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**A multi-scale analysis of the effects of alternative silvicultural treatments on
windthrow within balsam fir dominated stands**

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22 **Abstract**

23 Boreal ecosystem functioning is largely controlled by disturbance dynamics. There have
24 been efforts at adapting forest management approaches to emulate natural disturbance
25 effects as this is expected to maintain ecosystem resilience. In many instances, this
26 involves resorting to partial cutting strategies that are likely to increase windthrow losses.
27 The objective of this study was to determine the effects of alternative silvicultural
28 practices on windthrow damage and how these effects vary with the scale of treatment.
29 The study was conducted in the Quebec north shore region (Canada), an area dominated
30 by balsam fir (*Abies balsamea* (L.) Mill.) accompanied by black spruce (*Picea mariana*
31 (Mill) B.S.P.). Four different silvicultural treatments (overstory removal, heavy partial
32 cutting, and two patterns of selection cutting) and control areas were implemented in
33 2004 and 2005. The experiment used a nested approach where treatment at the plot level
34 was independent and yet nested within block-level treatment. At the block level,
35 treatments were applied over 10-20 ha units, leaving a small portion of the block for a
36 smaller application of each treatment (2500 m², plot scale). Inventory was carried out
37 before harvesting and monitoring was done yearly after harvesting, with the aim to better
38 understand the plot- and block-level factors that drive windthrow damage levels and the
39 effects of alternative silvicultural treatments. Results after 6-7 years show that, basal area
40 proportion windthrown differs substantially between treatments as well as when treated
41 sites were compared to control sites. Windthrow levels were higher under heavy cuts
42 relative to selection cuts and also increased with balsam fir proportion. Windthrow
43 proportions were better correlated to block-level treatment than plot-level treatment

showing that the environment surrounding the treated plot can have an important effect on windthrow losses. Overall, selection cutting system particularly SC2, retains most green-tree basal area and thus best meets the management objective of retaining old-growth attributes. A simple empirical model was calibrated which could aid in hazard rating.

Keywords: multi-scale, balsam fir, back spruce, partial cutting, windthrow, empirical model

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Résumé

Le fonctionnement des écosystèmes forestiers boréaux est largement régi par la dynamique naturelle des perturbations. Devant ce constat, des efforts ont été consentis afin de développer des approches d'aménagement s'inspirant des perturbations naturelles en vue d'assurer la résilience des écosystèmes. Dans bien des cas, ceci implique un recours accru aux coupes partielles mais celles-ci sont susceptibles d'augmenter les pertes par chablis. L'objectif de cette étude était de déterminer les effets de pratiques sylvicoles alternatives sur les pertes par chablis, en tenant compte de l'échelle d'application du traitement. L'étude s'est déroulée dans la région de la Côte-Nord du Québec (Canada). La forêt était dominée par le sapin baumier (*Abies balsamea* (L.) Mill.) accompagné de l'épinette noire (*Picea mariana* (Mill) B.S.P.). Quatre traitements sylvicoles (coupe avec protection de la régénération, coupe partielle forte, deux patrons de jardinage) et un témoin ont été implantés en 2004 et 2005. L'étude fait appel à un dispositif niché où l'application à l'échelle fine de la parcelle est indépendante de celle à l'échelle du bloc. A l'échelle du bloc, les traitements ont été appliqués sur des surfaces de 10-20 ha. Une petite portion de chaque bloc a été réservée pour une application de chaque traitement à une échelle plus fine (parcelle, 2500 m²). Des parcelles permanentes ont été établies avant la coupe et suivies annuellement en vue de mieux comprendre l'effet de l'application des traitements à diverses échelles, ainsi que l'effet des variables de peuplement susceptibles d'influencer le niveau de pertes. Les résultats après 6-7 ans montrent que la proportion de surface terrière en chablis varie fortement selon les traitements. Les pertes par chablis augmentaient avec l'intensité du prélèvement et avec la proportion de surface terrière en sapin. Les pertes par chablis étaient davantage

75 expliquées par le traitement appliqué à l'échelle du bloc qu'à celui de la parcelle. Ceci
76 indique que l'environnement autour de la parcelle traitée joue un rôle majeur sur
77 l'ampleur des pertes. En somme, le système de coupe de jardinage (notamment SC2)
78 maintient la surface terrière la plus élevée et conserve ainsi mieux les attributs des vieilles
79 forêts. Un modèle empirique simple a été paramétré et pourrait servir à évaluer le risque
80 de chablis selon le type de coupe.

81 **Keywords:** multi-échelle, sapin baumier, épinette noire, coupe partielle, chablis, modèle
82 empirique.

