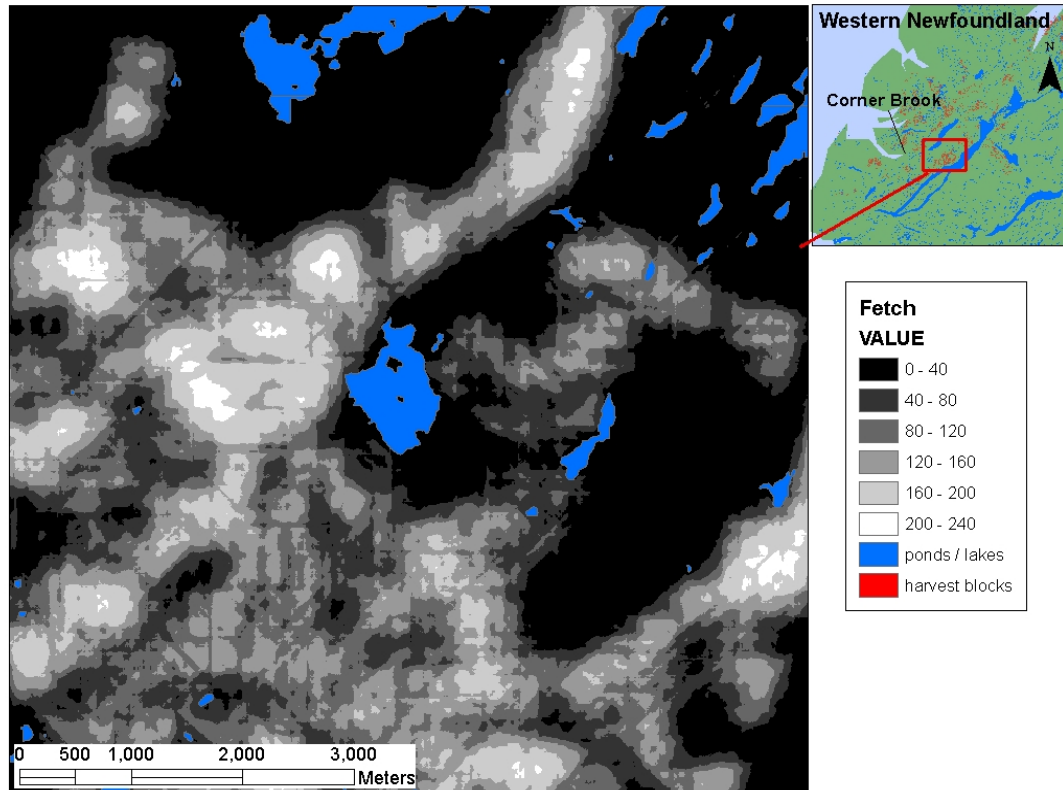


Figure 17. Fetch map for a section in western Newfoundland.

3.4 WINDTHROW RISK MAPPING

Risk maps showing the expected percentage of windthrow within in each mapped riparian zone were generated using the ArcGIS map calculator and regression models 1, 2 and 3. In so doing, 20 m buffers were placed on all mapped streams, ponds, and lakes including the streams derived from the digital flow-channel and wet-areas mapping effort (Chapter 2). The 20 m buffers were divided into inner (0-10m) and outer (10-20m) windthrow risk zones. An average stem density value was applied to each zone, based on the permanent sampling plot data from Newfoundland's DNR forest inventory.

The riparian zone risk map based on the inner and outer zone models (Model 1 and 2) is illustrated in Figure 18. As can be seen, the estimated windthrow risk is generally low for this example on account of the uncut areas next to the buffered flow channels, and the low occurrence of windthrow (< 10%) within the inner zones of the riparian areas in general. Appreciable windthrow, however, is estimated to occur along the outer zones where the cut areas are intersected by the flow channels.

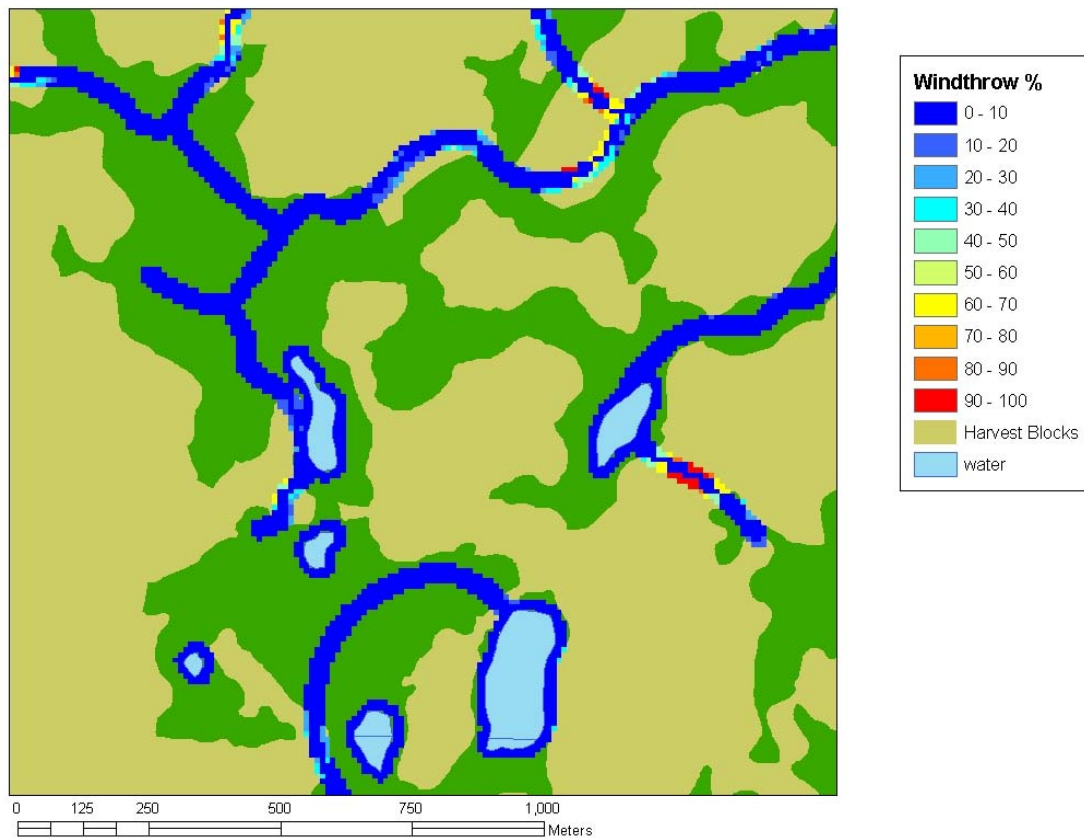


Figure 18. Section of windthrow risk map constructed using the inner (model 1) and outer models (model 2) that gives a percentage of expected stems windthrown for inner (0-10m) and outer (10-20m) zones, respectively.

Another inner and outer zone risk map was constructed for the same area of Figure 18 by assuming that all forest areas would have been harvested, except for the 20 m

riparian zones (Figure 19). As shown, this increased cutting would lead to increased windthrow risks, especially along the outer edges of the riparian zones.

