Silva Fennica 1993, Vol. 27 N:o 2: 99–111

A mechanistic model for calculating windthrow and stem breakage of Scots pines at stand edge

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TIIVISTELMÄ: MALLI MÄNTYIHIN TUULESTA KOHDISTUVIEN MURTAVIEN JA KAATAVIEN VOIMIEN LASKEMISEKSI METSÄNREUNATILANTEESSA

Peltola, H. & Kellomäki, S. 1993. A mechanistic model for calculating windthrow and stem breakage of Scots pines at stand edge. Tiivistelmä: Malli mäntyihin tuulesta kohdistuvien murtavien ja kaatavien voimien laskemiseksi metsänreunatilanteessa. Silva Fennica 27(2): 99–111.

A model for the mechanism of windthrow and stem breakage was constructed for single Scots pines (*Pinus sylvestris* L.) at the stand edge. The total turning moment arising from the wind drag and from the bending of stem and crown was calculated along with the breaking stress of the stem. Similarly, the support given by the root-soil plate anchorage was calculated. Windspeed variation within the crown and the vertical distribution of stem and crown weight were taken into account. Model computations showed that trees having a large height to diameter ratio were subject to a greater risk of falling down or breaking than trees with a small height to diameter ratio. The windspeed required to blow down a tree or break the stem of a tree decreased if the height to diameter ratio or the crown to stem weight ratio of trees increased.

Tutkimuksessa laadittiin malli tuulesta mäntyihin kohdistuvien murtavien ja kaatavien voimien laskemiseksi metsänreunatilanteessa siten, että puuhun kohdistuvaan kokonaisvääntömomenttiin vaikuttivat sekä tuulesta että puun taipumisen seurauksena painovoimasta aiheutuvat vääntövoimat. Näiden voimien perusteella laskettiin puun runkoon ja juuriin kohdistuvat vääntövoimat: jos ne ylittivät rungon tai juurten keston, puu kaatui tai puun runko murtui. Mallilaskelmien mukaan männyt, joiden pituus suhteessa läpimittaan oli suuri, kaatuivat tai niiden runko murtui huomattavasti helpommin kuin männyt, joiden pituus suhteessa läpimittaan oli pieni. Männyt kaatuivat tai murtuivat sitä pienemmän tuulen nopeuden vallitessa, mitä suurempi puun pituus suhteessa läpimittaan oli tai mitä suurempi latvus- ja runkomassan suhde oli.

Keywords: wind, breakage, stems, windspeed, breaking stress, bending models, calculation.
FDC 181.2 + 421

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Accepted September 1, 1993

Symbols and definitions

(Standard International Units: m, kg, Pa, S)

Symbol	Explanation	Dimension	Value
A(z)	Projected area of tree crown and and stem at height z	m^2	
C_d	Drag coefficient	-	0.29
d	Zero plane displacement; upward displacement of the wind profile by vegetation	m	
$d_{1.3}$	Diameter at breast height	m, cm	
h	Tree height	m	
E	Modulus of elasticity,	MPa	7000.0
F_1	Total force due to wind	N	
z	Height along stem	m	
$F_1(z)$	Force due to wind at height z	N	
$F_2(z)$	Force due to gravity at height z	N	
g	Gravitational constant	ms^{-2}	9.82
I	Area moment of inertia of the stem	m^4	
k	von Karman's constant	-	0.41
M(z)	Green mass of tree stem and crown at height z	kg	
p	Air density	kgm^{-3}	1.2226
RS_{sup}	Supporting moment of the root-soil plate anchorage	Nm	
S	Breaking stress of the stem	Pa	
T	Total turning moment at the stem base	Nm	
T(z)	Turning moment at height z	Nm	
U(z)	Windspeed at height z	ms^{-1}	
U_o	Friction velocity	ms^{-1}	
x(z)	Horizontal displacement of stem from the upright position at height z	m	
Z_o	Roughness length parameter	m	0.20
l(z)	Distance from the tree top	m	
RS_{mean}	Mean depth of the root-soil plate (volume)	m	
A_{rsw}	Percentage of the root-soil plate weight of the total below-ground anchorage	-	0.30
Mass	Fresh mass of the root-soil plate	kg	
b	Distance from crown centre and the tree top	m	
a	Distance from the ground level to crown centre	m	

1 Introduction

The structure and functioning of the boreal forest ecosystem is strongly affected by wind. In Finland, for example, two wind episodes in 1978 and 1982 caused the loss of about three million cubic meters of timber in both cases (Solantie 1983, Laiho 1987). Wind-induced damage is most likely whenever stands not previously thinned are thinned intensively (Lohmander and Helles 1987). Similarly, thinning combined with fertilization can increase the risk of wind-induced damage (Persson 1975, Valinger 1986, Laiho 1987). In particular, the risk of wind-induced damage is greatest in stands adjacent to new clear-cut areas (Neustein 1965, 1971, Alexander 1967, Flemming 1968, Persson 1975, Elling and Very 1978, Laiho 1987).

