Root anchorage and stem strength of black spruce (*Picea mariana*) trees in regular and irregular stands

C. BERGERON[1], J.-C. RUEL[2]*, J.-G. ÉLIE[2] AND S.J. MITCHELL[3]

[1] Ministère des Ressources Naturelles et de la Faune du Québec, 880 Chemin Sainte-Foy, Québec, Canada G1S 4X4
[2] Centre d'Études sur la Forêt, Faculté de Foresterie et de Géomatique, Pavillon Abitibi-Price, 2405, rue de la Terrasse, Université Laval, Québec, Canada G1V 0A6
[3] Faculty of Forestry, University of British Columbia, 3041-2424 Main Mall, Vancouver, British Columbia, Canada V6T 1Z4
*Corresponding author. E-mail: jean-claude.ruel@sbf.ulaval.ca

Summary

A tree winching experiment was conducted, simulating wind action and resulting damage, in order to assess mechanical resistance of black spruce (*Picea mariana* (Mill.) B.S.P.) trees in stands of regular and irregular structures. The critical bending moment (M_c) of winched trees was determined and the relationship between M_c and tree and stand characteristics was investigated through statistical analyses. Stem mass (SW), average spacing between trees (S) and height:diameter ratio (H/d.b.h.) were initially selected by a screening procedure to predict M_c. Potential differences between stand structures were tested in mixed models using different subsets of the data. Included fixed effects varied between the different models. SW was the most useful and significant variable in all models and H/d.b.h. was significant only when snapped trees were included in the analysis. When decayed samples were excluded, resistance to uprooting was higher in irregular stands. Decay seemed to play an important role in irregular stands and should be investigated further. Since no difference was observed in the relationship between stem mass and critical turning moment between distant sites, relationships should be applicable across wide regions. This study provides some of the basic relationships required to model windthrow risk in irregular stands. However, the effects of stand structure on wind load for individual trees will also need to be considered.

Introduction

Black spruce (*Picea mariana* (Mill.) B.S.P.) is a major commercial species with a wide distribution across Canada. Black spruce is a fire-adapted species and its stand dynamics have for long been recognized to be mainly influenced by the cyclic occurrence of fire (Heinselman, 1981; Cogbill, 1985; Johnson, 1992). This has led to the general belief that most black spruce stands were of regular structure (Johnson, 1992; Oliver and Larson, 1996), fire cycles being thought to be quite short in comparison with the life span of the species (Heinselman, 1981). However, reported fire cycles within the geographic range for black spruce are quite variable, ranging from 100 to 500 years (Heinselman, 1981; Foster, 1983; MRN, 2000; Bergeron

et al., 2001; Lesieur et al., 2002). The longest fire cycles are found in Eastern Quebec where proximity to the Gulf of Saint Lawrence is associated with more abundant precipitation. In fact, in this region, irregular stands occur frequently and even dominate some areas (Boucher et al., 2003). Given the long fire cycles in these areas, gap dynamics associated with insect outbreaks or wind damage prevail (Kneeshaw and Bergeron, 1998; De Grandpré et al., 2000; McCarthy, 2001; Pham et al., 2004). Accordingly, ecosystem management in this region which intends to mimic natural disturbance processes should rely heavily on partial cuts (Bergeron et al., 1999), but the increased harvesting costs and the fear of windthrow tend to limit their use.

A better understanding of the windthrow process is thus required to design robust silvicultural treatments in these stands. Empirical models can be developed relatively quickly but they provide only partial insight into the underlying processes. Mechanistic models have been developed that can predict windthrow risk for many species (Gardiner et al., 2000). Relationships describing overturning resistance in these models are derived from static tree pulling studies. Most of these studies have been conducted in plantations or natural stands with simple structure (Fraser and Gardiner, 1967; Fredericksen et al., 1993; Peltola et al., 2000; Achim et al., 2005; Cucchi et al., 2005; Nicoll et al., 2006). Recent work comparing pure and mixed stands has shown that the relationship between critical turning moment and stem mass could vary with stand complexity (Elie and Ruel, 2005).

The aim of this paper is to present an assessment of the resistance of black spruce trees to windthrow using a tree pulling experiment. A comparison will be made between regular and irregular structured stands while also determining the best variables for predicting tree resistance to overturning and stem breakage. Some authors suggest that irregular stands should be more windfirm because individual trees have greater wind exposure and generally have lower height: diameter ratios and this ratio has been reported as an important predictor of tree stability (e.g. Savill, 1983; Wang et al., 1998; Wilson and Baker, 2001; Mason, 2002). Our hypothesis therefore was that trees in irregular stands would be more resistant to windthrow.

Methodology

Site description

A total of 10 study sites located in two different regions were used for tree pulling. Eight of them, four having a regular structure and four with an irregular one, are located ~450 km north-east of Québec city, in the North Shore region of the Québec province, Canada (49° 40′ to 49° 55′ N; 69° 25′ to 69° 45′ W). They belong to the eastern part of the spruce-moss ecological domain (Saucier et al., 1998) where fire cycles are longer. Two other regular stands from another region (Elie and Ruel, 2005) were also used to increase the sample size of regular stands and look for possible differences between regions. The latter sites are located in central Quebec, close to the Gouin Reservoir, ~550 km northwest of Québec city, Canada (48° 87′ N, 74° 57′ W) in a region with much shorter fire cycles. They belong to the western section of spruce-moss (Bergeron et al., 1998) and balsam fir (Abies balsamea (L.) Mill.) – white birch (Betula papyrifera Marsh.) (Grondin et al., 1998) ecological domains.