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Introduction

In forest management, natural disturbances are becoming a model from which to design silvicultural strategies (Long 2009; Bose et al. 2014). Over much of the boreal forest, fire is considered the predominant mode of disturbance that shapes forest structure and composition (Stocks et al. 2003). However, in regions subject to a maritime influence, secondary types of disturbance (such as wind) become the predominant causes of the rarer disturbance events that do happen, and because these occur at longer intervals than fire, a larger fraction of the landscape reaches old-growth stages. Such a situation occurs in eastern Quebec where the fire cycle can exceed 500 years and where irregular and uneven-aged stands dominate the landscape (Bouchard et al. 2008). Traditionally, a harvesting strategy that protects advanced regeneration (CPRS) has been the standard harvest method in this region. However, when applied in irregular stands, this approach greatly simplifies forest structure. An alternative treatment that keeps small merchantable stems has been implemented in eastern Canada (Groot et al. 2005) but it still has a major impact on stand structure (Cimon-Morin et al. 2010). To minimize the impact of harvesting, lighter forms of partial cutting should also be considered (Ruel et al. 2013).

An increased use of partial cutting is however limited by the fear of windthrow. This is particularly relevant in previously unmanaged, old growth forests (Ruel 1995). The natural disturbance regime of eastern Quebec is influenced by partial windthrow (Waldron et al. 2013) and partial cutting is likely to increase the occurrence of windthrow through an increase of wind penetration into the stand (Gardiner et al. 1997). This increase in windthrow risk will vary depending on landscape, site and stand characteristics (Ruel 1995). At the landscape scale, topographic factors have been shown

107 to play a major role, creating strong variations in wind speed over short distances (Ruel et
108 al. 1998). Topex to distance, an index of topographic exposure, has been shown to be
109 closely related to these wind speed variations (Ruel et al. 1997). An increase in wind
110 speed with elevation has also been observed (Ruel 1995). Site factors that affect
111 anchorage strength, such as soil depth and drainage, are well known to have an impact on
112 the risk of windthrow (Ruel 1995). At the stand level, species composition, height,
113 density and age can all have an effect (Ruel 1995). Balsam fir (*Abies balsamea* (L.) Mill.)
114 has been shown to be more vulnerable than black spruce (*Picea mariana* (Mill.) B.S.P.)
115 (Ruel 2000) and vulnerability generally increases with height (Ruel 1995). Stand
116 structure has also been suggested to influence the risk of windthrow, uneven-aged stands
117 being perceived to be less at risk (Mason 2002; Boucher et al. 2006). The intensity and
118 the nature of the partial harvest will influence the amount of windthrow, more intensive
119 cuts leading to greater windthrow. Finally, in addition to the characteristics of the stand
120 itself and the treatment applied, those of adjacent stands can also have an important effect
121 (Ruel et al. 2003). Given the complexity of these influencing factors, it becomes very
122 difficult to predict mortality after partial cutting.

123 Because influential factors act at different scales, a good understanding of the impact of
124 partial cutting requires an approach that considers various scales (Ruel 2000). This study
125 adopts such an approach in examining partial cutting after windthrow in Eastern Quebec.
126 A range of harvesting intensities and patterns are examined in a nested experimental
127 design with the objective to determine: 1) the influence of alternative silvicultural
128 practices on windthrow damage; 2) the role of scale of treatment (block vs plot) on
129 windthrow damage; 3) how site factors interact with treatment in driving windthrow

damage, and finally 4) calibrate empirical models that could assist managers in hazard rating.

2.0 Materials and Methods

2.1 Study Site

The study area spanned from latitude 50 °N to 51 °N and longitude 67 °W to 69 °W. This area is part of the eastern black spruce-feathermoss bioclimatic domain dominated by black spruce and balsam fir. Being subjected to a maritime influence, the fire cycle is rather long, reaching more than 500 years in the eastern part of the region (Bouchard et al. 2008). In this context, stands are able to reach uneven-aged or irregular structures (Bergeron et al. 2007). Such structures represent over 60% of the unharvested area in the study region and are largely maintained through partial disturbances (Boucher et al. 2003). Partial windthrow (25-75% basal area damaged) has been shown to play a significant role in the region, impacting areas similar to fire over a thirty year period (Waldron et al. 2013). An analysis of photo-interpreted forest maps produced by the Quebec Ministry of Natural Resources (MRN) during its third inventory program (Létourneau et al. 2003) reveals that the area is dominated by coarse deposit types of mainly glacial origin and drainage is predominantly moderate. Available data for the period 1950 to 2000 show that annual mean temperature for the region ranges from -4 °C to 1.5 °C. The area receives a mean annual total rainfall of 993 mm (sd. 130 mm) and mean snowfall of 398 mm year⁻¹ (sd. 74 mm year⁻¹). Mean wind speed for the area ranges from 15 km/hour to 17km/hour (BioSIM model ver. 8, Régnière and Saint-Amant, 2008).