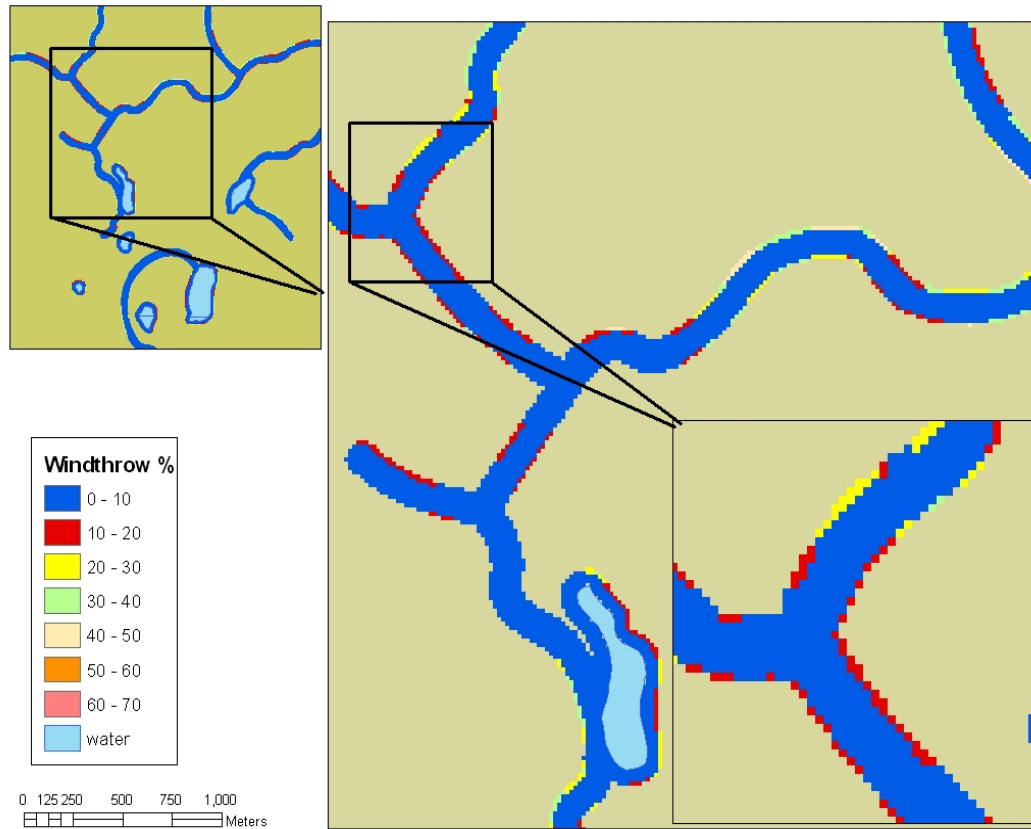


Figure 19. Section of windthrow risk map constructed using inner (model1) and outer (model2) models that gives a percentage of expected stems windthrown for inner (0-10m) and outer (10-20m) zones. In this risk map everything surrounding riparian zones is harvested.

Yet another riparian zone risk map was generated based on the combined windthrow model (Model 3, Figure 20). Similar to the risk map in Figure18, damage is higher along riparian zones that intersect the cutblocks, and remain relatively low in other areas.

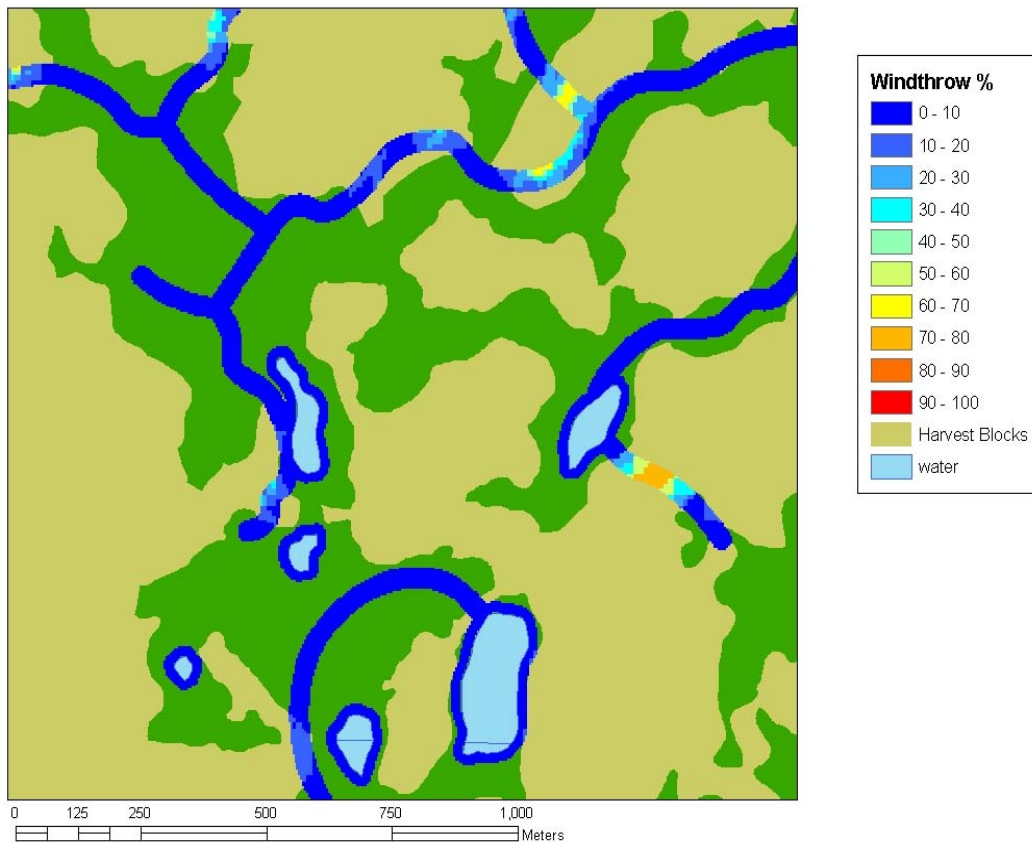


Figure 20. Section of windthrow risk map constructed using the combined model (model 3) that gives a percentage of expected stems windthrown for the riparian zone as a whole.

A final risk map was generated using the combined model (Model 3) to assess windthrow risk anywhere across the landscape, riparian or otherwise, to estimate the likelihood of windthrow from open stand conditions (as in cutblocks containing remnant tree, along existing cut edges, riparian or otherwise). Inspecting the result of doing this in Figure 21 reveals significant differences in estimated within-cutblock windthrow risks. This, by itself, has obvious implications with respect to designing cutblocks with tree retention.

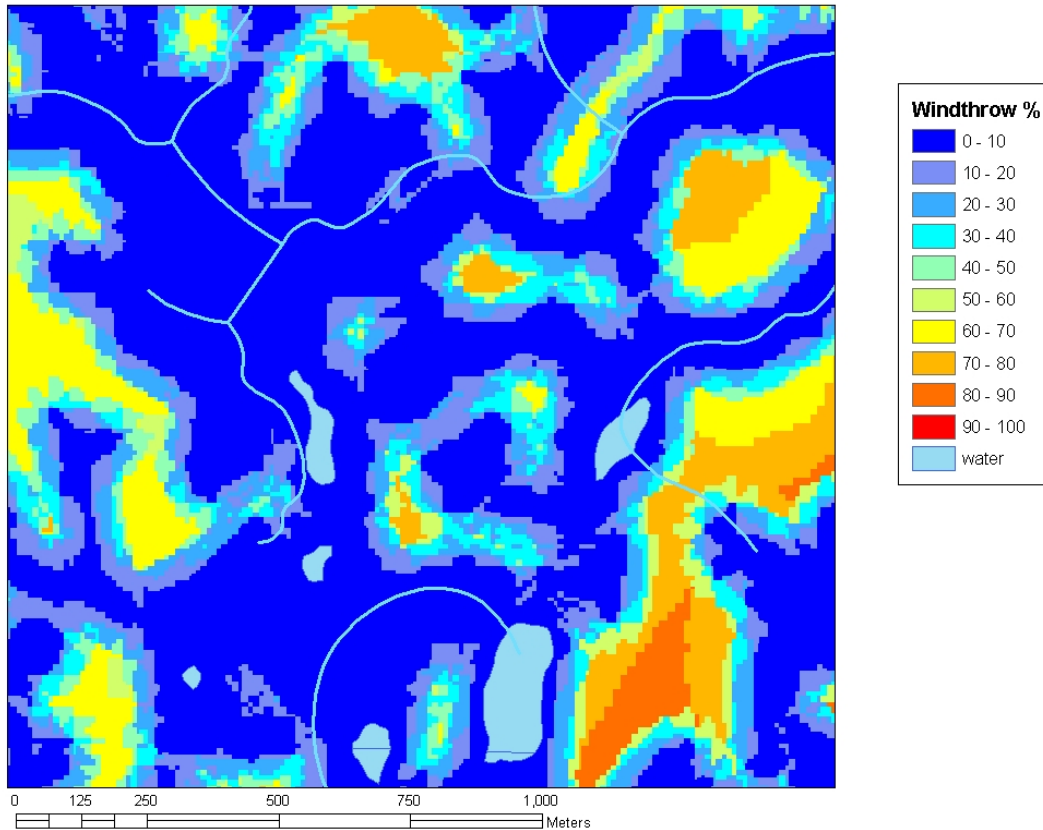


Figure 21. Section of windthrow risk map constructed using the combined model (model 3) that gives an expected percentage of stems windthrown for all cut block edges.