Fieldwork was performed during the summers of 2002 and 2003 for the Gouin Reservoir and the North Shore experiments, respectively. In each case, a year before tree pulling, the experimental sites were chosen from a set of potential stands first identified on a forest map. Very wet or very dry sites were not considered as potential sites since extensive thinning programs would not be conducted in these conditions. Regular stands had to be mature or close to rotation age. The final selection was done after collection of inventory data in order to ensure a representative structure and cover type. For the North Shore experiment, a set of four regular and four irregular stands were kept at the end of the selection process. Irregular stands presented a great variability in age and tree height and a low basal area with wider spacings (Tables 1 and 2). Regular stands were more uniform in terms of age and tree height and had a higher basal area (Tables 1 and 2). They were generally younger than the irregular stands, which is in line with the process of structural evolution generally observed for black spruce stands in the absence of fire (Bergeron and Dubuc, 1989). As time since stand initiation increases and without severe disturbances, stand

Table 1: Stand and site description

| Site | Structure | S (m) | Basal area (m² ha⁻¹) | | | | | Soil depth (cm) | Drainage | Stoniness (%) |
			Spruce[a]	Fir[b]	Pine[c]	Other	Total			
I1	Irregular	2.7	22	4			26	50–100	Moderate	25
I2	Irregular	3.3	18	2			20	>100	Good	20
I3	Irregular	3.9	12	2			14	>100	Moderate	45
I4	Irregular	3.4	18				18	<50	Moderate	20
R1	Regular	2.4	42				42	50–100	Good	60
R2	Regular	1.7	52				52	>100	Moderate	20
R3	Regular	2.4	21		3	8	32	>100	Good	5
R4	Regular	2.1	48				48	50–100	Moderate	10
E2[d]	Regular	1.7	36				36	<50	Moderate	60
E5[d]	Regular	2.1	36				36	>100	Moderate	10

[a] Black spruce (*Picea mariana* (Mill.) B.S.P.).
[b] Balsam fir (*Abies balsamea* (L.) Mill.).
[c] Jack pine (*Pinus banksiana* Lamb.).
[d] Data from Elie and Ruel (2005) in the Gouin Reservoir region.

Table 2: Sample tree description

| Site | Structure | n | d.b.h. (cm) | | | Tree height (m) | | | H/d.b.h. (dimensionless) | | | Age (years) | | |
			Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
I1	Irregular	10	12.5	17.7	24.7	10.6	13.2	20.0	66.3	75.2	85.1	103	166	313
I2	Irregular	10	12.7	18.8	23.6	10.5	15.3	19.7	70.8	82.5	96.2	102	179	246
I3	Irregular	11	13.0	17.7	25.0	11.6	14.8	19.3	71.0	84.1	96.7	221	241	288
I4	Irregular	11	12.7	17.6	22.9	9.8	12.2	15.9	59.0	70.4	81.0	114	134	175
R1	Regular	10	12.5	18.2	23.5	14.4	16.6	18.8	80.2	92.9	114.8	100	102	105
R2	Regular	10	13.5	16.9	23.2	13.4	15.1	19.3	80.9	89.8	99.3	76	81	108
R3	Regular	11	12.7	17.4	23.4	12.7	15.5	18.0	75.3	90.1	108.8	79	82	83
R4	Regular	10	14.9	17.8	21.6	14.2	16.4	18.1	77.4	91.9	107.1	152	164	174
E2[a]	Regular	11	12.9	15.2	17.2	12.1	13.0	14.0	76.9	86.4	99.1	66	70	73
E5[a]	Regular	13	11.4	15.8	19.4	12.2	15.0	17.1	81.3	96.7	129.8	68	73	75

[a] Data from Elie and Ruel (2005) in the Gouin Reservoir region.

structure of pure black spruce stands generally evolves toward an uneven-aged structure during the second cohort instalment, typically from 75 to 175 years after stand initiation (Harvey *et al.*, 2002). Stands were growing on loamy sands to sandy loams podzols. Soil depth varied from less than 50 cm to over 1 m. Stoniness also varied between sites (Table 1). Previous work by Elie and Ruel (2005) has shown that black spruce resistance to uprooting is not affected by soil depth ranging from less than 50 cm to over 1 m and by soil drainage varying from good to moderate. They also estimated that rooting depth was 20 cm, irrespective of the soil properties. Given this, the soil variability between our sites (Table 1) would not be expected to influence black spruce.

A total of 10–13 black spruce stems were pulled over at each site (*n*, Table 2). The sample trees were randomly selected from a group of 15–20 trees initially chosen to cover a wide range of stem size while excluding stems with apparent defects such as forks, wounds or obvious fungi infestations. This was done to limit the inclusion of too many interacting factors that could not be distinguished in the analysis. Moreover, from the perspective of simulating partial cutting effects, stems with defects would normally be the first to be removed in partial harvests.

Measurements

Measurements taken on sample trees included diameter at breast height (d.b.h., cm), diameter at stump height (DSH, cm), tree age (age, years) gathered from a disc cut at stump height and tree height (*H*, m), this last one being precisely measured once the tree was on the ground. Obvious presence of root rot and butt or stem decay was noted. The stem was cut into sections of ~2 m long and each section was weighed. Branches were removed and weighed separately in order to get total crown mass. Heights of the live crown base and of the attachment point were noted. For snapped stems, the height and diameter at the point of failure were measured. For uprooted trees, a simple three-dimensional set of measures was used to provide an index of the root–soil plate volume. Width and mean height of the plate were first measured. Thickness of the plate was evaluated with the mean of three measures taken at different random positions on the plate. The volume was then estimated by multiplying the three measures.

Tree pulling experiment

Winching of the sample trees was carried out using a method previously used and described by many authors (Silva *et al.*, 1998; Meunier *et al.*, 2002; Achim *et al.*, 2005; Elie and Ruel, 2005). A mechanical winch was used to pull down the trees. The force applied to each sample tree was measured every half second by a load cell (Sensortronics™, Hampton, VA, USA, model S-Beam 60001™). Data were recorded on a Unipulse L840™ (Tokyo, Japan) data logger. The cable was attached using a pulley at mid-height of the sample tree. This was done mainly for cable length and safety issues, since it is difficult to climb safely above mid-tree height. However, as pointed out Wood (1995), the cable should ideally be placed at ~80 per cent of tree height in order to have a uniform stress profile in the outer fibres. As a result, by placing it lower than the suggested height, trees that are likely to break will do so at a lower height than they would naturally. However, this height of attachment has been used by other authors (e.g. Achim *et al.*, 2005).

