Eurasian J. For. Res. 17-1: 11-17 , 2014

Tree Shape and Resistance to Uprooting - A Simple Model Analysis

SHIBUYA Masato[1]*, KOIZUMI Akio[1] and TORITA Hiroyuki[2]

[1] Research Faculty of Agriculture, Hokkaido University,
Sapporo 060-8589, Japan
[2] Forest Research Department, Hokkaido Research Organization,
Higashiyama, Koshunai, Bibai 079-0166, Japan

Abstract

We examined tree resistance to uprooting in relation to tree shape using a simple, qualitative model for the ratio of the resistive moment to the overturning moment. For this analysis, we used model trees and varied the crown size for a fixed stem size for a ratio of crown mass to stem mass that varied from 0.1 to 1. The results predicted the phase transition in the resistance trend in relation to the crown mass/stem mass ratio. Resistance increased on both sides of the crown mass/stem mass ratio, and was minimized at intermediate ratios. This indicates that crown expansion contributes to resistance to the right side of minimum, and vice versa. The same trend was recognized for actual Sitka spruce tree data. These results were consistent with previous observations of tree resistance to uprooting: trees with a small slenderness ratio (ratio of height to diameter at breast height) are resistant to uprooting, and trees/stands are vulnerable to uprooting after thinning, especially after belated thinning. We recommend sparse tree densities in plantations to manage the risk of physical tree damage such as overturning and stem failure. However, quantitative analyses of wind damage to trees and stands are necessary to improve risk management of plantations. The results of this study can be incorporated into such quantitative analyses.

Key words: Plantation, Resistance to uprooting, Tree density, Tree shape

Introduction

Wind presents a serious hazard to forests in various regions of the world, including Great Britain (Blackburn *et al*. 1988; MacCurrach 1991; Moore and Quine 2000), France (Ancelin *et al*. 2004; Cucchi *et al*. 2004), Scandinavia (Valinger *et al*. 1993), New Zealand (Moore 2000; Moore and Quine 2000), the United States (Fredericksen *et al*. 1993), Canada (Achim *et al*. 2005), and Japan (Chiba 2000). The vulnerability of trees and forest stands to wind damage depends on stand type, with coniferous plantations more vulnerable to wind damage than stands of broadleaved species (Ruel 1995; Wilson and Oliver 2000; Mitchell 2013).

Various factors including tree species, climate, topography, altitude, openness to wind, soil properties, silvicultural treatment, stand structure, and tree shape affect the occurrence and frequency of wind damage to trees and stands (Cremer *et al*. 1982; Savill 1983; Gardiner *et al*. 1997; Cucchi *et al*. 2005; Nicoll *et al*. 2006; Mitchell 2013). Among these factors, stand structure and tree shape are influenced by silvicultural treatment. For example, high tree density results in small diameter growth, a high slenderness ratio (ratio of height to the diameter at breast height [DBH]), small crown size, high tree mortality, and a high form factor (Kilpatrick *et al*. 1981; Rollinson 1988; form factor = v/gh, v: stem volume, g: cross-sectional area at breast height, h: tree height). Although many studies (e.g., Cremer *et al*. 1982; Savill 1983; Shibuya *et al*. 2011) have found that tree shape affects resistance to tree uprooting (toppling with root system), various incompatible conclusions have been reported. A low slenderness ratio (i.e., high taper) derived from low tree density has been reported to result in high stability to uprooting (Cremer *et al*. 1982; Blackburn and Petty 1988; MacCurrach 1991; Polley 1995; Papesch *et al*. 1997; Peltola *et al*. 1999; Gardiner *et al*. 2000; Ancelin *et al*. 2004). In contrast, high-density or non-thinned stands have been found to be resistant to uprooting (Valinger and Fridman 1997; Gardiner and Quine 2000; Moore and Quine 2000; Achim *et al*. 2005; Cucchi *et al*. 2005). This latter trend has been explained by decreased wind load due to the small crown size of trees in high-density stands (Gardiner and Quine 2000; Moore and Quine 2000), decreased wind penetration in high-density stands (Gardiner *et al*. 1997), damping of tree sway by canopy contact between trees in high-density stands (Blackburn *et al*. 1988), and the suppression of turbulence in high-density stands (Mitscherlich 1973; Richter 1975).

These mutually incompatible findings were examined in a previous study (Shibuya *et al*. 2011) of tree shapes in coniferous plantations damaged and undamaged by uprooting in central Hokkaido, Japan. The authors recognized a close relationship between tree shape and resistance to uprooting and found that trees with low slenderness ratios and large crowns were resistant to uprooting. Furthermore, in a tree-pulling experiment conducted in coniferous plantations, Urata *et al*. (2012) confirmed that the critical uprooting moment of a tree of a given stem mass with a large crown is greater than that of a tree of the same stem

(Received; April 23, 2014: Accepted; July 7, 2014)
* Corresponding author: shibuya@ for.agr.hokudai.ac.jp

mass with a small crown. Consequently, the authors recommended the low-density management of coniferous plantations to increase resistance to uprooting (Shibuya *et al*. 2011; Urata *et al*. 2012).