4.0 DISCUSSION

Wind damage to riparian zones in Newfoundland is not extensive, averaging 12%. Compared to other riparian studies, this damage is relatively low. For instance, research in the Pacific Northwest found that windthrow in riparian zones averaged 29%, 33%, and 21% in the Oregon Cascades, the Washington Cascades, and in the coastal region of British Columbia, respectively (Steinblums, 1978; Grizzel and Wolff 1998; Rollerson and McGourlick, 2001). These studies, however, also involved silvicultural interventions

(thinning) which likely increased windthrow damage as a result of lower stand density along the outer zone. Martin and Grotefendt (2007), in a study on buffer strip mortality, found cumulative windthrow was on average 22.5% in riparian zones with adjacent harvest blocks versus 15% for reference or control riparian areas. The variability of damage in these studies (0 – 100%) is similar to that found in Newfoundland (0 – 76%).

As already determined elsewhere, windthrown trees were concentrated at the outer edges of the riparian zone. For example, Martin and Grotefendt (2007) found that damage in riparian zones was concentrated on outer edges, i.e., damage was double along the outer edges of harvested blocks in comparison to control sites where riparian zones had no adjacent cut. Windthrow in the inner zone is generally reflective of stand internal accumulation of large woody debris as this arises from various factors, such as self-thinning and tree mortality, as caused by diseases, insect damage, root rot, and windthrow.

This study showed that trees are more likely to be uprooted than incurring stem snap. This is similar to observations by Flemming and Crossfield (1983), Ruel (1989, 2001), Coutts (1986), and Peltola et al. (2000). Extensive uprooting of trees on the slopes within the riparian zone has the potential to provide large sediment flux to the aquatic ecosystem below. However, this windthrow disturbance can also be beneficial to forest productivity, by creating gaps, increasing nutrient inputs into the available nutrient pools of the underlying soil, serving as woody debris recruitment, and rejuvenating podzols thereby obviating the natural trend towards soil acidification (Jonsson, 1993; Foster and Boose, 1995; Ulanova, 2000).

The failure mode is dependant on a host of variables. Differences between species are often detected due to differences in rooting behavior. In Newfoundland, balsam fir tree experience slightly higher levels of uprooting while black spruce trees experience higher levels of stem snap, especially under wet soil conditions such as bogs. Under such conditions, black spruce tends to propagate through branch layering, thereby generating clusters of single multi-stemmed trees all supported by the same gradually extending root stock . On uplands, black spruce rooting patterns revert to single-stem tree behavior because of a very low layering potential underneath fairly dense and ground-shading forest canopies and underlying bedrock.

Rot was prevalent in a high proportion of windthrown trees and it could have been higher since it was only noted when it could be readily seen. Nearly half of the windthrown trees were infected with rot. Many other studies have also found that rot increases the susceptibility of fir and spruce to windthrow (Frazer, 1962; Whitney et al., 2002). In contrast, however, other studies have found no such relationship. For example, Elie and Ruel (2005) found no evidence in a tree-winch study that sound and rotten trees had separate critical turning moments. In this study, however, rot incidence was not extensive in any of the pulled samples. Nonetheless, Silva et al. (1998) found no relationship between rot percentages and critical stem-breaking stress with stem rot up to 32 – 45%.

This study showed that rot type differed by species. This can be attributed to the failure mode of both fir and spruce and the opportunity to observe rot when windthrown. In trees, rot often follows insect infestations. However, there was no relationship between the amount of rot observed on the ground and the extent of defoliation as recorded

province-wide through air-photo inspection. Nor was there a relationship between air-photo recorded defoliation and windthrow. To some extent, this lack may be due to the procedural omission of not directly noting the level of defoliation per stand and windthrown tree in the field.

4.1 TREE LEVEL

Individual tree characteristics thought to be indicators of windthrow susceptibility were, in general, not good predictors of actual windthrow. For example, there was no windthrow difference with the height-to-diameter ratio, although this ratio is generally accepted as one of the best indicators of windthrow risk (Coates, 1997; Cremer et al., 1982; Peltola et al., 2000; Jull and Jager, 2001). Ruel (2003) also found no relationship between windthrow and height-to-diameter ratio in similar forests types. Instead, the field-observed wind damage along the riparian zones in Newfoundland was more related to height to live crown: the longer the stem towards the crown, the more windthrow prone that tree would be. Trees with a large height to live crowns are generally a result of stand internal tree by tree competition for light. Open grown trees, in contrast, generally react to wind through developing wind reactive wood structures within branches, stems and roots, and therefore have low height to live crown (Dunham and Cameron, 2000; Scott and Mitchell, 2005). Wang et al., (1989) found longer crowned trees generally had lower height to diameter ratios, but in this study no correlation existed between height-to-live crown or crown length and height- to-diameter ratio.

Stem diameter for windthrown trees was higher than that of standing trees: low damaged stands had diameter distributions primarily comprised of low diameter stems,

and the opposite was found for high damaged stands. In this study, the average diameter of windthrown trees in each plot was slightly correlated with stand density, crown base width, crown length, and highly correlated to windthrown tree height. No relationship between wind damage and tree height was found, but this is still an important factor as found in a number of studies (Cremer et al., 1982; Savill, 1983; Ruel, 1989, Mitchell et al., 2001). It is generally accepted that there is a 12m limit before trees become windthrow prone. During field sampling, this was observed to be the case, because younger shorter stands were stable, but older and taller stands were only stable in high sheltered situations. Also, younger and shorter stands have much higher stand densities than older stands, due to self-thinning. In this study, stand density was moderately correlated with standing and windthrown diameter, and with the length of tree crowns. Scott and Mitchell (2005) found the proportion of windthrown trees increased with decreasing post-harvest stand density. Through the use of wind tunnels, Gardiner et al. (1997) and Novak et al. (2000) found that shelter from wind damage is positively correlated with stand density.

Windthrown trees were found to increase with increasing depth-to-water, which would be zero everywhere right next to the actual stream channel within the riparian zone. This is opposite to what might have been expected because trees tend to be less stable when they grow on wet and therefore soft and poorly drained ground. In British Columbia, Mitchell et al. (2000) found damage was indeed more frequent on moist sites, but in a more recent study Scott and Mitchell (2005) found that damage did not vary with soil moisture. This lack of a negative relationship can be attributed to higher stem density in wet areas, higher damage in outer plots, and likely a combination of slope and

rockiness next to the streams in the stream valleys. When the area is flat next to the streams, windthrow occurrences decrease with increased depth to water in an almost linear fashion (Connors, 2005). Wet areas also appear to influence the tree failure mode, by making trees more susceptible to uprooting (Shaetzl, 1989; Connor, 2005). This study, however, failed to find such a relationship because of the predominant rockiness in the riparian zones of the study areas, especially in the western regions.

4.2 NEIGHBOURHOOD AND STAND LEVEL

4.2.1 Cut block Features

Cut block features were not related to wind damage as the size of the cut and its structure and shape did not influence the extent of windthrow within the riparian zones of this study. While the shape or structure of a cut block can influence the wind exposure of certain riparian zones, it was not affecting the amount of incurred damage significantly. There was no windthrow occurrence difference based on topex500 and fetch differences between patchy and contiguous cut blocks. Fetch is different between the two cutblock shapes because it accounts for the openness associated with cuts in each cardinal direction and can identify patches of stand remnants in cut blocks. Damage related to cut blocks 30 ha in size was similar to those of 120 ha. Cut blocks that reached 120 ha in size were generally a series of continuous blocks harvested over a 5 year period. Damage was not higher even in these large open blocks, the only difference was a higher amount of variability. While a positive relationship between gap size and the amount of wind loading on windward tree edges exists (Stacey et al., 1994), the results of this study may

explain the importance of exposure indices that include cardinal directions that better gauge the openness around a specific riparian zone.