The maximum tree resistance to either uprooting or stem breakage was assessed by evaluating the critical bending moment (M_c, Nm). The critical bending moment for a winched tree is calculated by multiplying the total force by the perpendicular distance to the fulcrum, which is at the base of the tree if it overturns and at the snapping height if it breaks. Actually, in order to be fully rigorous, the pivot point for uprooting is not exactly at the tree base, but somewhere in the root mound, on the side where a compressive force occurs in the roots. However, work by Nicoll *et al.* (2005) and Byrne and Mitchell (2007) suggests that the bias remains small.

The moment at failure includes the moment applied with the cable and self-loading due to tree deflection. The position of the stem at the time of failure was derived from images taken during winching. Two images were used, one taken just before the beginning of the process and the other at the time when the maximum force was applied. These images were gathered with a video camera, which was placed perpendicularly to the tree-winch-defined axis. After having digitized the two specific images, the fulcrum and the attachment point were positioned on the rectified images. The coordinate values on the images were converted into field distances by scaling them with a reference target of 2 × 2 m used on the first image, just before beginning winching (Achim *et al.*, 2005).

To calculate bending moments, the coordinate values gathered from the image analysis were used to take into account the angle at which the forces act on the tree. The applied bending moment is separated into a vertical and a horizontal component while the self-loading bending moment is calculated as a vertical moment. The general equation can be expressed this way:

$$M_c = M_{ax} + M_{ay} + M_g \tag{1}$$

where M_c (Nm) is the total critical bending moment, M_{ax} (Nm) is the horizontal component of the applied bending moment, M_{ay} (Nm) is the vertical component of the applied bending moment and M_g (Nm) is the bending moment due to self-loading. Each component of M_c is evaluated by multiplying each force by its corresponding lever arm length. The applied force comes from the maximum value recorded by the load cell while the self loading force is simply the tree mass above ground applied at centre of gravity. Specific lever arm length and related angles are evaluated

with the coordinate data from the image analysis. A more complete description of these calculations appears in Meunier *et al.* (2002) and Elie and Ruel (2005).

Statistical analyses

Statistical models were developed to predict M_c and to evaluate differences between stand structures. The SAS/STAT system was used to perform the analysis (SAS Institute Inc., 1999). First, a multiple regression model was fit in order to find the best covariates. Various independent variables of tree and stand characteristics and some of their combinations were included in these models. The R^2 and stepwise selection procedures were used to select the best group of variables, which was chosen based on best fit and optimal number of variables, using adjusted R^2 and Mallows $C(p)$ statistic (REG procedure, SAS Institute Inc., 1999; Freund and Littell, 2000). Multicollinearity was checked using the COLIN option and variables were excluded when necessary. Then, selected covariates were included in a second step to look at the effect of stand structure and test the significance of potential covariates, using the MIXED procedure (Littell *et al.*, 1996; SAS Institute Inc., 1999; Milliken and Dallas, 2002). This second step accounted for two different sources of variability, one being a random effect emerging from the presence of different sites within each structure and the other being a fixed effect from the presence of two stand structure types and the covariates. Four mixed models were fitted for M_c using different subsets of the available data in order to look for the impact of presence of decay and mode of failure. A square root-square root transformation was applied to correct heteroscedasticity and keep the relationship linear. Models thus includes the selected covariates, a categori-

cal effect for stand structure and a random site effect nested within each structure. The categorical variable for stand structure was set with three levels so that it differentiates regular structured stands in the Gouin Reservoir region from regular structured stands in the North Shore region. Pre-planned comparisons using orthogonal contrasts were used to look for possible differences between regions for the regular structured stands, in cases of significant structure effect.

The presence of two modes of failure (i.e. uprooting and stem breakage) and decay on a few sample trees had to be carefully accounted for. Their potential effect was first evaluated by analysing model residuals. Studentized residuals greater than 2.5 are considered to be rare with more than 10 degrees of freedom for the error term (Freund and Littell, 2000). Models with and without decayed and snapped samples were fit in order to look for possible effects and interactions. Analysis of variance postulates were verified to ensure variance homogeneity and normality. An appropriate data transformation was used in cases of heterogeneous variances.

Results

Two different modes of failure were observed in the winching experiment. Overturning was far more common than stem breakage. From a total of 107 winched trees, 93 uprooted and 14 snapped (Table 3). Overturning occurrence was similar in regular and irregular stands (89 and 83%, respectively). For snapped trees, rupture height on the stem varied between tree base and 3.2 m with a mean of 1.3 m. Obvious presence of root or heart rot was noted on seven trees overall even though trees with externally visible defects or signs of decay were excluded. Irregular stands appeared to be more affected since root rot or

Table 3: Number of tree samples by mode of failure and presence of decay

	Overturning			Stem breakage			
Structure	Healthy	Decayed	All	Healthy	Decayed	All	Total
Irregular	32	3	35	5	2	7	42
Regular	56	2	58	7	0	7	65
All	88	5	93	12	2	14	107

decay was observed on 12 per cent of the sample trees whereas only 3 per cent of the sample trees in regular stands were affected. Within these decayed samples, only two experienced stem breakage. The proportion of trees that snapped was 29 per cent when decay was observed and 12 per cent when they appeared sound.

Three potential covariates were retained by the selection procedure for predicting M_c. These were SW ($P < 0.0001$), average tree spacing (S) ($P = 0.125$) and H/d.b.h. ($P = 0.136$). All models with four or more variables as well as some models with three variables had to be excluded because of unacceptable collinearity or negligible increases in model fit. The selected variables S and H/d.b.h. have quite high P values, but the $C(p)$ statistic suggested that they could be useful and they still improved the model fit. This might be due to some collinearity between these two variables even though collinearity was lower than the threshold for rejection.

In all mixed models, transformed spacing (rS) was not significant at 5 per cent level while transformed stem mass (rSW) was strongly significant ($P < 0.0001$) (Table 4). Transformed height–diameter ratio (rH/d.b.h.) was significant for models including snapped trees (models (1) and (2)). Structure was significant ($P = 0.006$) only for uprooted and healthy trees (model (4), $n = 88$). Orthogonal contrasts showed that the regular stands from the North Shore region were not different ($P = 0.65$) from those of the Gouin reservoir region, while irregular stands were different ($P = 0.002$) compared with all regular stands. Intercepts differed with structure, but slopes did not. Interaction between structure and transformed stem mass was not significant ($P = 0.49$). The simplest model was found with uprooted trees including decayed ones (model (3), $n = 93$) which includes only transformed stem mass as a predictor.