However, these studies (Shibuya *et al*. 2011; Urata *et al*. 2012) did not examine non-thinned or very high-density stands. The mean slenderness ratios ranged from 53 to 83, 54 to 86, and 53 to 78 in *Larix kaempferi*, *Abies sachalinensis*, and *Picea jezoensis* plantations, respectively (Shibuya *et al*. 2011), and from 59 to 88 in three *Picea glehnii* plantations (Urata *et al*. 2012), whereas the mean slenderness ratio can exceed 100 in coniferous plantations (Cremer *et al*. 1982; Peltola *et al*. 2000; Wilson and Oliver 2000).

Therefore, in this study, we developed and analyzed a simple, qualitative model of tree resistance to uprooting in relation to tree shape, taking into consideration the large variation in crown size against stem size, using model trees and actual trees.

Model of tree resistance to uprooting in relation to tree shape

We examine the trend in resistance to uprooting in relation to large variations in tree shape. For the purpose of this study, we defined tree shape using the combination of crown and stem sizes. The variables DBH, height, height of the crown base, and crown radius are abbreviated as D, H, h, and r, respectively (Abbreviations for tree dimensions: see Fig. 1). We assumed the following:

1) Crowns have the shape of a right cone, independent of crown and stem sizes. Crown size increases (or decreases) similarly, at a constant ratio between crown diameter and length.
2) Wind load acts horizontally, on the crown only, and is proportional to the square of wind speed (v^2) and the frontal area of the crown. The center of gravity of the wind load is located at 2/3 of the crown length from the tree top (Koizumi 1987; Chiba 2000). The overturning moment (M_W) by wind is not influenced by the aboveground mass of the tree. The anchorage point of a tree is at the stem base.
3) Resistive moment (M_R) by roots is related to (aboveground mass)$^{\beta}$, as shown in Urata *et al*. (2012).

From the above assumptions, the frontal area of a crown exposed to wind (C_A) is given as

$$C_A = r(H-h) \quad (1).$$

Therefore, wind load on the crown is $ar(H-h)v^2$, where a = 0.5 ρ C_d , ρ is the density of the air (a constant > 0), and C_d is the drag coefficient (Koizumi 1987; Chiba 2000). M_W is then determined as

$$M_W = ar(H-h)v^2 \cdot \frac{H+2h}{3} = \frac{arv^2}{3}(H+2h)(H-h) \quad (2).$$

If stem and crown masses are W_S and W_C, respectively, then

$$M_R = \alpha(W_S+W_C)^{\beta} \quad (3),$$

where α and β are constants (>0). Furthermore, we assumed that stem failure by wind never occurs. Thus, as the ratio $\frac{M_R}{M_W}$ increases, the more resistant the tree becomes, and vice versa.

From Assumption 1,

$$\frac{H-h}{r} = \delta \text{ , where } \delta \text{ is a constant} > 0 \quad (4).$$

Substituting this into Eq. (2) results in

$$M_W = \frac{av^2}{3\delta}(H+2h)(H-h)^2 \quad (5).$$

Therefore,

$$\frac{M_R}{M_W} = \frac{3\alpha\delta}{av^2} \cdot \frac{(W_S+W_C)^{\beta}}{(H+2h)(H-h)^2} \quad (6).$$

In Eq. (6), if we set $\Delta = \frac{(W_S+W_C)^{\beta}}{(H+2h)(H-h)^2}$,

we can numerically examine the change in the $\frac{M_R}{M_W}$ ratio for various tree shapes using the Δ, because a, α, and δ are constants and v is wind speed.

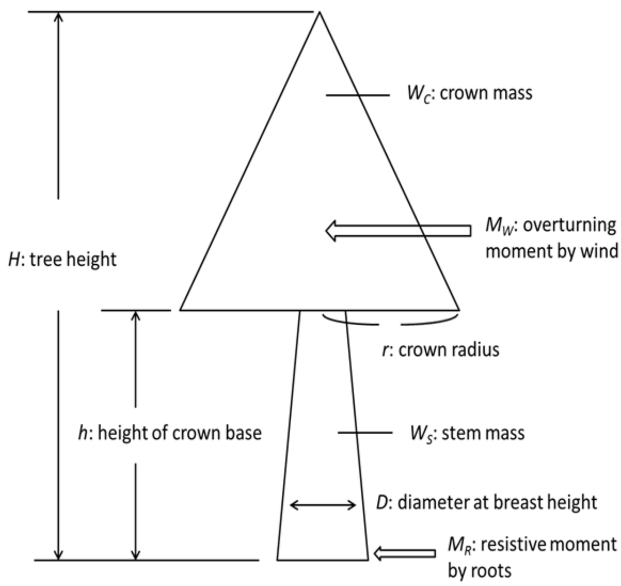

Fig. 1. Abbreviations for tree dimensions and moments. D: diameter at breast height, H: height, h: height of crown base, W_S: stem mass, W_C: crown mass, r: crown radius, M_W: overturning moment by wind, M_R: resistive moment by roots.