No difference was detected in damage related to the position of the riparian zone in the cut block. Riparian zones located in the middle of a cut block rather than at the edge, having an adjacent cut on both sides of riparian zone, were no more vulnerable than those riparian zones at the edge of cut blocks or one side with an adjacent cut. In both cases, damage was similar in extent and variability. While the percentage of stems windthrown does not differ in plots between these two scenarios, an increased number of stems will be windthrown on the riparian zone as a whole because damage will occur on both sides of the riparian rather than just the one. Damage in this case is also dependent on the position of the riparian edge in relation to other exposure factors, and if all factors are equal the damage occurring on both sides will be similar, a natural thinning will occur until the riparian zone adapts to the newly created edge..

4.2.2 Exposure

In this study wind damage was related to all three exposure indices since shelter is an important variable minimizing windthrow risk to forest edges. Fetch is an index that takes into account cardinal direction and is a measure of the uninterrupted distance, up to 300 m (i.e. the cut block) that wind travels before hitting an edge in each direction. Direx is a modification of fetch, which instead of a measure of distance; it is a measure of the number of cardinal directions open within a specified distance. Fetch was relatively important, suggesting openness surrounding a riparian zone at larger scales than that detected by direx60 is important. The Direx index has also only recently been examined

as a potential windthrow predictor variable (Lanquaye, 2003; Scott and Mitchell, 2005). For the riparian zones in Newfoundland, larger Direx distances are related with windthrow, with Direx60 being the most predictive. The significance of these indices shows the importance of directional exposure to wind damage. Riparian zone edges afforded the shelter of being exposed to less than three cardinal directions remain much more stable than those exposed in a higher number of directions which increases the chances for wind loading on a riparian zone edge. The 20 and 40 m direx indices are not predictive as these distances searched resulted in a lack of variability, since most cardinal directions are always present. These shorter distances don't identify the patches and other forested edges, which are detected by the longer distances of 60 and 100 m and its these features that afford protection to newly created edges (Scott and Mitchell, 2005).

Topex indices relate to the topographic modification of local wind speeds. It is the sum of angle to skyline in eight cardinal directions within a specified distance. It's a measure of exposure in the topography, regardless of openings as a result of harvest. Significant wind damage due to topographic exposure has only recently been examined with significant (Mitchell et al., 2001) and non significant results (Ruel, 2000; Scott and Mitchell, 2005). The fact that the topex2000m index was not a significant windthrow predictor suggests that windthrow occurrence depends more on finer local tree-atmosphere interactions and wind speeds than on general, laminar air-flow patterns. For example, Ruel et al. (2002) found that the topex1000m predicted local wind speeds better than longer-range indices. Also, for inner riparian zones, topex500 appears to be the optimal wind-exposure predictor for windthrow.

Riparian zones that face windward to predominant winds experience a higher variability of damage. Due to the lack of wind data, which is generally a problem in windthrow studies, it is difficult to tell whether this damage is a result of predominant winds or if it is from winds that blow during the spring months. The relationship between windthrow and wind direction and speed requires better modeling of winds over terrain (Mitchell et al., 2000). In relatively sheltered situations, stands remain quite stable (Moore, 1977; Steinblums et al., 1984) as lower damage was present in riparian zones in less exposed locations.

In Newfoundland, regardless of the position of the riparian zone, windthrown trees fall towards the stream or lake. Other authors have speculated that the windthrow direction would be determined by the direction of dominant storm winds, or by the prevailing wind directions (Steinblums et al., 1984; Andrus and Froelich, 1992; Ott, 1997). In this study, the majority of windthrown trees fell into the riparian zone even when both sides had exposed faces. This suggests riparian tree fall has a strong tendency to fall directly towards the stream (see also Harriston-Strang and Adams, 1998; Welty et al., 2002), and therefore does not reflect dominant wind directions (Sobata et al., 2006). This tendency is likely attributed to the weakening of the roots along the outer part of the riparian zones, due to a variety of factors, such as accelerated root decay following harvesting, harvest-induced root damage, and overall lessening of tree-to-tree root interlocking within the harvest-affected root plates. As a result, outer zone root plates will likely give way at any time when air turbulence and wind gusts of sufficient force are turned towards the riparian zone and is likely accelerated as a result of inner trees, whose

interlocked root plate with outer trees is not damaged, and acts to pull outer trees into the riparian zone.

4.3 WINDTHROW MODELS

The four variables selected for by the models were related to exposure and stand structure. The addition of any tree level variables and cut block features to the model did not increase predictive ability and were removed. The importance of direx60 for predicting damage to outer plots demonstrates the importance of small opening exposure. As mentioned previously, stand density likely accounts for a host of tree characteristics, those that were correlated in this study and likely other variables that were not correlated, such as height. It supports the importance of neighbour interactions that protect trees from failing. Topex500 accounts for the position of the riparian zone in the landscape and has been shown to be well correlated with local wind speeds (Ruel et al., 2002). Both exposure variables were significant in other models, topex was an important variable in a cut edge model (Mitchell et al., 2001) and direx was an important variable in a patch retention study (Scott and Mitchell, 2005). In general, the approach taken shows promise in projecting likely extent of windthrow based on topographic factors alone, with an overall map reliability of about 60%. Factors due to particular tree characteristics and synoptic wind speed and direction did not increase the overall reliability of the predictions.

Windthrow models developed in British Columbia assess risk from aerial photography so large datasets can be formed, which can be split to test model building data (Mitchell et al., 2001). This method is not conducive to this type of study,

considering wind damage detection and interpretation from aerial photograph may not accurately detect low level damage that may be present and important in finer scale, sensitive areas such as riparian zones. While the models in this study have not been tested against another dataset the predictability of damage in this study is similar to other author's findings, with the exception of model 2 (35.5%). Model 1 (69.0%) and model 3 (65.3%) was similar to Kramer et al.(2001) who correctly predicted 72% of damage in a stand level windthrow study in Alaska, Peterson (2004) who correctly predicted 68-90% of trees in Minnesota, and Scott and Mitchell (2005) who correctly predicted 72 and 74% of damage in British Columbia.

4.4 WINDTHROW RISK MAP

Predicting and mapping windthrow risk in riparian zones is an important new addition to riparian zone management, and to cutblock design in general. Recent windthrow risk maps focused on cutblock edge risk (Mitchell et al., 200; Lanquaye, 2003). This study is the first effort concerning windthrow risk mapping for riparian zone, and by treating inner and outer portions of a riparian zone separately.

To apply the above windthrow risk models properly, it is important that the local vegetative, hydrographic topographic data layers are as accurate as possible. Working with the current data layers revealed a number of important data issues. For example, the hydrographic were found to be fairly discontinuous, incomplete, and not always aligned with the actual stream and bufferzone locations in the field. Working with the DEM data made the hydrographic coverage more and complete and continuous from ridge tops to

the ocean shores, and through lakes and wetlands as well. Nevertheless the DEM derived flow channels would not fully coincide with existing stream and bufferzone locations either in all cases. Similarly, the cut-block borders as digitized in the forest inventory coverage would also deviate from actual. It is therefore suggested that the data layers be inspected and corrected for actual ground locations in order to remove such input discrepancies in the process of generating the best-possible windthrow risk maps. Additional gains can undoubtedly be made by increasing the elevational point resolution of the digital elevation map for the areas of interest. The potential for increasing this resolution cost-effectively for large areas such as the island of Newfoundland exists, using photogrammetric techniques and new DEM derivation algorithms

5.0 CONCLUSIONS

Forest harvesting exposes riparian edges and wind damage is inevitable. While some damage is beneficial to ecosystem functioning, through the addition of coarse woody debris, excessive damage can pose problems. While windthrow is a complex interaction of tree, neighbourhood, and stand - level factors it is possible to predict. Through the construction of windthrow models and risk maps wind damage is now manageable.

Wind damage to Newfoundland riparian zones is lower than other author's findings and riparian zone structural integrity and therefore functionality is likely not compromised. Damage to riparian zones is concentrated to outer edges and trees within are generally protected from damaging winds, suggesting internal structure remains intact. The most frequent form of failure is uprooting and it may be important in terms of sedimentation in high risk areas on steep slopes or in inner plots. Defoliation likely plays a role in the weakening of stems and breaking up of forest stands; however this study did not detect any relationship. Rot was a large component of windthrown trees, comprising almost half of the population measured. Although it may be an important factor in stem strength, this study was unable to compare rot percentages between both standing and windthrown trees. It may be beneficial to do cull surveys of stumps along recent harvest block riparian edges to determine the actual impact of rot on wind firmness.