Average tree spacing (S) of each stand and H/d.b.h. ratio characterizing each sample tree seem to quantify differences between stand structures. Mean tree spacing value for each stand structure was compared and found to be significantly different ($P = 0.0011$). At the tree level, the height–diameter relationship was compared between structures and significant differences were found. To compare both stand structures, the relationship between d.b.h. and H was investigated. The mixed model fitted to the whole data set with d.b.h. predicting H resulted in a lower intercept ($P < 0.0001$) and slightly higher slope for trees in irregular stands ($P = 0.048$) (Figure 1). This particular combination clearly gives lower tree height for small d.b.h. values in irregular stands, but this difference diminishes as d.b.h. increases because of higher slope. Figure 1 and Table 2 show that the d.b.h. range of the sample trees is comparable between structures, given that the sample was designed to cover the whole range in diameters.

Stem mass is the most influential variable included in the different models. The relationship between M_c and SW is presented in Figure 2 for all tree samples while distinguishing structures, modes of failure and presence of decay. All decayed trees and especially those in irregular stands are below the regression line. Also, few samples from irregular stands are below the regression line while samples from regular stands are mostly below. Most snapped sample trees appear over the regression line, no matter the structure type, but the two snapped and decayed trees are clearly below the regression line. The higher turning moment associated with sound broken trees is particularly interesting considering that the calculation of M_c for these trees used a shorter lever arm than for uprooted trees. It then remains possible that the turning moment experienced at the base of the tree was even higher just before stem breakage.

Analysis of studentized residuals was performed on model (1) which includes all samples and retaining only significant variables. Of particular interest were the residuals of snapped and decayed trees. Residuals exceeding the suggested limit for outliers all had negative values, meaning that predicted values were far greater than measured values. Two uprooted and healthy trees had low residuals (-2.28 and -2.41), but no particular reason could explain these values and justify their exclusion. Generally, the residuals of decayed trees were quite low, with a mean of -1.68 ($n = 5$). However, two sample trees in irregular stands had a value of -2.34 and -3.26, respectively. Two decayed trees experienced stem breakage and one of them had a low residual value of -2.10. The mean residual of all snapped but healthy trees was 0.75 ($n = 12$), ranging from -0.02 to 1.80. These results suggest higher critical turning moments for stem breakage in sound trees and lower ones for decayed trees. However,

Table 4: Test of structure effect and significance of covariates for predicting the critical bending moment (M_c) using mixed models

		Variables				
Model	n	Dependent	Fixed effect	Degrees of freedom	*F*-value	*P* > *F*
(1)	106[a]	rM_c	rSW	1	276	<0.0001*
			rH/d.b.h.	1	6.28	0.014*
			rS	1	1.30	0.287
			Structure	2	0.04	0.964
			Structure × rSW	2	0.01	0.987
			Structure × rS	2	0.72	0.516
			Structure × rH/d.b.h.	2	0.66	0.518
(2)	99[b]	rM_c	rSW	1	315	<.0001*
			rH/d.b.h.	1	8.56	0.004*
			rS	1	3.54	0.097
			Structure	2	0.32	0.738
			Structure × rSW	2	0.87	0.421
			Structure × rS	2	1.05	0.395
			Structure × rH/d.b.h.	2	0.82	0.442
(3)	93[c]	rM_c	rSW	1	340	<0.0001*
			rS	1	<0.01	0.974*
			rH/d.b.h.	1	0.04	0.840
			Structure	2	4.26	0.062
			Structure × rSW	2	0.73	0.486
			Structure × rS	2	0.13	0.880
			Structure × rH/d.b.h.	2	1.72	0.186
(4)	88[d]	rM_c	rSW	1	421	<0.0001*
			Structure	2	12.0	0.006*
			rS	1	0.06	0.812
			rH/d.b.h.	1	0.63	0.431
			Structure × rSW	2	0.72	0.491
			Structure × rS	2	0.02	0.979
			Structure × rH/d.b.h.	2	0.46	0.633

rM_c: square root of critical turning moment; rSW: square root of stem mass; rS: square root of spacing; rH/d.b.h.: square root of height over diameter at breast height ratio.
[a] All samples included except one missing d.b.h. value.
[b] Decayed sample trees excluded.
[c] Snapped sample trees excluded.
[d] Snapped and decayed sample trees excluded.
* Significant at 0.05 level.

the small sample size for decayed (n = 7) and snapped (n = 14) trees does not allow more detailed analysis.