2.2 Experimental design

The study region is composed of four sites, namely Arbec (A), Abitibi site-1 (AB1), Abitibi site-2 (AB2) and Kruger (K). Study sites were located in areas dominated by stands over 120 years old, presenting an irregular or uneven-aged structure typical of the region and for which alternatives to clearcutting would be sought. Each site has five blocks, each 10 to 20 ha (Fig. 1A and 1B).

<<<Fig. 1>>>

The experimental design includes a nested application of silvicultural treatments. One of five silvicultural treatments was randomly assigned to each block, reserving a small portion of the block for a small scale application of each treatment. At this finer scale, treatments were randomly applied on 2500 m² units, leaving a 15 m buffer zone receiving the same treatment around each permanent plot. To ensure that the finer scale treatment was indeed different from the block treatment application, trees to cut were marked within the smaller units.

Treatments include an uncut control, two heavy cut types, and two selection cut variants. The first heavy cut type involves the harvesting of merchantable trees (>9 cm dbh) but with protection of advanced regeneration (CPRS); this is similar to the overstory removal in a shelterwood system and is the current silvicultural technique applied on most commercial forests in the region. It only leaves a few residual trees removing about 90% of total basal area. The second heavy cut type involves the removal of all trees of diameter 14 cm and above (Groot et al. 2005); this is a kind of heavy partial cutting system removing about 70% of total basal area, and is currently practiced in Ontario and Quebec (CPPTM) with the objective to create a two-story or irregular stand structure;

skid trail spacing is left to the harvester operator and is largely governed by the reach of the equipment. The first variant of selection cutting leads to an intensive removal (50% of basal area) close to skid trail (within 5 m) but leaving a strip of intact canopy between skid trails at the first cutting cycle. At the next rotation, harvesting is carried out in areas adjacent (5m) to a new skid trail established within the previously intact strip (SC1). In the second variant, permanent primary skid trails are established every 35 m and secondary skid trails, perpendicular to the main trails provide access to the rest of the stand where 25% of basal area is removed (SC2). The two selection cutting systems are similar in that they both eventually remove 35% of stand basal area, the major difference being in the harvesting pattern. With both approaches, an optimisation procedure was used to define the target residual structure and hence the planned harvest. Small merchantable stems (10-12 cm DBH) were not targeted for removal except in skid trails. Since the intent was to preserve the old forest attributes, including species composition, no species was prioritized for harvesting. Harvesting was carried out in the summer of 2004 at the AB1 and Kruger sites and in 2005 at the AB2 and Arbec sites. Additional details on the treatment development and implementation can be found in Ruel et al. (2007, 2013)

Windthrow was monitored using a network of permanent plots established prior to cutting. A 400 m² plot was established at the center of each of the small scale treatment unit (2500 m²). Three additional plots were randomly allocated to the remaining portion of the block, corresponding to the larger scale treatment application (Fig. 1). Due to logistical difficulties, there were some departures from this sampling pattern. Within site AB2, blocks had 4 plots each, with no smaller scale application of treatments. Within one

of the blocks in Kruger, an additional plot was established in the larger scale application of the treatment. There was therefore a total of 141 study plots, 40 located at the AB1 study site, 41 in Kruger, 40 in Arbec and 20 in AB2. Overall, there were 28 permanent plots under each of the treatments (except CPRS which had 29 plots) (Table 1).

<<<Table 1>>>

2.3 Site monitoring

Inventory was carried out before harvesting in which all merchantable trees were counted by 2 cm DBH classes. Monitoring was repeated after the harvesting and every year following the harvesting until 2011 (6-7 years after harvesting) by identifying and distinguishing uprooted trees, broken as well as standing dead trees.

2.4 Modelling windthrow

2.4.1 Explanatory variables

Species composition is a common factor influencing the amount of windthrow after partial cutting. We therefore verified the effects of basal area proportion of black spruce, balsam fir, white birch (*Betula papyrifera* Marsh.) and white spruce (*Picea glauca* (Moench) Voss) on windthrow damage. Because stem (and tree) mass is principally a function of tree diameter and height and correlates highly with critical turning moment (the force required to either uproot or break trees) (Elie and Ruel 2005), diameter and height were tested as predictors. Height was estimated using equations from Fortin et al. (2009). We also verified the effects of structural diversity measured with Shannon evenness index (Boucher et al. 2006; Anyomi et al. 2013) on windthrow damage. Shannon evenness index was estimated with Eqn. 1 below;

[1]
$$S_h = -\sum_{i=1}^s p_i \ln(p_i)$$

Where p_i is basal area proportion of a diameter class i relative to total stand basal area, s is number of diameter classes.

Finally, a site may be more vulnerable to windthrow owing to its elevation and exposure to wind. Data were therefore obtained on elevation and topographical exposure to wind (topex). To calculate Topex values, a digital elevation model with a grid size of 100 m was developed from topographic maps with an equidistance with 20-m contour lines. From this grid, Topex values were calculated using a routine developed by Ruel et al. (2002). Table 2 has the major variables considered in this modelling exercise.