Analyses

Analysis of the effect of tree shape on resistance to uprooting using model trees

First, we examined the effect of tree shape on resistance to uprooting using Eq. (6) and model trees of various crown sizes with a fixed stem size. In the analysis, we assumed that stem mass was 100 kg and that crown mass ranged from 10 to 100 kg at 10-kg intervals. For the numerical analysis, we used larch tree (*L. kaempferi*) data from plantations in Nagano Prefecture, central Japan (Research Group of Four Japanese Universities 1963), to determine H and h for W_S = 100 kg and W_C = 10–100 kg. Samples were taken from seven plantations aged 9–56 years old. From the data set, relationships between W_S and D^2H and between h/H and W_C/W_S (Fig. 2) were determined as follows:

$$W_S = 0.0679\left(D^2H\right)^{0.909} \quad \left(r^2 = 0.984,\ p < 0.01\right) \quad and$$
$$\frac{h}{H} = -0.258\log\left(\frac{W_C}{W_S}\right) + 0.084 \qquad \left(r^2 = 0.804,\ p < 0.01\right) \qquad (7).$$

We determined $D \approx 14$ cm and $H \approx 15$ m for $W_S = 100$ kg from Fig. 2a and Eq. (7), and h was estimated from Eq. (7) with H = 15 m and $\frac{W_C}{W_S} = 0.1 - 1$. Figure 2d shows that crown length ($H - h$) was proportional to r, because a regression through the origin was significant ($H - h = 3.67\ r$, $r^2 = 0.964$, $p < 0.01$; Assumption 1).

In addition, we needed to determine β in Eq. (6) for the analysis. Unfortunately, we had no tree-pulling data for larch trees; therefore we used data from a tree-pulling experiment conducted in *P. glehnii* plantations in Uryu Experimental Forest (44°3′–44°29′ N, 142°1′–142°20′ E) of Hokkaido University, northern Japan (Urata *et al*. 2012). In the experiment, the relationship between M_R and aboveground mass ($W_S + W_C$) was not stand specific and was determined as

$$M_R = 1.39\times10^{-2}\left(W_S + W_C\right)^{1.39} \quad \left(r^2 = 0.88,\ p < 0.001\right) \qquad (8).$$

The regression coefficient was significantly different from 1 (p < 0.01), and we adopted β = 1.39 in the analysis.

Analysis of the trend in resistance to uprooting using actual tree data

In the analysis in the above section, we assumed that stem size was constant against various crown sizes. However, both stem and crown size vary in coniferous plantations of the same age depending on tree density (Rollinson 1988). Therefore, we reanalyzed the tree data (Table 2) from Gardiner *et al*. (1997), excluding tree No. 56 because of its irregular crown base value, to examine the trend in resistance to uprooting with actual tree data using Eq. (6). The data were from 10 Sitka spruce trees, excluding No. 56, from five 23-year-old plantations of varying densities (420–3222 trees/ha), and did not include crown width (r); mean spacing, however, was included. We first examined the data under Assumption 1 for the significance of a regression of $H - h$ on mean spacing, substituting mean spacing