Neighbourhood and stand level factors are more robust predictors than tree level factors. The structure of the riparian zone is an important characteristic for determining wind firmness. Stand densities below 1500 stems/ha are vulnerable to excessive wind

damage, which can in turn compromise the structural function of the riparian zone. Stand density takes other tree characteristics into account in the models.

Exposure plays a large role in determining the wind firmness of a riparian zone. Exposure at all scales affects the wind firmness of riparian zones. Topex500 is a good predictor of riparian zone vulnerability as it relates to its position in the landscape. Larger direx indices were significantly related to damage and direx60 was the most robust of all the indices in the model. Direx60 shows the importance of small openings affecting wind firmness. Fetch was also related to wind damage, indicating that riparian zones associated with cut blocks that have large distances of exposure in numerous cardinal directions are at greater risk for damage. The cutblock size, shape, and structure were not an important factor of wind damage in riparian zones which shows the importance of directionality in exposure related windthrow variables.

While tree characteristics were not good predictors of wind damage they should not be discounted during the assessment of riparian zones for wind firmness. Some such as height to diameter ratio are strongly supported in the literature as a robust predictor. Tree diameter is significantly larger for windthrown trees than standing trees and distinct diameter distributions existed which can be used as a guide in removal and retention when managing a riparian zone.

Managing to minimize windthrow is not an easily achieved task. Wind damage needs to be first quantified. To ensure management plans are not compromised by extensive wind damage, the tools used to assess the risk need to be properly used and updated. Field assessments, risk maps, and subsequent exposure and wet areas maps can all be used in determining an accurate prescription for managing windthrow risk. Wind

damage in Newfoundland does not seem to compromise the functionality of riparian zones from a forest structure point of view and operational research should continue with the knowledge this study provides to improve riparian zone management.

6.0 RECOMMENDATIONS

The recommendations given here are for forest managers and others that are interested in windthrow research and management. The recommendations are based on the findings from this study and in most cases are specific to Newfoundland riparian zones. There are recommendations based on the results as well from the author's personal experience and observations from having worked in the windthrow field in Newfoundland for a number of years. Recommendations will first be discussed which pertain to general windthrow management and then some recommendations will be made specifically to the NLRZWG which pertain to Newfoundland riparian zones.

The following recommendations are:

6.1 GENERAL WINDTHROW MANAGEMENT

1. Windthrow is a complex process and can interrupt management plans. Risk models and risk maps should be constructed and used in forest management planning to prevent losses from a timber perspective and to minimize ecological damage. Not only should it be used to minimize damage in sensitive areas such as riparian zones it has also proved adequate in minimizing cutblock edge damage where applicable.
2. While windthrow risk maps are important management tools it should not be a substituted for on the ground assessments. Often forest coverage data may not be representative of what is on the ground, assessing the site in the field will allow

- managers a more detailed view of riparian zone firmness, allowing the collection of some tree level measurements and observations that can be used to get a more accurate portrait of windthrow risk.
3. Exposure plays a major role in the wind firmness of riparian edges. Where possible ensure that topex values are greater than 20, and that direx60 and fetch values are minimal. The more exposed the riparian the higher the risk. It is also critical where applicable to maintain or protect non merchantable trees or retention patches that afford some protection to the riparian zone edge.
 4. This study showed the importance of wet areas mapping for identifying unmapped streams. It may be advantageous for managers to construct wet areas maps for their land base. It would definitely be an asset in areas where cutblock edges or riparian zones consist of highly valuable timber, where if wind damage is extensive can disrupt management plans. It could also help timing the harvest so remnant trees have the longest period of exposure possible before soils are saturated.
 5. Monitoring of windthrow should be a high priority. Windthrow assessments should be completed shortly after a new harvest and then a couple of years after to keep adapting plans based on new findings. It would be advantageous to keep an accurate database of windthrown data which can be updated each time a new assessment is made. Managers could become familiar with their operating area and learn to adjust plans accordingly for their specific areas of operation.
 6. There is definitely a need for more accurate wind data and wind flow models over complex terrain which could certainly increase the predictability of wind damage.

6.2 NLRZWG RECOMMENDATIONS

1. In central Newfoundland non merchantable leave patches definitely increased wind firmness of the riparian zone. As mentioned above where applicable maintain and protect this features on the landscape in both western and central Newfoundland.
2. Windthrow is a process that is certainly going to occur whenever an edge is created and while during the first number of years the riparian zone structure may look as if it is compromised it certainly is not in most cases. This study has shown that internally the structure is still intact and only the first couple of meters into the riparian are where trees are felled. The only instance where damage reaches the inner zone of the riparian is where harvesting of the block created small openings in beyond the required buffer width. Creating holes in the riparian zone should be avoided.
3. If harvesting of the riparian zone is going to implemented it should be done during the harvesting of the block, not only from a cost basis, but also because trees can be marked for removal based on a forester's recommendation when the block is being laid out. Relying on the operator to selectively remove trees while maintaining a certain stand density is not wise. Certainly do not allow night harvest within riparian zones.
4. When treating a riparian zone it is important to keep stand density at a favorable level to maintain wind firmness. Where possible maintain density above 1500 stems/ha. This may pose a problem in older riparian zones, where density is already quite low and although an even lower density may have to be left, ensure

- that the distance into the buffer with the lower density is minimal. This way the internal structure is still protected and not compromised.
5. While tree level characteristics were not very good predictors of damage there are trees that should be targeted to be retained. The diameter of trees to be retained should be lower than 16 cm dbh. Trees above this diameter that should be focused on removing are dependant on species. Black spruce trees targeted should be those that are greater than 13 m in height and have short, wide crowns. Fir trees targeted should be greater than 12 m in height and have long, wide crowns. Trees already showing signs of damage should also be removed.
 6. In western Newfoundland areas of interest are those with rocks and bedrock showing under existing windthrown trees. These areas were noted for having some extensive windthrow since it is basically tree roots laying on a layer of rock with only a small amount of soil and moss for anchorage.

7.0 LITERATURE CITED

- Achim, A., Ruel, J.C., Gardiner, B.A., Laflamme, G., Meunier, S., 2005. Modelling the vulnerability of balsam fir forests to wind damage. *Forest Ecology and Management* 204, 35–50.
- Andrus, C., Froehlich, H., 1992. Wind damage in streamside buffers and its effect on accelerated sediment in coastal Oregon streams. *Fundamental Cope Report*, Vol. 5, No. 1. Oregon State University, Corvallis OR, pp. 7 -9.
- Beese, W.J., 2001. Windthrow monitoring of alternative silvicultural systems. In: *Proceedings of the Windthrow Researchers Workshop*, Richmond, BC, January 31-February 1, 2001 (compiled by Mitchell, S.J., Rodney, J.), pp. 2–11 (<http://faculty.forestry.uc.ca/mitchell/publications/wtreswkshp2001.pdf>).
- Behr, C.E., 1921. A study of windfall in the Adirondacks. *Journal of Forestry*. 19. 632-637.
- Canham, C.D., Papaik, M.J., Latty, E.F., 2001. Interspecific variation in susceptibility to windthrow as a function of tree size and storm severity for northern temperate tree species. *Canadian Journal of Forest Research*. 31, 1-10.
- Coates, K.D., 1997. Windthrow damage 2 years after partial cutting at the Date Creek silvicultural systems study in the interior Cedar - Hemlock forests of northwestern British Columbia. *Canadian Journal of Forest Research*. 27, 1695 - 1701.
- Connors, T.L., 2005. Do water table levels correlate with windthrow occurrence? BScF Thesis. University of New Brunswick.
- Coutts, M.P., 1986. Components of tree stability in Sitka spruce on peaty gley soil. *Forestry* 59 (2), 173-197.
- Cremer, K.W., Borough, C.J., 1982. Effects of stocking and thinning on wind damage in plantations. *New Zealand Journal of Forestry Science* 12 (2), 244–268.
- Damman, A.W.H., 1983. An ecological subdivision of the Island of Newfoundland. in South, G.R. (editor). *Biogeography and Ecology of the Island of Newfoundland*. Netherlands, The Hague: Dr. W. Junk Publishers.
- Department of Natural Resources, 2007. Newfoundland Ecoregions. Online http://www.env.gov.nl.ca/parks/library/pdf/Ecoregions/Island_1b_corner_brook%20-202007.pdf, accessed September 10, 2007.
- Department of Natural Resources, 2007. Online http://www.nr.gov.nl.ca/forestry/maps/west_eco.stm, accessed September 10, 2007