<<<Table 2>>>

2.4.2 Quantifying windthrow

Windthrow damage is defined in this study as the proportion of plot total basal area damaged, including broken and uprooted trees (Eqn. 2).

$$[2] \ W = \left(\frac{\sum_{i=1}^n G_{w,i}}{G_T} \right) * 100$$

Where W is windthrow damage, $\sum_{i=1}^n G_{w,i}$ is the sum of basal area ($G_{w,i}$) of all damaged trees i to n on a plot and G_T is total plot basal area before logging.

Windthrow damage was compared for treated (CPRS, CPPTM, SC1 & SC2) and non-treated (control) sites, as well as for different treatment types using analysis of variance and Tukey's multiple comparison tests. Data was also collected on the residual tree population. Equation (2) was also used in computing basal proportion of green trees i.e. residual trees.

2.4.3 Model form

We used an approach where mean damage is either reduced or increased by modifiers (Eqn. 3).

$$[3] \quad W = \overline{W} \prod_{i=1}^n f_i(x_i)$$

where W is estimated damage, $\overline{W}$ is mean damage estimated from the calibration data set and $f_i(x_i)$ denotes the product of n modifiers of selected explanatory variables x_1 to x_n (Eqn. 4).

$$[4] \quad f_i(X_i) = 1 + \beta_{l.X_i} \left(\frac{X_i - \bar{X}_i}{\bar{X}_i} \right) + \beta_{q.X_i} \left(\frac{X_i - \bar{X}_i}{\bar{X}_i} \right)^2$$

where $\beta_{l.X_i}$ and $\beta_{q.X_i}$ represent the linear and quadratic effects of the variables X_i on windthrow damage. We introduced a random error (s) component into Eqn. (3) to verify if, besides selected fixed effect variables, there were substantial random effects of either site or block or even plot and hence Eqn. (5). NLMIXED procedure was used (SAS Institute, Cary, NC).

$$[5] \quad W = (\overline{W} + s) \prod_{i=1}^n f_i(X_i)$$

Since the study design was such that we had treatment at two spatial scales, two sets of models were calibrated; i) a plot-level model that first accounted for plot-level treatment effects and ii) a block-level model with block-level treatment effects as first entry variable. Through a stepwise procedure with forward selection, other plot-level variables were introduced into the model and, for a variable to be retained in the model, it had to be significant ($\alpha=5\%$), contribute substantially ($>1\%$) to total variance explained (Anyomi et

al., 2015) and its entry into the model needed to be associated with significant reduction in AIC values (>2). Additionally, a variable is retained when it contributes the highest, to the total variance explained relative to the other candidate explanatory variables considered.

Because variables occur at block, and plot levels, the modifier approach and the stepwise procedure enabled verifying if a concurrent and interactive effect drives windthrow damage or whether spatial effects are mutually exclusive. Finally, we also determined if a plot-level model was adequate in predicting the same results as a multiple-scale model. The fit statistics (AIC, coefficient of determination and RMSE) of the two models were considered. Treatment effects were compared using Tukey's HSD test. Statistical analyses were carried out in SAS v9.3 (SAS Institute, Cary, NC) and JMP v12 (SAS Institute, Cary, N.C.).

3.0 Results

3.1 Change in stand conditions following silvicultural treatments

Balsam fir was the most abundant species (65%) in the study region with moderate black spruce (33%) and a few white birch (2%) and white spruce ($<1\%$). Only minor changes in species composition occurred after harvesting. Basal area was reduced by about 87% under CPRS, 72% under CPPTM, and by about 45% and 40% respectively under SC1 and SC2. Structure was also strongly simplified by CPRS and CPPTM.

3.2 Importance of different mortality types

After about 6-7 years of post-harvest monitoring, mortality was observed to be highest in heavily cut plots (62%, 56% respectively for CPPTM and CPRS) and lower on selection

cuts sites (38%, 28% for SC1 and SC2, respectively) as well as on control plots (18%). Overall, a higher proportion of standing dead (24% s.d.: 21) trees was observed compared to windthrown trees (12%, s. d.: 17). However, the proportion of standing dead and wind-driven damage were correlated ($r=0.78$, $p=0.000$) and the pattern was similar by block- and plot-level treatments as well as by species (results not shown) suggesting that for our study region, windthrow and standing dead dynamics might have common facilitating factor(s). Results also show insignificant differences in green-tree basal area proportion between CPRS and CPPTM ($p=0.799$) sites (Fig. S1A). Residual basal area proportion was higher on selection cut sites as well as control sites (Fig. S1A & S1B). Total absolute post-harvest mortality was lowest for heavy cut sites compared to selection cut plots (Fig. S1C & S1D).