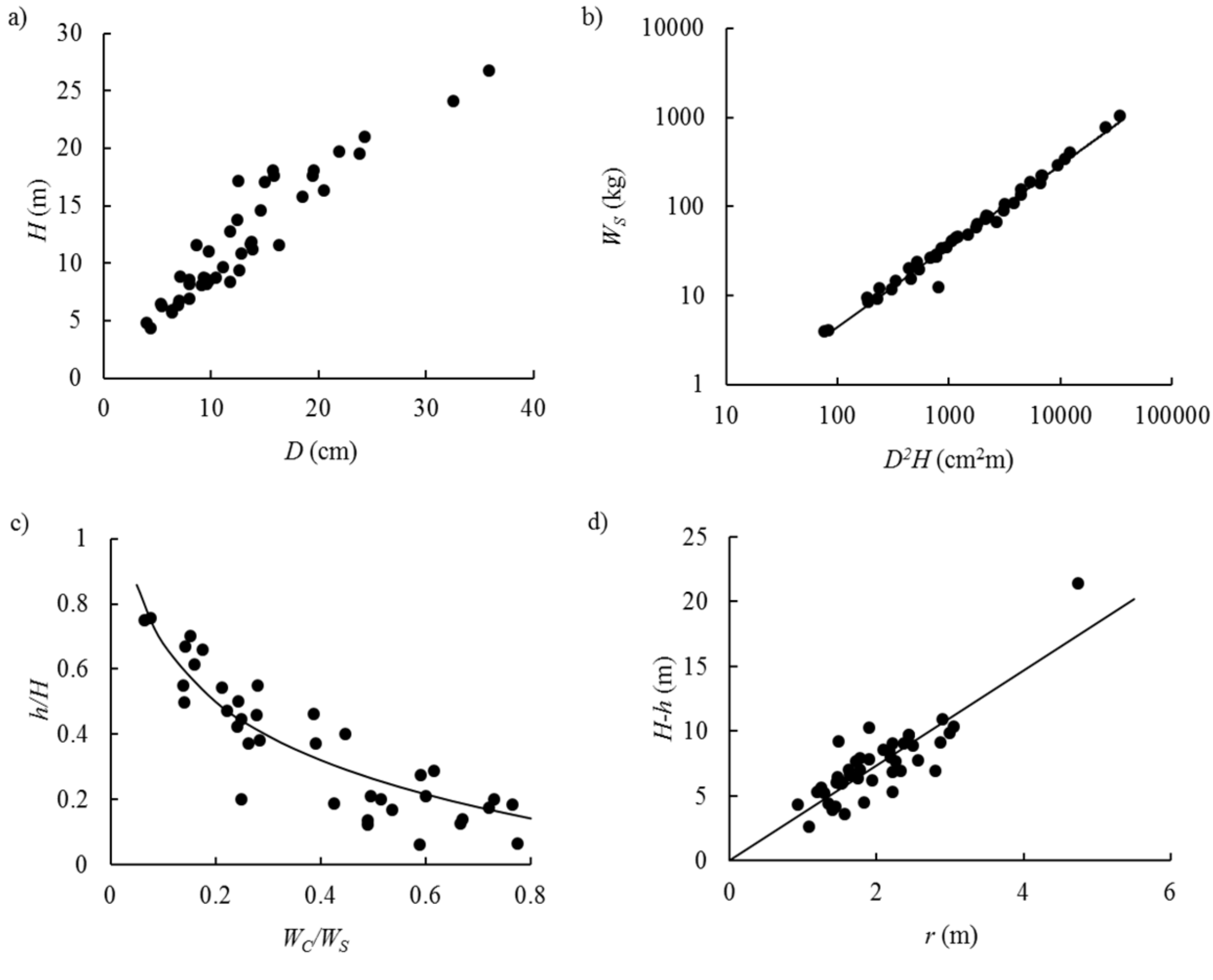

Fig. 2. Relationships among tree size parameters of larch trees (Research Group of Four Japanese Universities 1963). Abbreviations: See Fig.1. Regressions: See Eq. (7) and the text.

for r, but the regression through the origin was not significant (p > 0.05). Then, we abandoned the assumption of similarity of crown shape and calculated resistance from Eqs. (2) and (3) as follows:

$$\frac{M_R}{M_W} = \frac{3\alpha}{av^2} \cdot \frac{(W_S + W_C)^{1.39}}{r(H+2h)(H-h)} \quad (9),$$

substituting mean spacing for r and using the second term on the right side of Eq. (9) as an estimate of resistance.

Table 1. Dimensions of model trees

W_S (kg)	W_C (kg)	H (m)	h (m)
100	100	15	1.3
100	90	15	1.7
100	80	15	2.1
100	70	15	2.6
100	60	15	3.2
100	50	15	3.9
100	40	15	4.8
100	30	15	5.9
100	20	15	7.5
100	10	15	10.2

Abbreviations: See Fig. 1.

Results

The effect of tree shape on resistance to uprooting in the model-tree analysis

Using the value of Δ, we examined the trend in resistance to uprooting when crown size was assumed to be considerably variable for a fixed stem size (Table 1, Fig. 3).

Starting from $\frac{W_C}{W_S} = 1$, resistance to uprooting decreased with a decrease in the $\frac{W_C}{W_S}$ ratio; it then reached its minimum value and increased thereafter. Consequently, resistance to uprooting changed with $\frac{W_C}{W_S}$ ratio, i.e., tree shape, and the relationship between them was concave. Resistance was greatest at $\frac{W_C}{W_S} = 0.1$ in the analysis (Fig. 3).

Reanalysis of Sitka spruce data

For the Sitka spruce data from Gardiner *et al*. (1997), W_S and W_C ranged from 82 to 167 kg and from 36 to 180 kg, respectively. The $\frac{W_C}{W_S}$ and $\frac{h}{H}$ ratios were 0.44–1.08 and 0.11–0.60, and decreased and increased, respectively, with increased density (Table 2). Reanalysis of the data with Eq. (9) showed a similar trend for the relationship between tree shape and resistance to that found in the model-tree analysis (Fig. 3). Although there was variation in the resistance and $\frac{W_C}{W_S}$ ratio within each stand, resistance decreased with increasing density up to 1717 trees/ha, and then increased with further increases in density (Fig. 4). It is likely that the minimum resistance occurred at a density between 3222 and 1717 trees/ha. The maximum resistance was found at a density of 420 trees/ha.