Predicted values of the four models predicting M_c are compared in Figure 3. Since models (1) (all sample trees) and (2) (decayed trees excluded) include two predictors, two cases were compared using mean H/d.b.h. of regular and irregular stands, being respectively of 91.5 and 78.0. While variations in predicted values are less than ~4000 Nm between most models, predicted values for uprooted healthy trees in irregular stands (model (4)) are higher. This is particularly true for larger stem masses, the slope being higher with this last model. The effect of H/d.b.h. ratio in models (1) and (2) gives higher critical turning moments with a lower value of the ratio, the difference being nearly constant with increasing stem mass. Also, the presence of decayed trees in the analysis leading to models (1) and (3) results in lower predicted values compared with the other models.
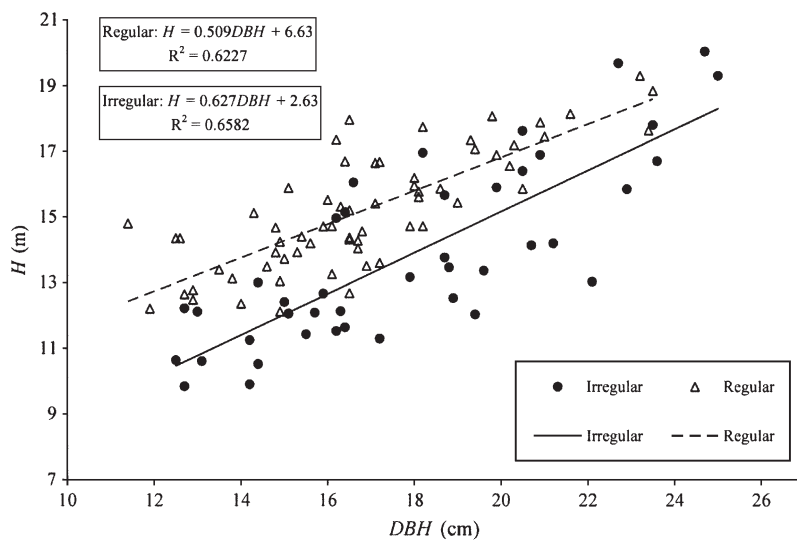
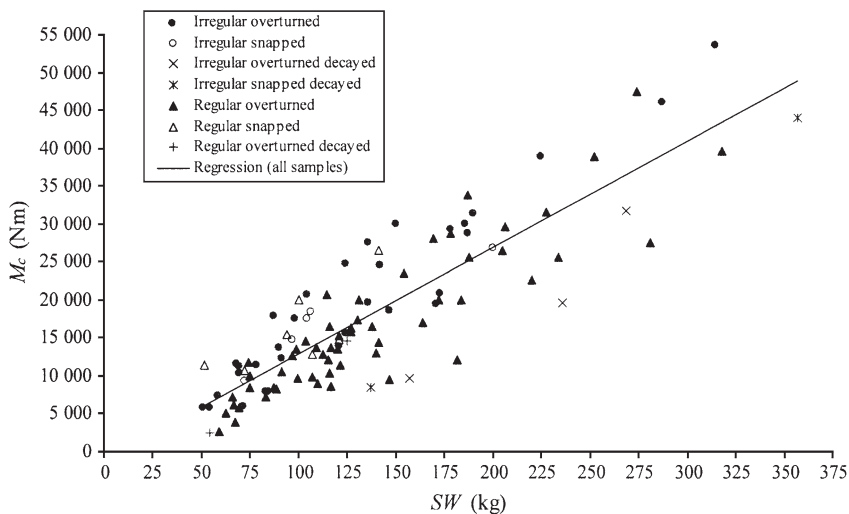*Figure 1.* Relationship between height and diameter for regular and irregular stands.

Figure 2. Relationship between critical turning moment (M_c) and stem mass (SW) for all tree samples winched (*n*=107).

Discussion

The use of selection methods to identify potential variables to predict critical bending moment resulted in a multiple regression model with stem mass, *H*/d.b.h. ratio and spacing as potential predictors. However, increase in fit was small over

a simple regression model using only stem mass. Moore (2000) also obtained a small increase in model fit with stem volume and *H*/d.b.h. over a model using only stem volume. A wide variety of predictors have been found for critical turning moment in other winching studies. For example, Smith *et al.* (1987) found that best fit for black
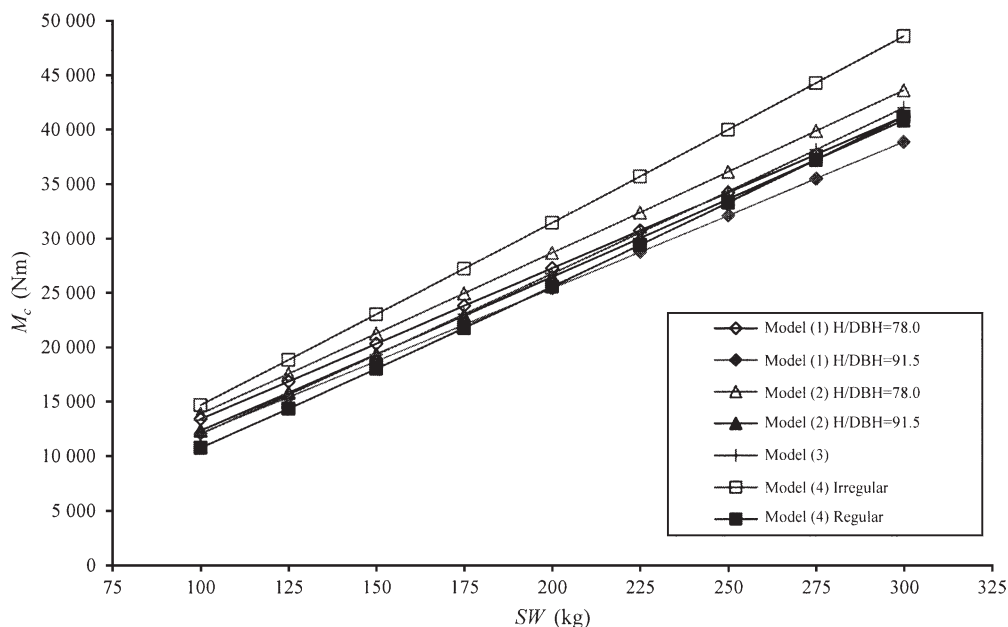
Figure 3. Comparison of predicted critical turning moment (M_c) as a function of stem mass (*SW*) using different models.

spruce in northern Ontario was achieved with tree height and green crown mass. Nonetheless, it has become standard to use only stem mass in windthrow prediction models (Gardiner *et al.*, 2000; Elie and Ruel, 2005). For our purposes, inclusion of *H*/d.b.h. ratio and spacing is interesting in that it partially accounts for the differences between stand structures by incorporating stand and tree factors that vary between structures. Tree spacing is higher in irregular stands and *H*/d.b.h. ratio is lower, especially for small d.b.h. stems.

Testing selected variables in mixed models where a random site effect was included and structure tested as a potential fixed effect led to have different significant fixed effects depending on the samples used in the analysis. Inclusion of the random site effect makes it more difficult to have significant fixed effects because it accounts for between site and within stand structure variability. Achim *et al.* (2005) also used a mixed model for predicting M_c and found only stem mass to be significant. However, they did not compare models with different subsets of the data.