3.3 Variables retained in models at plot and block levels

3.3.1 Plot-level model

Plot-level treatment effect accounted for 7% of variability in windthrow (AIC= 537). Stand mean dbh contributed 28% to total variance explained, reducing model AIC by 18. Balsam fir basal area proportion further reduced model AIC by 3, contributing an additional 7% to variance explained. The final plot-level model is thus:

$$[6] \quad W_p = \left[\bar{W}_p + \sum_{i=1}^n (\beta_{p,i} \times z_{p,i}) \right] \times f_{dbh} \times f_{Gbsamf}$$

Where $\bar{W}_p$ is plot-level mean basal area proportion damaged by wind, $z_{p,i}$ is a binary variable referring to plot-level treatment and $\beta_{p,i}$ is the effect of this plot-level treatment,

and f_{dbh} , $f_{GBalsamf}$ are modifiers linked to stand mean dbh and balsam fir basal area respectively. Model parameter values are in Table 3.

<<<Table 3>>>

3.3.2 Block-level model

Block-level treatment explained most of the variability ($R^2=48\%$) in windthrow levels (with AIC value of 450). Balsam fir basal area proportion was the second explanatory variable retained in the model, reducing AIC by 11 and contributing 13% to the total variance explained. Eqn. 6 thus explains 61% of variability in windthrow at the block level.

$$[7] \quad W_B = \left[\bar{W}_B + \sum_{i=1}^n (\beta_{B,i} \times z_{B,i}) \right] \times f_{GBalsamf}$$

$\bar{W}_B$ is block-level mean basal area proportion damaged by wind, $z_{B,i}$ is a binary variable referring to block-level treatment and $\beta_{B,i}$ denotes effect of this block-level treatment. $f_{GBalsamf}$ is the modifier linked to balsam fir basal area proportion. This model is essentially a hierarchical model since silvicultural treatments were at block level and balsam fir basal area proportion is a stand-level variable. Parameter values of the block-level model (Eqn. 7) can be found in Table 3.

Overall, Eqn. 7 explained 61% of variability in windthrow at the block level and has AIC of 439 and the plot-level model (Eqn. 6) explained 42% of variability in windthrow at the plot level with AIC of 516.

3.4 Influence of variables retained in models

3.4.1 Plot- and block-level treatment effects on windthrow levels

Multiple comparison tests show that basal area proportions windthrown at the plot level was significantly higher in treated plots compared to control plots (Fig. 2A). Overall, windthrow does not differ between CPPTM and CPRS treated plots ($p=0.779$, Fig. 2A). SC1 also led to higher losses in comparison with SC2. Windthrow also significantly differed by block-level treatment, differences among treatment being similar to those associated to the plot level (Fig. 2B).

<<<Fig. 2>>>

Standing dead mortality responded to treatment quite similarly to windthrow. Tukey HSD tests show that the proportion of standing dead trees was similar ($p=0.395$) between CPPTM and CPRS for plot-level treatments. Significant differences were however observed when compared to other plot-level treatments and also when compared to control/background tree death (Fig. 3A). Similarly at the block level, proportion of standing dead trees varied significantly from one treatment type to another except between CPPTM and CPRS ($p=0.925$, Fig. 3B).

<<<Fig. 3>>>

3.4.2 Effect of balsam fir proportion on windthrow

Balsam fir basal area proportion was observed to be positively linked to wind damage (Fig. 4).

<<<Fig. 4>>>

3.4.3 Effect of diameter

As a single variable, diameter was weakly and negatively correlated with windthrow ($p=0.0025$, $R^2=0.003$), but after controlling for the effects of treatment, the effect of diameter on windthrow levels exponentially increased ($R^2=0.28$) and became positive. This explains why diameter is the second retained variable in the plot-level model. With the block-level model, even though mean diameter was still significantly correlated to windthrow, its contribution to the overall explained variability in windthrow was relatively low, hence not retained in the final model.

3.4.4 Effect of adjacent stands on the amount of windthrow

The fact that the block-level model was more accurate suggests that the surrounding area characteristics may also play an important role. Windthrow proportion was lower (12%) at the plot level compared to the block level (18%). To further illustrate this pattern, we compared windthrow for different block-level treatments (matrices) for plots that were treated to SC 1 and SC2 (Fig. 5). Results suggest that blocks treated to heavy cut types showed higher windthrow (Fig. 5).

<<<Fig. 5>>>

3.4.5 Site variables

Most of the site variables considered in this study were not significantly correlated with windthrow ($p=0.202$, $p=0.278$, $p=0.112$ respectively for latitude, longitude and Topex). Altitude significantly ($p < 0.0001$) explained about 2 % of the variability in windthrow. However, altitude was not retained in any of the final models because after accounting for silvicultural treatment effects and stand structural variables, the effect of altitude was relatively weak.