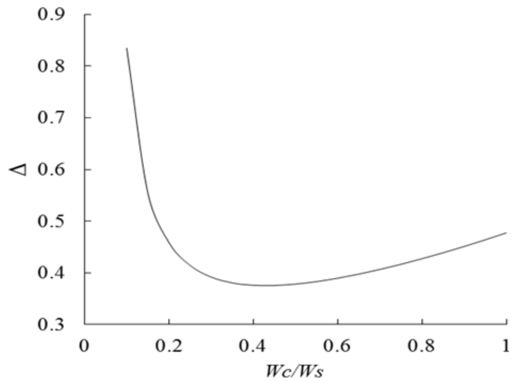

Fig. 3. Change in resisitance to uprooting (Δ) with tree shape (W_C/W_S). Stem mass is assumed to be 100 kg, and crown mass ranges from 10 to 100 kg. Abbreviations: See Fig.1.

$$\Delta: \frac{(W_S + W_C)^{1.39}}{(H+2h)(H-h)^2}$$

Discussion

Our results for tree resistance to uprooting based on Eqs. (6) and (9) are qualitative and differ from the results of analyses by mechanical models such as GALES and HWIND, which estimate the critical wind speed for tree uprooting (e.g., Gardiner *et al*. 2000). However, our results predicted some important trends in tree resistance to uprooting. First, they suggest a phase transition in the resistance to uprooting in relation to tree shape. In Fig. 3, the relationship between Δ and the $\frac{W_C}{W_S}$ ratio showed a minimum at around $\frac{W_C}{W_S} = 0.45$. The increase in W_C increased the resistance on the right side of the minimum and decreased it on the left side of the minimum. The same trend was recognized for actual Sitka spruce tree data (Fig. 4). In relation to stand density, tree shapes with small and large $\frac{W_C}{W_S}$ ratios generally occur in high-density and low-density stands (Rollinson 1988), respectively. Therefore, resistance is generally expected to be large for both low- and high-density stands of the same age.

The expected phase transition in the trend of resistance to uprooting in relation to tree shape (Fig. 3) can complicate the understanding of resistance, depending on the experimental design. That is, if only trees on the right side of the minimum in Fig. 3 are examined, the conclusion would be reached that trees with low slenderness ratios and large crowns are more resistant to uprooting. Conversely, examination of only trees from the left side of the minimum in Fig. 3 would result in the inverse conclusion, namely, high slenderness ratios and small crowns are favorable for tree resistance. Furthermore, if we examined trees in a narrow range on both sides of the minimum, we might

Table 2. Summary of Sitka spruce data (Gardiner *et al.* 1997)

Tree number*	Density (trees/ha)	H (m)	D (cm)	h (m)	W_S (kg)	W_C (kg)
121	3222	12.1	14.2	6.6	82	36
71	3222	12.7	14.3	6.6	91	40
25	3222	12.1	14.5	7.3	101	45
70	1717	11.5	15.1	3.5	82	48
34	1717	11.5	15.6	3.4	88	61
64	1257	11.5	18.3	3.9	116	75
45	879	10.4	19.9	2.9	129	105
26	879	10.9	20.3	1.6	125	101
43	420	11.8	21.8	1.3	167	180
21	420	10.5	22.6	1.5	151	162

* Tree number is the same as in Gardiner et al. (1997).
Abbreviations: See Fig. 1.

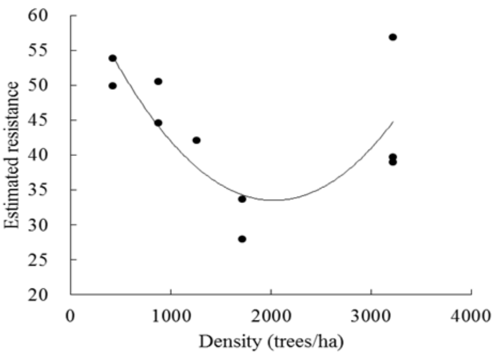

Fig.4. Change in resistance to uprooting of 23-year-old actual Sitka spruce trees (Gardiner et al. 1997), with change in desnity. Abbreviations: See Fig. 1. Fitted curve: $y=8\times10^{-6}x^2-0.0032x+66.4$ ($r^2=0.57$, $p<0.05$).

not reach a definite conclusion. Consequently, it is important to examine the relationship between tree resistance to uprooting and tree shape for a wide range of stand densities and tree shapes (i.e., slenderness ratios and crown size/stem size balances).