For models including snapped and uprooted trees (models (1) and (2)), the *H*/d.b.h. ratio

was significant. This is logical for stem breakage since breaking resistance is a function of the third power of d.b.h. (Petty and Worrell, 1981; Peltola *et al.*, 2000), which means that for a given height, a larger d.b.h. would lead to a much higher critical turning moment. However, stem mass would be increased at the same time. Model (3), coming from the analysis of all uprooted trees, includes only stem mass for predicting M_c. In this case, presence of decay might have more influence overall as the graphs of data points and residuals suggest. Decay increases variability, especially within samples in irregular stands, which makes fixed effects other than stem mass insignificant. Thus, it is not surprising to observe that in the model for uprooted trees without decayed ones (model (4)), structure is significant with different intercepts for regular and irregular stands.

Comparison of predicted M_c values from our four models shows that limited differences are observed between most models, but they are still noticeable. The effect of *H*/d.b.h. ratio is in line with trends observed elsewhere, lower ratios leading to higher resistance (Petty and Worrell, 1981; Cremer *et al.*, 1982). There are however

some cases in the literature, especially in very strong storms, where H/d.b.h. ratio was found to have no effect (Schütz *et al.*, 2006). For the compared values of H/d.b.h. ratio in models (1) and (2), the predicted effect is similar in both models. Thus, critical bending moments are from 12 to 6 per cent higher with the mean value of the ratio for irregular stands and as stem mass varies between 100 and 300 kg. Since the effect of stand structure is not significant when this ratio is taken into account, it seems able to capture the major differences in growing conditions between stand types. This is consistent with the collinearity observed in the initial screening procedure between H/d.b.h. ratio and S. Using a continuous variable (H/d.b.h. ratio) rather than a classification of stand structures (regular *vs* irregular) better accounts for intermediate structures between these two extremes.

One case clearly stands out from all other models, which is model (4) for irregular stands. This case, which results from the analysis of uprooted and healthy sample trees only, clearly gives larger critical bending moments, especially for the larger stem masses, the slope being steeper than in other models. Comparison of models (1) and (2) which includes both uprooted and snapped trees also shows a reduction of predicted M_c when decay is present. In the case of uprooted trees, the effect of including decayed samples in the analysis is particularly important since it makes the structure effect insignificant. These effects of including decayed trees in the analysis are in line with studies showing that an increase in the amount of decay, either in the root or in the stem, eventually leads to reduced tree resistance and increased susceptibility to windthrow (Whitney, 1989; Matheny and Clark, 1994; Kane *et al.*, 2001; Whitney *et al.*, 2002). In a winching study, Lundström *et al.* (2007) attributed a 21 per cent decrease in critical turning moment to the presence of root rot, even though the roots of their trees were not badly attacked. The effect of decay may be less noticeable on snapped trees because the decay column in the stem needs to become quite large before it effectively reduces stem resistance (Matheny and Clark, 1994). Above-ground decay has also been found to be significantly related to root rot incidence in black spruce (Whitney, 1989). Thus, by setting aside decayed trees, we tend to reduce the impact of root rots on resistance to overturn-ing since root rot importance also increases with stand age. Our results show that sound healthy trees in irregular stands are more resistant to uprooting than similar trees in regular stands. Since this model is the only one where a structure effect was declared significant, it was used to compare the two regions sampled for regular stands and no difference was found. This confirms that these relationships are robust and can be applied across wide regions.

Assessment of the effects of structure and of general resistance of healthy black spruce trees seem to be best achieved with the model (2). It represents both modes of failure as they both occur in natural conditions. Difference between structures is partly taken in account with the slenderness ratio, this ratio being lower on average in irregular stands.

Even though we have clear indications that the role of decay can be important in irregular stands, we are unable to precisely evaluate its overall effect since we excluded trees with visible defects in our sampling meaning that our sampling includes only an unknown fraction of the real proportion of decayed trees in black spruce stands. Works from many authors suggest that the occurrence of root rot, butt rot and stem decay, is underestimated in our samples. In the North Shore region, Lavallée (1987) found that 26 per cent of the black spruce stems showed evidence of butt rot and 6 per cent had stem decay. Also, the proportion of trees affected was found to increase with mean age of dominant stems and d.b.h.. For ages between 61 and 80, which best represent our regular stands, he found that 2.4 per cent of the volume was decayed, in contrast with 7.1 per cent for trees over 160 years, which would correspond to our irregular stands. Root rot may be even more frequent since Whitney (1989) found that from 56 to 93 per cent of living dominant and codominant black spruce trees in northern Ontario were infected, the highest proportions being found in older trees. Work from Whitney (1989) and Whitney *et al.* (2002) suggest that decay would play a major role in the stability of old, irregular stands. The real occurrence of decay, both below and above ground, and its impact on tree stability should be studied more thoroughly, especially in irregular black spruce stands. The amount of stem decay could be related to stand characteristics and the calculation

of stem resistance to breakage could be adjusted based on formulas presented by Matheny and Clark (1994). Since the amount of root rot is also correlated with stem decay, these relationships could also be useful in adjusting the relationship between M_c and stem mass to account for the presence of root rot.

As mentioned in the methods, the height of the attachment point could lead to an underestimation of rupture height under wind or snow loading. However, stem breakage was not very frequent in this study and using mid-tree height is in line with the work of many authors who used height from ¼ to ½ of total tree height for the attachment point (Smith *et al.*, 1987; Fredericksen *et al.*, 1993; Moore, 2000; Peltola *et al.*, 2000; Achim *et al.*, 2005; Elie and Ruel, 2005).

The proportions of stem breakage and overturning in this study are quite similar to the observed proportions in previous static winching experiments, uprooting being generally more frequent (Smith *et al.*, 1987). These results differ from the observed proportion of each mode of failure reported in many forest stands. From a literature review, McCarthy (2001) suggests that mortality from stem snapping is dominant in boreal forests as in other forest ecosystems. In the same region as our study sites, Pham *et al.* (2004) observed a higher proportion of snapped trees both for black spruce and balsam fir, with ~60 per cent of fallen trees being snapped trees. Studies by Peltola *et al.* (2000) suggest that this divergence might be due to a much higher occurrence of stem breakage during winter, since they observed that all the 20 Scots pine winched on frozen soil experienced stem breakage while unfrozen soil gave similar occurrence of uprooting as observed here. Interaction between presence of decay and mode of failure could also explain these discrepancies since we likely underestimated the impact of decay in old-growth, untreated stands. However, our results remain valid for the application of partial cuts where trees with decay would be targeted for harvesting.