4.0 Discussion

4.1 Mortality levels

Mortality levels in this study were high, even in control stands. If such levels were sustained over time, complete canopy destruction would occur within 35 years. Previous studies in the region have found that the standing volume of these old forests fluctuates over time around some relatively stable level (Garet et al. 2009). In our case, an episode of wet snow occurred the year before the first blocks were treated. Even though stands with severe damage were avoided, it remains possible that some trees were weakened by this episode, leading to high amounts of trees that simply died standing. In the same region, dendrochronological studies by Girard et al. (2014) have identified long periods of low mortality, followed by important windthrow episodes starting in the 1990s. Such a pattern may be occurring here.

4.2 Mortality types

Much of the mortality was composed of trees that simply died standing. According to Bose et al. (2014), the increased wind penetration after harvesting would increase evapotranspiration, leading to water stress and eventually tree death. Both types of mortality were closely correlated and responded similarly to treatments. This fact could indicate that they were governed by the same underlying factors. The studied stands were old stands containing many trees of low vigor that were predisposed to die, whether still standing or damaged by wind. The fact that overall mortality reached around 20% after six to seven years probably reflects this. However, it must be emphasized that both types of mortality show additive treatment effects with no compensation through a change in mortality type.

4.3 Treatment effects on mortality

Treatment, both at the plot and block level, had a strong impact on both windthrow and standing dead proportions, both being higher under heavy cutting systems (CPRS and CPPTM) relative to selection cutting systems. Indeed, heavy cuts did not differ from each other and produced twice as much windthrow as was observed under the selection cutting systems (Fig. 2A and 3A). Selection cutting systems, particularly SC2 retains the most overall living basal area and thus best meets the management objective of retaining old-growth attributes.

Treatment effects largely reflect differences in harvesting intensity. Higher cutting intensity is linked to increased wind penetration into the stand as inter-tree spacing increases (Gardiner et al. 1997). This in turn translates into higher turning moments on residual trees. Achim et al. (2005a) reported reduced critical wind speeds (Their Fig. 3b) for both overturning and breakage following commercial thinning that removed 30% of stand basal area in stands dominated by balsam fir.

In addition to cutting intensity, the spatial pattern of harvesting can have an impact on windthrow levels. Hence, selection cut type 2 produced significantly lower vulnerability to both types of mortality than selection cut type 1 (Fig. 2A, 2B, S1C & S1D), even if both harvested comparable amounts of basal area. In SC1, intensive logging is concentrated in narrow strips along skid trails at any given harvesting time while with SC2, only 25% of total basal area is removed at a time along skid trails. With a high local harvesting rate, wind is able to penetrate more deeply into the stand, increasing windthrow losses. Thorpe et al. (2008) found that stems close to skid trails were

particularly vulnerable to windthrow. A higher cutting intensity close to skid trails could thus lead to increased windthrow since it would tend to funnel wind within these areas. Stand structure has been suggested to influence windthrow levels. In old-growth stands of West Switzerland, Hanewinkel et al. (2014) observed low storm damage following a major storm event (Lothar), which was attributed to the uneven-aged structure of the forest. Bonnesoeur et al. (2013) also observed higher wind firmness within stands managed under a coppice-with-standards system, in comparison with stands of a simpler structure. Through a modeling exercise, Mason (2002) also concluded that irregular stands should be more windfirm. Heavy partial cuts tend to homogenize forest structures while selection cuts produce attributes similar to old-growth forests (Bose et al. 2014). In our case, treatments have an effect on both stand density and structure. Selection cutting treatments had stand structure diversity indices quite similar to control stands (Shannon evenness indices of 0.830, 0.816, 0.877 respectively for SC1, SC2 and Control) but still experienced very different levels of mortality (Fig. S1C & S1D). This suggests that cutting intensity had a stronger impact on mortality than did stand structure. This observation is further demonstrated by the lower AIC values for treatment effects (498) when compared to the effects of Shannon evenness index (517).

4.4 Influence of stand characteristics on windthrow levels

Balsam fir basal area proportion was observed to be positively linked to wind damage (conferring higher vulnerability). Within eastern boreal forests, balsam fir proportion increases with succession (Bouchard et al. 2008) and it is a relatively less stable species when compared to other species e.g. black spruce (Ruel, 2000). For a given stem mass, resistance to uprooting of balsam fir and black spruce is quite similar but crown

characteristics differ (Achim et al. 2005b, Elie and Ruel 2005). The high incidence of butt and root rot in balsam fir at old age could have a marked influence on the higher vulnerability of the species to windthrow (Whitney 1989). Plot mean diameter was also observed to be a positive predictor of windthrow. Diameter often correlates with height and an increase in damage with height has often been observed (Ruel 1995). In addition, diameter can reflect age and a higher incidence of rot is normally found at old ages. However, given that the effect of diameter on windthrow was weak at the block level, it suggests that, at the plot level, diameter effects reflect the inter-stand differences owing to the silvicultural treatments not captured by the treatment variable in the plot-level model.