Our results are also consistent with important observational results for resistance to uprooting: 1) trees with low slenderness ratios, including trees at the forest edge, tend to be resistant to uprooting (e.g., Cremer *et al*. 1982; Savill 1983); and 2) trees/stands are vulnerable to uprooting just after thinning, especially after belated thinning (Cremer *et al*. 1982; Savill 1983; MacCurrach 1991). The results shown in Fig. 3 suggest that trees with large $\frac{W_C}{W_S}$ ratios tend to be more resistant to uprooting. A large $\frac{W_C}{W_S}$ ratio was closely related to a low slenderness ratio (Rollinson 1988). At the same time, the results suggest that trees with small $\frac{W_C}{W_S}$ ratios tend to be resistant to uprooting. Generally, in plantations with no thinning for several decades, trees tend to have high slenderness ratios. For example, the slenderness ratio (mean height/mean DBH) in a 23-year-old radiata pine plantation in Australia was 100, where the density at 15 years old was approximately 1300–1400 trees/ha (Siemon *et al*. 1980). In a Sitka spruce plantation in Ireland with an initial tree density of 2900 trees/ha, the slenderness ratio was 90 at 31 years old (Kilpatrick *et al*. 1981). Thinning results in the crown expansion of residual trees; therefore, thinning in a stand consisting of slender trees should decrease tree resistance to uprooting (Fig. 3) and allow for increased wind penetration into the stand (Blackburn and Petty 1988). Our results agree with previous observations for coniferous plantations (Cremer *et al*. 1982; Savill 1983; MacCurrach 1991).

Tree resistance to uprooting is high at both extremes of the $\frac{W_C}{W_S}$ ratio in Fig. 3. Thus, we examined factors that contributed to this trend in resistance. Resistance was estimated by Δ:

$$\Delta = \frac{(W_S + W_C)^{\beta}}{(H+2h)(H-h)^2}\,.$$

In this equation, $(W_S + W_C)^{\beta}$ and $(H+2h)(H-h)^2$ are related to M_R and M_W, respectively. Figure 4 shows trends in Δ, $M_R\left[(W_S + W_C)^{1.39}\right]$, and M_W $\left[(H+2h)(H-h)^2\right]$ with the $\frac{W_C}{W_S}$ ratio in the model-tree analysis (Fig. 3). The value of Δ decreased and increased with the $\frac{W_C}{W_S}$ ratio when $\frac{W_C}{W_S} \le 0.4$ and ≥ 0.5, respectively. M_R increased with $\frac{W_C}{W_S}$ ratio, almost linearly. M_W also increased with $\frac{W_C}{W_S}$ ratio, but asymptotically. From trends in M_R and M_W shown in Fig. 5, the increase in Δ from $\frac{W_C}{W_S} = 0.4$ to $\frac{W_C}{W_S} = 0.1$ resulted mainly from the rapid decrease in M_W. M_W is proportional to C_A and height of the center of gravity of the wind load. Height of the center of gravity increased from $\frac{W_C}{W_S} = 0.4$ to $\frac{W_C}{W_S} = 0.1$; therefore, the decrease in C_A contributed intensively to the large resistance to uprooting for small crown size. In contrast, Δ increased with $\frac{W_C}{W_S}$ ratio when $\frac{W_C}{W_S} \ge 0.5$. In this range of $\frac{W_C}{W_S}$ ratio, both M_R and

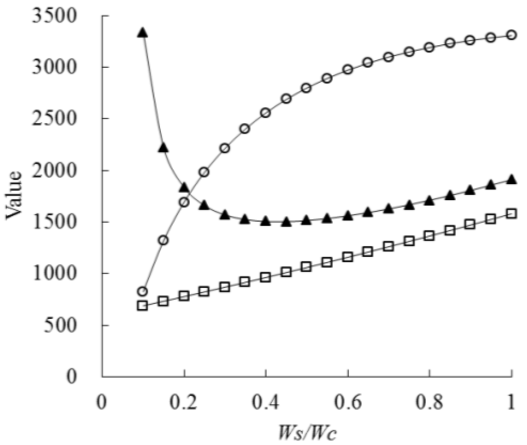

Fig. 5. Changes in tree resistance (Δ), M_R $\left[(W_S + W_C)^{1.39}\right]$, and M_W $\left[(H+2h)(H-h)^2\right]$ with W_C/W_S in the model-tree analysis. The resistance is multiplied by 4000. Abbreviations: See Fig. 1. ▲: Δ, □: M_R, ○: M_W.

M_W increased with $\frac{W_C}{W_S}$ ratio. Therefore, M_R increased more rapidly than M_W with $\frac{W_C}{W_S}$ ratio and contributed significantly to the increase in Δ. In the model-tree analysis, as stem mass was constant, the increase in W_C affected the increase in resistance to uprooting. We omitted the influence of aboveground mass on the overturning moment. Although aboveground mass increases the overturning moment of a tree (M_R) by approximately 5–20% (Blackburn and Petty 1988; Peltola and Kellomäki 1993; Gardiner *et al*. 1997, 2000; Urata *et al*. 2012), it may not change trends in resistance to uprooting shown in Figs. 3 and 4.