Adequately describing individual tree resistance to windthrow is only a necessary first step in modelling windthrow risk for irregular stands. Since wind load is related to spacing and since spacing varies with stand structure, the applied average wind load is also likely to vary between stands of different structures. In addition, in contrast with closed and regular stands, wind load in irregular stands will be more variable. This suggests that modelling efforts for irregular stands should look at wind load at the individual tree level.

Conclusion

The presence of decay on some tree samples and of two modes of failure lead us to compare models produced with different subsets of the data. Adding slenderness ratio along with stem mass eliminates any effect of stand structure differences. This indicates that, for identical trees, there is no general increase in resistance in irregular stands, considering both stem breakage and overturning. However, stand structure influences stem slenderness and this can influence resistance at the stand level. Irregular stands having smaller H/d.b.h. ratios would then be more resistant. This enhanced resistance could likely be offset by the lower resistance of decayed trees and the increased levels of decay in older, irregular stands. Since our sampling of decayed trees is very small and does not fully represent natural occurrence and variability of decay, the model without decayed trees (model (2)) is the best for representing the resistance of healthy trees in black spruce stands of regular and irregular structure. The observed effect of decay on tree resistance suggests that further investigations are necessary. Quantifying the relationship between the amount of decay in the stems and in the roots and resulting critical bending moments would be of particular interest.

Our results have some silvicultural implications. To maintain higher tree resistance, particular attention should be paid to minimizing the presence and development of decay. In windy climates, the slenderness ratio should be kept low through periodic thinning entries while taking care not to lower stand density too rapidly or drastically, as wind loading on trees would then increase and trees would not be adapted to it. Healthy trees and trees with low slenderness ratios should be preferentially retained when performing a thinning or other partial cuttings.

Conflict of Interest Statement

None declared.

References

Achim, A., Ruel, J.-C., Gardiner, B.A., Laflamme, G. and Meunier, S. 2005 Modelling the vulnerability of balsam fir forests to wind damage. *For. Ecol. Manage.* **204**, 35–50.

Bergeron, J.-F., Grondin, P. and Blouin, J. 1998 *Rapport de classification écologique du sous-domaine bioclimatique de la pessière à mousses de l'ouest.* Ministère des Ressources naturelles du Québec, Direction des inventaires forestiers, Quebec, 204 p.

Bergeron, Y. and Dubuc, M. 1989 Forest succession in the southern part of the boreal forest. *Can. Veg.* **79**, 51–63.

Bergeron, Y., Harvey, B., Leduc, A. and Gauthier, S. 1999 Stratégies d'aménagement forestier qui s'inspirent de la dynamique des perturbations naturelles: considérations à l'échelle du peuplement et de la forêt. *For. Chron.* **75**, 55–61.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P. and Lesieur, D. 2001 Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. *Can. J. For. Res.* **31**, 384–391.

Boucher, D., De Grandpré, L. and Gauthier, S. 2003 Développement d'un outil de classification de la structure des peuplements et comparaison de deux territoires de la pessière à mousses du Québec. *For. Chron.* **79**, 318–328.

Byrne, K.E. and Mitchell, S.J. 2007 Overturning resistance of western redcedar and western hemlock in mixed species stands in Coastal British Columbia. *Can. J. For. Res.* (in press).

Cogbill, C.V. 1985 Dynamics of the boreal forests of the Laurentian Highlands, Canada. *Can. J. For. Res.* **15**, 252–261.

Cremer, K.W., Borough, C.J., McKinnel, F.H. and Carter, P.R. 1982 Effects of stocking and thinning on wind damage in plantations. *N. Z. J. For. Sci.* **12**, 244–268.

Cucchi, V., Meredieu, C., Stokes, A., de Coligny, F., Suarez, J. and Gardiner, B.A. 2005 Modelling the windthrow risk for simulated forest stands of Maritime pine (*Pinus pinaster* Ait.). *For. Ecol. Manage.* **213**, 184–196.

De Grandpré, L., Morisette, J. and Gauthier, S. 2000 Long-term post-fire changes in the northeastern boreal forest of Quebec. *J. Veg. Sci.* **11**, 791–800.

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.

Foster, D.R. 1983 The history of fire in the boreal forest of southeastern Labrador. *Can. J. Bot.* **61**, 2459–2471.

Fraser, A.I. and Gardiner, J.B.H. 1967 Rooting and stability in Sitka spruce. London Forestry Commission Bulletin No. 40. HMSO, London, 28 pp.

Fredericksen, T.S., Hedden, R.L. and Williams, S.A. 1993 Testing Loblolly pine wind firmness with simulated wind stress. *Can. J. For. Res.* **23**, 1760–1765.

Freund, R.J. and Littell, R.C. 2000 *SAS System for Regression.* 3rd edn. SAS Institute Inc, Cary, NC, 236 p.

Gardiner, B., Peltola, H. and Kellomäki, S. 2000 Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. *Ecol. Model.* **129**, 1–23.

Grondin, P., Blouin, J. and Racine, P. 1998 *Rapport de classification écologique du sous-domaine bioclimatique de la sapinière à bouleau blanc de l'ouest.* Ministère des Ressources naturelles du Québec, Direction des inventaires forestiers, Quebec, 220 p.

Harvey, B.D., Leduc, A., Gauthier, S. and Bergeron, Y. 2002 Stand-landscape integration in natural disturbance-based management of the southern boreal forest. *For. Ecol. Manage.* **155**, 369–385.

Heinselman, M.L. 1981 Fire and succession in the conifer forests of northern North America. In *Forest Succession: Concepts and Application.* H.H. Shugart, D.B. Botkin and D.C. West (eds). Springer-Verlag, New York, pp. 374–415.