- Dunham, R.A., Cameron, A.D., 2000. Crown, stem, and wood properties of wind damaged and undamaged Sitka spruce. *Forest Ecology and Management* 135, 73–81.
- Elie, J.-G. and Ruel, J.-C. 2005. Windthrow hazard modelling in boreal forests of black spruce and jack pine. *Can. J. For. Res.* **35**: 2655–2663.
- Environment Canada, 2007. Canadian climate normals 1961-2000. Atmospheric Environment Service, Downsview, Ontario.
- ESRI, 2006. Using ArcView GIS. Environment Research Systems International Inc. Redlands, CA.
- Everham, E.M., III, Brokaw, N.V.L., 1996. Forest damage and recovery from catastrophic wind. *Bot. Rev.* 62. 113-185.
- Fleming, R.L. and Crossfield, R.M., 1983. Strip cutting in shallow-soil upland black spruce near Nipigon., Ontario. Windfall and mortality in the leave strips : preliminary results. Canadian Forestry Service. Great Lakes Forestry Research Center Information Report. O-X-354. 27p.
- Foster, D. and Boose, E. 1992. Patterns of forest damage resulting from catastrophic wind in central New England, USA. *Journal of Ecology* 80, 79-98.
- Frazer, A.I., 1962. The soil and the roots as factors in tree stability. *Forestry* 35. 117-127.
- Gardiner, B.A., Stacey, G.R., Belcher, R.E., Wood, C.J., 1997. Field and wind tunnel assessments of the implications of re-spacing and thinning for tree stability. *Forestry* 70, 233-252.
- Gardiner, B.A., Quine, C.P., 2000. Management of forests to reduce the risk of abiotic damage - a review with particular references to the effects of strong winds. *Forest Ecology and Management* 135, 261–277.
- Gardiner, B.A., Peltola, H., Kellomaki, S. 2000. Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. *Ecol. Model.* 129: 1-23.
- Grizzel, J.D., Wolf, N. 1998. Occurrence of windthrow in forest buffer strips and its effect on small streams in Northwest Washington.. *Northwest Science.* 72. 214-223.
- Hairston-Strang, A.B., and Adams, P.W. 1998. Potential large woody debris sources in riparian buffers after harvesting in Oregon, U.S.A. *Forest Ecology Management.* 112: 67–77.

- Hannah, P., Palutikof, J.P., Quine, C.P., 1995. Predicting wind speeds for forest areas in complex terrain. In: Coutts, M.P., Grace, J. (Eds.), *Wind and Wind Related Damage to Trees*. Cambridge University Press, Cambridge, pp. 113-129.
- Harris, A.S., 1989. *Wind in the forest of southeast Alaska and guides to reducing damage*. USDA Forest Service PNW-GTR-244, 63pp.
- Holmes, S.R., 1985. An analysis of windthrow along clearcut boundaries in the Tsitika Watershed. BScF Thesis, University of British Columbia p. 104.
- Huggard, D.J., Klenner, W., Vyse, A., 1999. Windthrow following four harvest treatments in Engelmann spruce-sub alpine fir forest in southern interior British Columbia, Canada. *Canadian Journal of Forest Research* 29, 1547–1556.
- Jalkanen, A., Mattila, U., 2000. Logistic regression models for wind and snow damage in northern Finland based on the National Forest Inventory data. *Forest Ecology and Management* 135, 315–330.
- Jonsson, B.G., 1993. Treefall disturbance, succession, and diversity in boreal forest floor vegetation. Doctoral Dis. Thesis. University of Umea, Sweden, pp. 27.
- Jull, M., Sagar, B., 2001. Wind-resistant silvicultural systems research project: identification of wind risk factors and mitigation measures in central and northern interior partial cuts. Five year final report to FRBC, Prince George, BC, p. 32.
- Languaye, C.O., 2003. Empirical modeling of windthrow risk using GIS. Masters Thesis. University of British Columbia, Vancouver, BC.
- Mason, W.L. 2002. Are irregular stands more windfirm? *Forestry* 75, 347-355.
- Mallett, K.I. 1992. Armillaria root rot in the Canadian prairie provinces *For. Can.. Nor. For. Cenl. Rep. NORX -329*. 22 pp.
- Meng, F.-R., Case, B.S., Arp, P.A. 2005. Digital elevation modelling of soil type and drainage within small forested catchments. *Canadian Journal of Soil Science*. Vol. 85:127-137.
- Mickovski, S.B., Stokes, A., Van Beek, L.P.H., 2005. A decision support tool for windthrow hazard assessment and prevention. *Forest Ecology and Management* 216, 64-76.
- Miller, K.F., 1985. Windthrow hazard classification. *Forestry Commission Leaflet* 85, 14pp.
- Mitchell, S.J., 1995. A synopsis of windthrow in British Columbia: occurrence,

- implications, assessment, and management. In: Coutts, M.P., Grace, J. (Eds), Wind and Trees. Cambridge University Press, Cambridge, pp. 448 – 449.
- Mitchell, S. 1998. A diagnostic framework for windthrow risk estimation. *Forestry Chronicle* 74, 100-105.
- Mitchell, S.J., Hailemariam, T., Kulis, Y., 2001. Empirical modeling of cutblock edge windthrow on Vancouver Island, Canada, using stand level information. *Forest Ecology and Management* 154, 117-130.
- Novak, M.D., Warland, J.S., Orchansky, A.L., Ketler, R., Green, S., 2000. Wind tunnel and field measurements of turbulent flow in forests. Part I. Uniformly thinned stands. *Boundary-Layer Meteorology* 95, 457-495.
- Ott, R.A. 1997. Natural disturbance at the site and landscape levels in temperate rainforests of southeast Alaska. Ph.D. dissertation, University of Alaska, Fair Banks, Alaska.
- Peltola, H., Kellomaki, S., Hassinen, A., Granander, M., 2000. Mechanical stability of Scots pine, Norway spruce and birch: an analysis of tree pulling experiments in Finland. *Forest Ecology and Management* 135, 143 – 153.
- Pham, A.T., L. De Grandpre, S. Gauthier, and Y. Bergeron. 2004. Gap dynamics and replacement pattern in gaps of the northeastern boreal forest in Quebec. *Canadian Journal of Forest Research* 34:353-364.
- Quine, C.P., 1995. Assessing the risk of wind damage to forests: practice and pitfalls. In *Wind and Trees*. M.P. Coutts and J. Grace (eds). Cambridge University Press, Cambridge, pp. 379-403.
- Ravn, H.P., 1985. Expansion of the populations of *Ips typographus* L. and their local dispersal following gale disaster in Denmark. *Zeitschrift fur angewandte Entomologie* 99 (1), 27-33.
- Richter, J., 1996. Sturmschladen in Fichten bestanden (Wind damage in Norway spruce stands) (in German). *Allgemeine Forst-und Jagdzeitung*. 167, 234 – 238. Cited in Dunham, R.A., Cameron, A.D., 2000. Crown, stem, and wood properties of wind damaged and undamaged Sitka spruce. *Forest Ecology and Management* 135, 73–81.
- Rollerson, T.P. and McGourlick, K., 2001. Riparian Windthrow – Northern Vancouver Island. In proceedings of the windthrow researchers workshop, January 31 – February 1, 2001, Richmond, BC. Compiled by S.J. Mitchell and J. Rodney. pp. 139-156.
- Ruel, J.C., 1995. Understanding windthrow: silvicultural implications. *Forestry Chronicle* 75, 434-445.