4.5 Influence of neighbouring stand characteristics on windthrow levels

One of our objectives was to determine the role of multiple-scale factors on windthrow vulnerability. Mortality across treatments generally followed the same trend at the plot and the block levels. Results show that changing the spatial scale did not lead to a substantial change in the windthrow predisposing factors, it however did change their relative importance (Table 3). At both plot and block levels, lower levels of windthrow were observed under selection cuts relative to heavy partial cuts and the strength of this relationship was higher at block level ($R^2=0.48$) when compared to plot level ($R^2=0.07$). At the block level, study plots were located in an environment treated the same way as the plots. In contrast, at the plot level, a study plot could be located in an environment submitted to a completely different treatment type. These findings are consistent with results of Ruel et al. (2003) who reported that the characteristics of stands surrounding partial cuts could have an effect on the amount of windthrow.

The fact that after accounting for block-level treatment effects on mortality, significant effects of plot-level basal area proportions contributed by balsam fir was observed (Eqn. 6) shows concurring effects of multiple-scale factors. Site variables (altitude, topographic exposure) were largely insignificant in explaining windthrow patterns because of the relatively uniform landscape of this study region (Table 2). Considering the higher proportion of explained variance (61%) that is associated with the block-level model, it should be preferable for forecasting windthrow. For operational purposes however, a plot-level model should be adequate in understanding mortality dynamics given the similarity in the driving factors.

5.0 Implications for forest management

Heavy cuts (CPRS and CPPTM) are widely practiced in eastern Canadian boreal forests, and here we observed that these are associated with twice as much post-treatment relative damage as selection cuts. With CPRS, this high level of mortality, combined with the low basal area left after harvesting, means that there remains very little canopy at the end of the study (Fig. S1). Retention in clearcuts has been promoted as a way to include structural elements in a regenerating stand. In some cases, these elements are expected to be maintained over a full rotation (Mitchell and Beese, 2002) but high levels of windthrow could compromise this objective. Even though the retained elements could be expected to contribute to dead wood input, their role could be limited if high mortality occurs within a short period of time after harvesting. From a stand production perspective however, the fact that a substantial proportion of residual basal area is damaged from windthrow under CPRS, does not become a concern because the overstory residual trees are not expected to contribute to the yield of the next rotation. Group retention, targeting

black spruce stands or portions of stands with a well-developed structure, has been suggested as a means to reduce windthrow damage in clearcut stands (Lavoie et al. 2012). With CPPTM, the amount of mortality remains high in relative terms but not in absolute terms (Fig. S1C & S1D). Given a larger residual basal area left after harvesting with this treatment, the canopy finally remaining is higher than with CPRS (Fig. S1A & S1B). Also, residual trees are expected to enable a 10 year reduction of the normal rotation but, considering the combined effects of the two mortality types (Fig. 2, 3, S1C & S1D), losses become a major concern.

Selection cuts enable minimizing relative windthrow damage (Fig. 2) but not absolute damage (Fig. S1C & S1D). They also maintain the densest canopy levels at the end of the study. Selection cut sites thus present better opportunities for foraging, cavity nesting birds, mammals and therefore biodiversity conservation (Knapp, 2015; Nappi et al. 2015). However, selection cuts are associated with rather high implementation costs relative to heavy cuts (Moore et al. 2012) and losses remain high, especially considering the slow growth rate in these northern environments. Reducing windthrow losses associated with CPPTM and selection cuts therefore becomes critical in enhancing the overall profitability of these strategies.

Results also suggest that block-level interventions correlate better to mortality relative to plot-level interventions, showing that the environment surrounding the partially harvested area must be carefully considered. Partially cut stands should be located within portions of uncut or partially cut forests rather than close to clearcuts.

Finally, tools (Eqn. 5 and 6) developed in this study could assist managers in identifying areas of high vulnerability to windthrow, either at the stand or harvesting unit level. With

503 a proper selection of stands to be treated and consideration of the effect of neighbouring
504 stands, losses could therefore be reduced.

505 **Conclusion**

506 This study examined windthrow levels at multiple scales after various levels of
507 harvesting. Mortality increased in direct relation with cutting intensity. Mortality was
508 also a function of diameter and species composition. Since treatment had an effect on
509 stand structure, no additional effect of stand structure (Shannon evenness index) could be
510 detected.

511 Wind damaged trees and trees that died standing responded, similarly suggesting a
512 common driver without compensation. Even though the low vigour of the stands could
513 play a role, this factor would more likely lead to some form of compensation, the less
514 vigorous trees that would die standing being also more likely to break or uproot. The
515 absence of compensation between mortality types would require further investigation.
516 Among the two models developed, the one using both variables coming from the stand
517 (stand total basal area composition contributed by balsam fir species) and block levels
518 (treatment) proved superior. This means that a gain in precision can be obtained when
519 considering multiple scales for windthrow hazard estimation. However, since both
520 models retained the same variables, a model developed from the monitoring of individual
521 plots still provides a valuable approach to derive a relative estimate of windthrow
522 vulnerability.