Johnson, E.A. 1992 *Fire and Vegetation Dynamics – Studies from the North American Boreal Forest.* Cambridge University Press, Cambridge, UK.

Kane, B., Ryan, D. and Bloniarz, D.V. 2001 Comparing formulae that assess strength loss due to decay in trees. *J Arbor.* **27**, 78–87.

Kneeshaw, D.D. and Bergeron, Y. 1998 Canopy gap characteristics and tree replacement in the southeastern boreal forest. *Ecology.* **79**, 783–794.

Lavallée, A. 1987 *Les caries de l'épinette noire dans la forêt boréale au Québec.* Service canadien des

forêts, Centre de foresterie des Laurentides, Rapport d'information LAU-X-76, Quebec, 16 p.

Lesieur, D., Gauthier, S. and Bergeron, Y. 2002 Fire frequency and vegetation dynamics for the south-central boreal forest of Quebec, Canada. *Can. J. For. Res.* **32**, 1996–2009.

Littell, R.C., Miliken, G.A., Stroup, W.W. and Wolfinger, R.D. 1996 *SAS System for Mixed Models*. SAS Institute Inc, Cary, NC, 633 p.

Lundström, T., Jonas, T., Stöckli, V. and Ammann, W. 2007 Anchorage of mature conifers: resistive turning moment, root-soil plate geometry and root growth orientation. *Tree Physiol.* **27**, 1217–1227.

Mason, W.L. 2002 Are irregular stands more wind-firm?. *Forestry.* **75**, 347–355.

Matheny, N.P. and Clark, J.R. 1994 *A Photographic Guide to the Evaluation of Hazard Trees in Urban Areas*. International Society of Arboriculture, Savoy, IL, 85 p.

McCarthy, J. 2001 Gap dynamics of forest trees: a review with particular attention to boreal forests. *Environ. Rev.* **9**, 1–59.

Meunier, S., Ruel, J.-C., Laflamme, G. and Achim, A. 2002 Résistance comparée de l'épinette blanche et du sapin baumier au renversement. *Can. J. For. Res.* **32**, 642–652.

Milliken, G.A. and Dallas, E.J. 2002 *Analysis of Messy Data, Volume III: Analysis of Covariance*. Chapman and Hall/CRC, Boca Raton, FL, 605 p.

Moore, J.R. 2000 Differences in maximum resistive bending moments of *Pinus radiata* trees grown on a range of soil types. *For. Ecol. Manage.* **135**, 63–71.

MRN 2000 *La limite nordique des forêts attribuables*. Rapport final du comité, Ministère des Ressources Naturelles, Québec, Canada, 101 p.

Nicoll, B.C., Achim, A., Mochan, S. and et Gardiner, B.A. 2005 Does steep terrain influence tree stability? A field investigation. *Can. J. For. Res.* **35**, 2360–2367.

Nicoll, B.C., Gardiner, B.A., Rayner, B. and Peace, A.J. 2006 Anchorage of coniferous trees in relation to species, soil type and rooting depth. *Can. J. For. Res.* **36**, 1871–1883.

Oliver, C.D. and Larson, B.C. 1996 *Forest Stand Dynamics. Update edition*. John Wiley & Sons, New York, 520 p.

Peltola, H., Kellomäki, S., Hassinen, A. and Granader, M. 2000 Mechanical stability of Scots pine, Norway spruce and birch: an analysis of tree-pulling experiments in Finland. *For. Ecol. Manage.* **135**, 143–153.

Petty, J.A. and Worrell, R. 1981 Stability of coniferous tree stems in relation to damage by snow. *Forestry.* **54**, 115–128.

Pham, A.T., De Grandpré, L., Gauthier, S. and Bergeron, Y. 2004 Gap dynamics and replacement patterns in gaps of the northeastern boreal forest of Quebec. *Can. J. For. Res.* **34**, 353–364.

SAS Institute Inc. 1999 *SAS/STAT User's Guide, Version 8*. SAS Institute Inc, Cary, NC.

Saucier, J.-P., Bergeron, J.-F., Grondin, P. and Robitaille, A. 1998 Les régions écologiques du Québec mérdional (3ᵉ version): un des éléments du système hiérarchique de classification écologique du territoire mis au point par le ministère des Ressources Naturelles du Québec. *L'Aubelle.* **124**, S1–S12.

Savill, P.S. 1983 Silviculture in windy climate. *For. Abst.* **44**, 473–488.

Schütz, J.-P., Götz, M., Schmid, W. and et Mandallaz, D. 2006 Vulnerability of spruce (*Picea abies*) and beech (*Fagus silvatica*) forest stands to storms and consequences for silviculture. *Eur. J. For. Res.* **125**, 291–302.

Silva, G., Ruel, J.-C., Samson, M. and Pin, D. 1998 Influence de quelques défauts externes sur la résistance des arbres à une simulation mécanique de l'action du vent. *Can. J. For. Res.* **28**, 123–131.

Smith, V.G., Watts, M. and James, D.F. 1987 Mechanical stability of black spruce in the clay belt region of northern Ontario. *Can. J. For. Res.* **17**, 1080–1091.

Wang, Y., Titus, S.J. and LeMay, V.M. 1998 Relationships between tree slenderness coefficients and tree or stand characteristics for major species in boreal mixed-wood forests. *Can. J. For. Res.* **28**, 1171–1183.

Whitney, R.D. 1989 Root rot damage in regenerated stands of spruce and balsam fir in Ontario. *Can. J. For. Res.* **19**, 295–308.

Whitney, R.D., Flemming, R.L., Zhou, K. and Mossa, D.S. 2002 Relationship of root rot to black spruce windfall and mortality following strip clear-cutting. *Can. J. For. Res.* **32**, 283–294.

Wilson, J.S. and Baker, P.J. 2001 Flexibility in forest management: managing uncertainty in Douglas-fir forests of Pacific Northwest. *For. Ecol. Manage.* **145**, 219–227.

Wood, C.J. 1995 Understanding wind forces on trees. In *Wind and Trees*. M.P. Coutts and J. Grace (eds). Cambridge University Press, Cambridge, pp. 3–40.