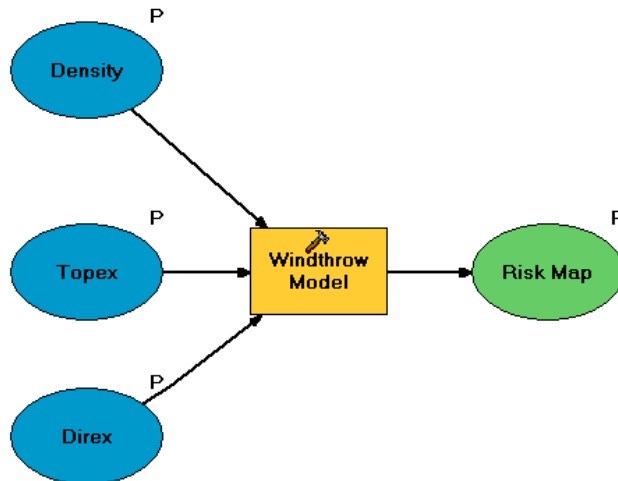
- Ruel, J.C., 1989. Mortalite du bois laisse sur pied a la suite d' une coupe par bandes dans trios regions du Quebec. *Forestry Chronicle*. 65, 107-113.
- Ruel, J.C., 2000. Factors influencing windthrow in balsam fir forests: from landscape studies to individual tree studies. *Forest Ecology and Management* 135: 169-179.
- Ruel, J.C., Quine, C.P., Meunier, S., Suarez, J., 2000. Estimating windthrow risk in balsam fir stands with the ForestGales model. *Forestry Chronicle* 76, 329-337.
- Ruel, J.C., Pin, D., and Cooper, K. 2001. Windthrow in riparian buffer strips: effect of wind exposure, thinning and strip width. *Forest Ecology and Management* 143, 105-113.
- Ruel, J.C., Mitchell, S.J. and Dornier, M. 2002. A GIS based approach to map wind exposure for windthrow hazard rating. *Northern Journal of Applied Forestry* 19,183-187.
- Ruel, J.C., Raymond, P., Pineau, M., 2003. Windthrow after shelterwood cutting in balsam fir stands. *Northern Journal of Applied Forestry* 20, 5 – 13.
- Ruth, R.H., Yoder, R.A., 1953. Reducing wind damage in the forests of Oregon Coast Range. USDA Forest Service PNW Forest and Range Experimental Station Research Paper 7, Portland, OR, 30pp.
- SAS, 1989. SAS/STAT User's Guide, Version 6, Vol. 2, 4th Edition. SAS Institute Inc., Cary, NC, 848 pp.
- Savill, P.S., 1983. Silviculture in windy climate. *Forestry Abstract* 44, 473-488
- Schaetzel R.J., D.L., Johnson, S.F., Burns and T.W., Small, 1989a. Tree uprooting: review of impacts on forest ecology. *Vegetation* 79: 165-176.
- Schroeder, L.M. and Eidmann, H.H., 1993. Attacks of bark beetle and wood boring Coleoptera on snow broken conifers over a two-year period. *Scandinavian Journal of Forest Research* 8, 257-265.
- Scott, R.E., Mitchell, S.J., 2005. Empirical modeling of windthrow risk in partially harvested stands using tree, neighbourhood, and stand attributes. *Forest Ecology and Management* 218, 193–209.
- Silva, G., J.C. Ruel, M., Samson, D. Pin, 1998. Influence de quelques défauts externes sur la resistance des arbres a une simulation mecanique de l'action du vent. *Canadian journal of Forest Research*. 28:123-131.
- SPSS for Windows, Rel. 11.0.1. 2001. Chicago: SPSS Inc.

- Stathers, R.J., Rollerson, T.P., Mitchell, S.J., 1994. Windthrow handbook for British Columbia Forests, BC Ministry of Forests, Victoria, BC. Working Paper 9401, p. 31.
- Steinblums, I.J., 1978. Streamside buffer strips: survival effectiveness and design. Masters Thesis. Oregon State University, Oregon.
- Steinblums, I.J., Froehlich, H.A., Lyons, J.K., 1984. Designing stable buffer strips for stream protection. *J. For.* 82, 49-52.
- Sobota, D. J., Gregory, S.V., and Van Sickle, J., 2006. Riparian tree fall directionality and modeling large wood recruitment to streams. *Canadian Journal of Forest Research*. Vol. 36, 2006
- Solantie, R., 1986. Effect of weather and climatological background on snow damage of forest in southern Finland in November 1991. *Silva Fennica* 28 (3), 203-211.
- Stoeckler, J.H., Arbogast Jr, C., 1955. Forest Management lessons from a 1949 windstorm in northern Wisconsin and upper Michigan. Lake State Forest Experiment Station Paper No. 34 11 pp.
- Taylor, S.L., MacLean, D.A., 2007. Spatiotemporal patterns of mortality in declining balsam fir and spruce stands. *Forest Ecology and Management*. 253. 188-201.
- Ulanova, N.G., 2000. The effects of windthrow on forests at different spatial scales: a review. *Forest Ecology and Management*. 135, 155-167.
- Valinger, E., Friedman, J., 1997. Modeling probability of snow and wind damage in Scots pine stands using tree characteristics. *Forest Ecology and Management* 97, 215–222.
- Valinger, E., Friedman, J., 1999. Models to assess the risk of snow and wind damage in pine, spruce, and birch forest in Sweden. *Environmental Management* Vol. 24, No. 2, 209–217
- Wang, Y., Titus, S.J., LeMay, V.M., 1998. Relationships between tree slenderness coefficients and tree and or stand characteristics for major species in boreal mixedwood forests. *Canadian Journal of Forestry Research*. 28, 1171 – 1183.
- Welty, J.J., Beechie, T., Sullivan, K., Hyink, D.M., Bilby, R.E., Andrus, C., and Pess, G., 2002. Riparian aquatic interaction simulator (RAIS): a model of riparian forest dynamics for the generation of large woody debris and shade. *Forest Ecology Management*. 162: 299–318.

Whitney, R.D., Flemming, R.L., Zhou, K., Mossa, D.S., 2002. Relationship of root rot to black spruce windfall and mortality following strip clear cutting. *Canadian Journal of Forest Research*. 32, 283-294.

APPENDIX I

Models and scripts for construction of riparian zone windthrow risk maps



Steps to create risk map for entire landscape, involving input of individual model parameter raster's.

Full Cutblock Edge Risk Map Script

```

# Script arguments...
Combined = sys.argv[1]
if Combined == '#':
    Combined = "D:\\combine" # provide a default value if unspecified

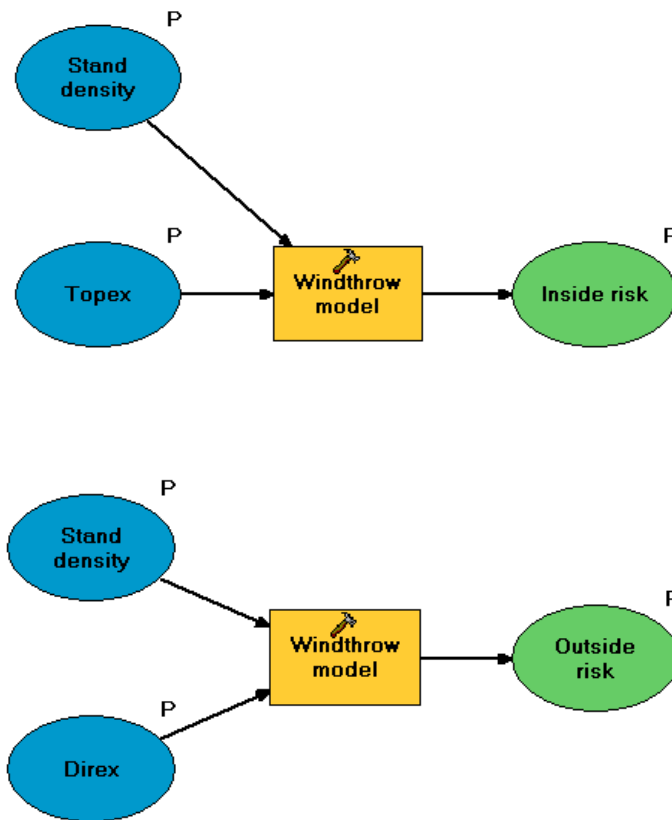
Density = sys.argv[2]
if Density == '#':
    Density = "Density" # provide a default value if unspecified

Topex = sys.argv[3]
if Topex == '#':
    Topex = "topex" # provide a default value if unspecified

Direx = sys.argv[4]
if Direx == '#':
    Direx = "Direx" # provide a default value if unspecified

# Local variables...

# Process: Single Output Map Algebra...
gp.SingleOutputMapAlgebra_sa ("exp10(0.663 + -0.008 * topex + -0.001 *Density +
0.166 * direx)", Inside, "topex;Density;direx")
  