The substitution of mean spacing for r in the analysis of Sitka spruce data (Gardiner *et al*. 1997) using Eq. (9) might have biased the estimation of tree resistance. The canopy was likely closed in high-density stands, and thus the estimation bias is presumed to be small in such stands. In low-density stands, however, the canopy might not be closed. In this case, half the mean spacing is greater than crown radius, and thus resistance would be underestimated. Therefore, the substitution of mean spacing for r may underestimate resistance in low-density stands, but should not affect the trend in resistance shown in Fig. 4.

Resistance to uprooting generally changes with stand age and tree height (e.g., Gardiner and Quine 2000). Several studies have pointed out that young trees are resistant to uprooting (Slodičák 1995; Gardiner and Quine 2000; Moore and Quine 2000) and that trees become more vulnerable to uprooting with increasing height (Peltola and Kellomäki 1993; Wilson and Oliver 2000; Ancelin *et al*. 2004; Cucchi *et al*. 2005). Our model analysis, using Eqs. (6) or (9), however, is presently not suitable for analysis of the trend in tree resistance to uprooting with tree growth, because it is doubtful that $\beta = 1.39$ in Eq. (3) is applicable to a wide range of tree sizes and shapes. The value of $\beta = 1.39$ was determined for three approximately 30-year-old *P. glehnii* plantations (Urata *et al*. 2012). It was not stand-specific, but its applicability to a wide range of tree sizes and shapes is unknown.

For risk management of tree uprooting, management at both ends of the $\frac{W_C}{W_S}$ ratio in Fig. 3 is recommended. However, trees at the left end of the ratio are considerably more slender and would thus be vulnerable to stem failure due to wind and snow damage. Consequently, taking physical damage other than uprooting into consideration, plantation management on the right side of the minimum in Fig. 3 is more favorable. In coniferous trees, the crown base will remain high after intensive pruning, whereas a high $\frac{W_C}{W_S}$ ratio contributes to tree stability. Therefore, low planting density and early re-spacing (pre-commercial thinning) should increase tree/plantation stability (Cremaer *et al*. 1982; Savill 1983; MacCurrach 1991; Wilson and Oliver 2000).

To manage the risk of wind damage to trees and stands, quantitative analyses using mechanistic models such as ForestGALES and HWIND (Gardiner and Quine 2000; Gardiner *et al*. 2000; Moore and Quine 2000) are necessary. Our results may contribute to improving these models and understanding their results. Our results in Fig. 4 are not consistent with the conclusion of Gardiner *et al*. (1997). This inconsistency may be due in part to different assumptions about M_R. We assumed that M_R is related to the aboveground mass of a tree, whereas Gardiner *et al*. (1997) assumed it to be proportional only to stem mass.

In this study, we examined trees that did not have crown contact with neighboring trees. However, the damping effect of canopy contact on tree sway affects the occurrence of uprooting (Blackburn *et al*. 1988; Gardiner *et al*. 1997). Therefore, vulnerability to uprooting differs between trees with and without contact with neighboring trees. Variation in the crown size/stem size balance (i.e., tree shape) of trees should be incorporated into mechanical models such as ForestGALES (Gardiner and Quine 2000) to comprehensively examine tree resistance to uprooting in relation to tree shape.

References

Achim, A., Ruel, J-C., Gardiner, BA., Laflamme, G. and Meunier S (2005) Modelling the vulnerability of balsam fir forests to wind damage. For Ecol Manage., 204: 35–50. doi: 10.1016/j.foreco.2004.07.072

Ancelin, P., Courbaud, B. and Fourcaud, T. (2004) Development of an individual tree-based mechanical model to predict wind damage within forest stands. For Ecol Manage., 203: 101–121. doi: 10.1016/j.foreco.2004.07.067

Blackburn, P. and Petty, JA. (1988) Theoretical calculations of the influence of spacing on stand stability. Forestry, 61: 235–244.

Blackburn, P., Petty, JA. and Miller, KF. (1988) An assessment of the static and dynamic factors involved in windthrow. Forestry, 61: 29–43.

Chiba, Y. (2000) Modelling stem breakage caused by typhoons in plantation *Cryptomeria japonica* forests. For Ecol Manage., 135: 123–131.

Cremer, KW., Borough, CJ., McKinnel, FH. and Carter, PR. (1982) Effects of stocking and thinning on wind damage in plantations. New Zealand J For Sci., 12: 244–268.