523 In this study, very high levels of mortality were observed, even in control stands. Such
524 levels may have been influenced by individual weather events that occurred just prior to
525 the study establishment or during the monitoring period. The models that were developed

here provide some useful insights into how to reduce losses in future applications. Lower cutting intensity located within portions of uncut or partially cut forests, and targeting balsam fir for removal should be tested.

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Table 1: Plot distributions under each of the plot (columns) and block (rows) level treatments

Block level treatment	Plot level treatment				
	SC1	SC2	CPPTM	CPRS	Control
SC1	16	3	3	3	3
SC2	3	16	3	3	3
CPPTM	3	3	16	3	3
CPRS	3	3	3	17	3
Control	3	3	3	3	16

Table 2: Variables considered in windthrow modelling, stand and site attributes after silvicultural treatment.

Variable	Mean (standard dev.)/ Number of Classes	Minimum, Maximum
Treatment	5	-
<i>Stand structural variables</i>		
Stand mean height	10.77 (1.80)	6.48, 13.61
Stand mean DBH	15.45 (2.36)	9.80, 20.65
Shannon Evenness Index	0.78 (0.18)	0, 0.99
Number of trees per plot	31 (12.10)	1, 54
<i>Species basal area compositions (%)</i>		

Balsam fir	57.20 (25.53)	0, 100
Black spruce	39.90 (26.24)	0, 100
White birch	2.33 (5.45)	0, 79
White spruce	0.06 (0.63)	0, 7
<i>Site variables</i>		
Latitude (⁰ N)	50.88 (0.33)	50.36, 51.28
Longitude (⁰ W)	-68.85 (0.60)	-69.43, -67.98
Altitude (m)	548 (50.97)	454, 656
Topographic exposure (Topex)	0.90 (10.41)	-32.20, 33.06

Table 3: Model parameter estimates

Variable	Plot-level model		Block-level model	
	Parameter	Estimate (SE)	Parameter	Estimate (SE)
Treatment	$\beta_{p.SC_1}$	-15.267 (7.332)	$\beta_{b.SC_1}$	4.515 (3.923)
	$\beta_{p.SC_2}$	-13.335 (7.702)	$\beta_{b.SC_2}$	-5.992 (4.825)
	$\beta_{p.CPPTM}$	25.761 (11.429)	$\beta_{b.CPPTM}$	8.672 (3.492)
	$\beta_{p.CPRS}$	43.251 (22.049)	$\beta_{b.CPRS}$	11.224 (4.506)
	$\beta_{p.C}$	-24.670 (7.051)	$\beta_{b.C}$	-11.485 (4.851)
Mean DBH	$\beta_{l\bar{db}_h}$	4.562 (1.101)	-	-
	$\beta_{q\bar{db}_h}$	5.652 (3.341)	-	-

Balsam fir basal	β_l	0.809 (0.387)	β_l	0.964 (0.456)
area proportion	$\beta_{\frac{G_{ba}}{p}}$	0.834 (0.843)	$\beta_{\frac{G_{ba}}{p}}$	1.044 (0.754)
	$\frac{S_{G_{ba}}}{W_p}$	27.740 (7.075)	$\frac{S_{G_{ba}}}{W_B}$	14.934 (3.103)
	$\frac{S_{am}}{f}$		$\frac{S_{am}}{f}$	

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Fig. 1. A; Study area map showing the location of the four study sites and an illustration of plot distribution within a site. The hatchings highlight plot-level treatment within a block. The area outside the hatched zone is treated with a single treatment, corresponding to the block-level treatment. B; Schematic illustration of the experimental design showing the main (block-level) units and plot-layout within blocks. Selection cut type 1 is denoted by 1, Selection cut type 2 by 2, CPRS is 3, CPPTM is 4 and Control is 5.

Fig. 2. Basal area proportion windthrown by **A)** plot-level treatment and **B)** block-level treatment. Red lines indicate 95% confidence interval of the mean. Means marked with same letters do not differ significantly (Tukey's HSD, $\alpha=5\%$).

Fig. 3. Effect of A) plot-level treatment and B) block-level treatment on patterns of standing dead trees. Red lines indicate 95% confidence interval of the mean. Means marked with same letters do not differ significantly (Tukey's HSD, $\alpha=5\%$).

Fig. 4. Variability in windthrow levels (log₁₀ transformed) by the proportions of balsam fir within stands.

Fig. 5: Variation in windthrow levels within plots treated to selection cut and with adjacent stands treated to various treatment types. Adjacent stands that were heavily cut (CPPTM, CPRS), show higher windthrow levels. Red line denotes the mean windthrow and the blue indicates standard error of the mean.

Fig. S1. Living residual basal area by A) plot and B) block level treatments. Total absolute post-harvest mortality at the C) plot and D) block levels.