```



Steps to create risk map for inner and outer riparian zone risk map

Inside Riparian Risk Map Script

```
# Script arguments...
```

```
Inside = sys.argv[1]
```

```
if Inside == '#':
```

```
    Inside = "D:\\Wind\\March27\\newinside" # provide a default value if unspecified
```

```
density = sys.argv[2]
```

```
if density == '#':
```

```
    density = "density" # provide a default value if unspecified
```

```
topex = sys.argv[3]
```

```
if topex == '#':
```

```
    topex = "topex" # provide a default value if unspecified
```

```
# Local variables...
```

```
# Process: Single Output Map Algebra...
```

```
gp.SingleOutputMapAlgebra_sa("exp10(1.068 + -0.0089 * topex + -0.000743 * density)",  
Inside, "topex;density")
```

Outside Riparian Risk Map

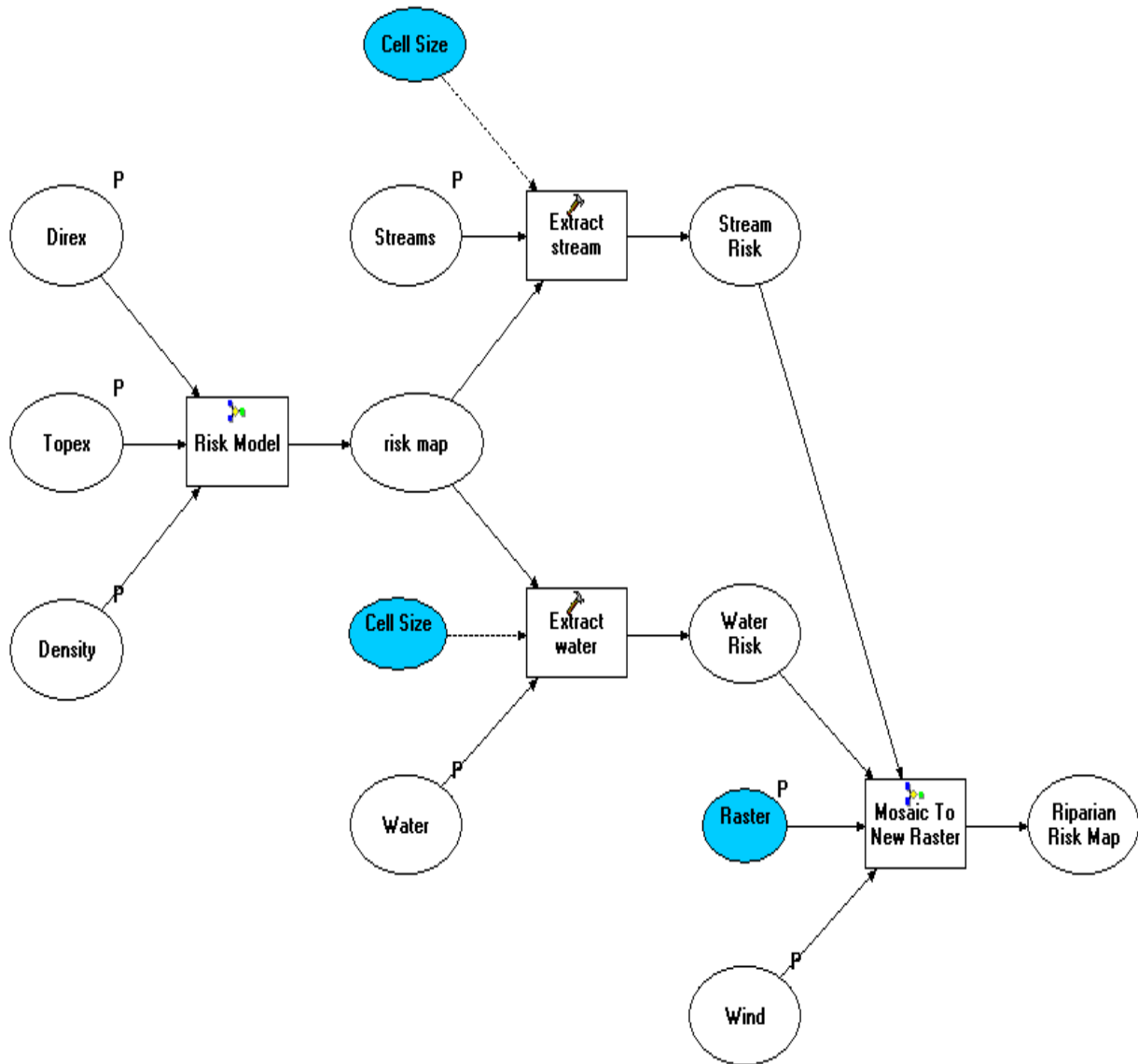
```
# Script arguments...
densitynew = sys.argv[1]
if density == '#':
    density = "density" # provide a default value if unspecified

Direx = sys.argv[2]
if Direx == '#':
    Direx = "Direx" # provide a default value if unspecified

Inside = sys.argv[3]
if Inside == '#':
    Inside = "D:\\Wind\\March27\\newoutside" # provide a default value if unspecified

# Local variables...

# Process: Single Output Map Algebra...
gp.SingleOutputMapAlgebra_sa("exp10(0.96 + 0.142 * Direx + -0.0002915 *density)",
Inside, "Direx;densit
```



Steps to create the final riparian zone risk maps for all streams and lakes

Riparian Zone Risk Map Script Using Combined Model

```

# Script arguments...
Stream_Inside = sys.argv[1]
if Stream_Inside == '#':
    Streams = "PFLines_Smooth_Buffer" # provide a default value if unspecified

Water_Inside = sys.argv[2]
if Water_Inside == '#':
    Waterpoly = "erase10" # provide a default value if unspecified
  
```

```

Wind = sys.argv[3]
if Wind == '#':
    Wind = "F:\\Wind" # provide a default value if unspecified

Raster_dataset_name_with_extension = sys.argv[4]
if Raster_dataset_name_with_extension == '#':
    Raster_dataset_name_with_extension = "Risk_Combined4m" # provide a default value
if unspecified

Density = sys.argv[5]
if Density == '#':
    Density = "Density" # provide a default value if unspecified

Topex = sys.argv[6]
if Topex == '#':
    Topex = "topex" # provide a default value if unspecified

Direx = sys.argv[7]
if Direx == '#':
    Direx = "Direx" # provide a default value if unspecified

# Local variables...
Water_Risk = "D:\\Scratch\\extract2"
Stream_Risk = "D:\\Scratch\\extract"
Risk_Combined4m = ""
Cell_Size__2_ = "4"
Cell_Size__3_ = "4"
Inside = "D:\\combine"

# Process: Combined...
gp.toolbox = "C:/Documents and Settings/johnny/Application
Data/ESRI/ArcToolbox/My Toolboxes/Wind.tbx"
gp.Model4(Inside, Density, Topex, Direx)

# Process: Extract Stream...
tempEnvironment0 = gp.cellSize
gp.cellSize = "4"
gp.ExtractByMask_sa(riskmap, Stream, Stream_Risk)
gp.cellSize = tempEnvironment0

# Process: Extract Water...
tempEnvironment0 = gp.cellSize
gp.cellSize = "4"
gp.ExtractByMask_sa(riskmap, Water, Water_Risk)
gp.cellSize = tempEnvironment0

```

```
# Process: Mosaic To New Raster...
gp.MosaicToNewRaster_management("D:\\Scratch\\extract;D:\\Scratch\\extarct2", Wind,
Raster_dataset_name_with_extension,
"PROJCS['NAD_1983_Transverse_Mercator',GEOGCS['GCS_North_American_1983',
DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.25722210
1]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Tr
ansverse_Mercator'],PARAMETER['False_Easting',304800.0],PARAMETER['False_No
rthing',0.0],PARAMETER['Central_Meridian',-
56.0],PARAMETER['Scale_Factor',0.9999],PARAMETER['Latitude_Of_Origin',0.0],U
NIT['Meter',1.0]]", "8_BIT_UNSIGNED", "4", "1", "LAST", "FIRST")
```