Cucchi, V., Meredieu, C., Stokes, A., Berthier, S., Bert, D., Najar, M., Denis, A. and Lastennet, R. (2004) Root anchorage of inner and edge trees in stands of Maritime pine (*Pinus pinaster* Ait.) growing in different podzolic soil conditions. Trees, 18: 460–466. doi: 10.1007/s00468-04-0330-2

Cucchi, V., Meredieu, C., Stokes, A., Coligny, F., Suarez, J. and Gardiner, B. (2005) Modeling the windthrow risk for simulated forest stands of Maritime pine (*Pinus pinaster* Ait.). For Ecol Manage., 213: 184–196. doi: 10.1016/j.foreco.2005. 03.019

Fredericksen, TS., Hedden, RL. and Williams, SA. (1993) Testing loblolly pine wind firmness with simulated wind stress. Can J For Res., 23: 1760–1765.

Gardiner, BA. and Quine, CP. (2000) Management of forests to reduce the risk of abiotic damage –a review with particular reference to the effects of strong winds. For Ecol Manage., 135: 261–277.

Gardiner, BA., 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.

Gardiner, BA., Stacey, GR., Belcher, RE. and Wood, CJ. (1997) Field and wind tunnel assessments of the implications of respacing and thinning for tree stability. Forestry, 70: 233–252.

Kilpatrick, DJ., Sanderson, JM. and Savill, PS. (1981) The influence of five early respacing treatments on the growth of Sitka spruce. Forestry, 54: 17–29.

Koizumi, A. (1987) Studies on the estimation of the mechanical properties of standing trees by non-destructive bending test. Res Bull Coll Exp For, Hokkaido Univ., 44: 1329–1415. (in Japanese)

MacCurrach, RS. (1991) Spacing: an option for reducing storm damage. Scot For., 45: 285–297.

Mitchell, SJ. (2013) Wind as a natural disturbance agent in forests: a synthesis. Forestry, 86: 147–157.

Mitscherlich, G. (1973) Wald und Wind. Allgemeine Frost- und Jagdzeitung, 144: 76–81.

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

Moore, J. and Quine, CP. (2000) A comparison of the relative risk of wind damage to planted forests in Border Forest Park, Great Britain, and the Central North Island, New Zealand. For Ecol Manage., 135: 345–353.

Nicoll, BC., Gardiner, BA., Rayner, B. and Peace, AJ. (2006) Anchorage of coniferous trees in relation to species, soil type, and rooting depth. Can J For Res., 36: 1871–1883.

Papesch, AJG., Moore, JR. and Hawke, AE. (1997) Mechanical stability of *Pinus radiata* trees at Eyrewell Forest investigated using static tests. New Zealand J For Sci., 27: 188–204.

Peltola, H. and Kellomäki, S. (1993) A mechanistic model for calculating windthrow and stem breakage of Scots pines at stand edge. Silva Fenn., 27: 99–111.

Peltola, H., Kellomäki, S., Väisänen, H. and Ikonen, V-P. (1999) A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce, and birch. Can J For Res., 29: 647–661.

Peltola, H., Kellomäki, S., Hassinen, A. and Granander, 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.

Polley, VH. (1995) Beurteilung der mechanischen Stabilität der Waldbäume auf der Grundlage der Bundeswaldinventur. Forst und Holz, 50: 594–597.

Research Group of Four Japanese Universities (1963) Productivity of forest ecosystem in relation with nutrient cycle – Material No.1. 258 pp. (in Japanese)

Richter, J. (1975) Sturmschäden bei der Fichte im Sauerland. Der Frost- und Holzwirt, 30: 106–108.

Rollinson, TJD. (1988) Respacing Sitka spruce. Forestry, 61: 1–22.

Ruel, J-C. (1995) Understanding windthrow: silvicultural implications. For Chron., 71: 434–445.

Savill, PS. (1983) Silviculture in windy climates. For Abst., 44: 473–488.

Shibuya, M., Urata, T., Torita, H. and Iijima, H. (2011) Windthrow damage and tree shape in coniferous plantations in central Hokkaido, northern Japan. Jpn. J. For. Environment, 53: 53–59.

Siemon, GR., Müller, WJ., Wood, GB. and Forrest, WG. (1980) Effect of thinning on the distribution and biomass of foliage in the crown of radiata pine. New Zealand J For Sci., 10: 461–475.

Slodičák, M. (1995) Thinning regime in stands of Norway spruce subjected to snow and wind damage. *In* Coutts MP, Grace J (Eds.) Wind and Trees. Cambridge University Press, Cambridge, UK. pp. 436–447.

Urata, T., Shibuya, M., Koizumi, A., Torita, H. and Cha, JY. (2012) Both stem and crown mass affect tree resistance to uprooting. J. For. Res., 17: 65–71.

Valinger, E. and Fridman, J. (1997) Modeling probability of snow and wind damage in Scots pine stands using tree characteristics. For Ecol Manage., 97: 215–222.

Valinger, E., Lundqvist, L. and Bondesson, L. (1993) Assessing the risk of snow and wind damage from tree physical characteristics. Forestry, 66: 249–260.

Wilson, JS. and Oliver, CD. (2000) Stability and density management in Douglas-fir plantations. Can J For Res., 30: 910–920.