Studies on wind-induced forest damage are mainly statistical and indicate how the properties and position of a tree stand are related to the frequency and size of damage (e.g. Laitakari 1952, Neustein 1965, 1971, Alexander 1967, Flemming 1968, Persson 1975, Solantie 1983, 1986, Miller 1985, Valinger 1986, Laiho 1987, Lohmander and Helles 1987). However, high windspeed is, by definition, responsible for wind-induced forest damage, i.e. wind-induced forces with gravity-induced forces exceed the strength of stem or roots. Therefore, the mechanics of wind-induced forces, in conjunction with the mechanical strength of stems and roots, allow one to model wind effects on trees in relation to the properties of wind and trees and how the properties of wind and trees effect the mechanisms of wind-induced damage as summarized by Grace (1977).

The aim of this study was to develop a simulation model for windthrow and stem breakage of Scots pines (*Pinus sylvestris*) in order to predict the windspeed and turning moment needed to uproot a tree or break the stem of a tree at stand-edge conditions. The model is theoretical, and it is based on the physical properties of trees and the vertical wind profile at the edge of a stand.

2 A model for the mechanism of windthrow and stem breakage

2.1 Wind-induced forces acting on the tree

The study deals with stand-edge conditions, where the wind force on trees is mainly due to the mean wind, i.e. little fluctuating force (e.g. Papesh 1974). Thus, the static approach was used instead of the dynamic one. The forces affecting a tree are divided into the horizontal force due to the wind and the vertical force due to gravity. The horizontal and vertical forces are substantiated by the total turning moment applied at any height of the stem or the root system. Trees are assumed to deflect to a point of no return in a wind of constant velocity and direction. This makes it possible to calculate the maximum windspeed a tree can withstand when the rooting resistance and the breaking strength of the stem are known. A tree is assumed to fall down or break, if the total turning moment exceeds the support provided by the root-soil plate anchorage (Coutts 1986), or if the breaking stress of the stem exceeds the critical value for stem breakage (Sunley 1968, Petty and Worrel 1981, Petty and Swain 1985) (Fig. 1).

The total horizontal force is the sum of the drag forces due to the stem and crown systems

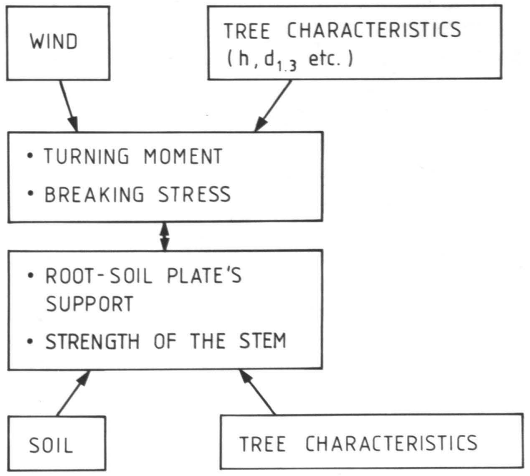

Fig. 1. Structure of the wind damage model.

(Grace 1977, Melargno 1982, Smith et al. 1987). The wind-induced force at the height z [m] is

$$F_1(z) = 0.5 \cdot C_d \cdot p \cdot A(z) \cdot U(z)^2 \quad (1)$$

where $F_1(z)$ is the wind force [N], U(z) is the windspeed [ms^{-1}], A(z) is the projected area of the tree against the wind [m^2], C_d is the drag coefficient (dimensionless) and p is the air density [kgm^{-3}]. The wind profile is calculated from the aerodynamic characteristics of friction velocity, roughness length, zero plane displacement and von Karman's constant, i.e.

$$U(z) = (U_o / k) \cdot \log((z - d) / Z_o)) \quad (2)$$

where U(z) is the windspeed [ms^{-1}] at height z, Z_o is the roughness length parameter [m], d is the zero plane displacement [m], k is von Karman's constant (dimensionless) and U_o is the friction velocity [ms^{-1}] (Gloyne 1968, Oliver and Mayhead 1974).

The crown projection area against the wind was computed assuming that the crown shape is formed by two triangles having a common base equal to twice the length of the longest branch in the crown. The length of the longest branch was regressed against stem diameter (Hakkila 1971). The crown area was assumed to streamline as a function of windspeed, i.e. the reduction of crown area was 20 % for windspeeds of less than 10 ms^{-1} and 60 % for windspeeds of more than 20 ms^{-1}, the value of streamline between these two points being interpolated (Raymer 1962, Walshe and Fraser 1963). The stem projection area against the wind was compiled from the projections of stem segments 1 m in length. The mid-diameter of the stem segments was calculated on the basis of stem taper (Laasasenaho 1982).

2.2 Forces related to gravity

Once any substantial bending of a tree occurs, an additional force due to gravity becomes present. The total force due to gravity is obtained by dividing the stem and crown into segments 1 m in length and by then totalling up the forces acting on each segment (Grace 1977, Jones 1983, Petty and Swain 1985). The force due to gravity at height z arises from the green mass of the segment and gravitational constant

$$F_2(z) = M(z) \cdot g \quad (3)$$

where $F_2(z)$ is the force due to gravity [N], M(z) is the green mass of the stem and crown (kg) and g is the gravitational constant [ms^{-2}].

The green mass of a stem segment is estimated from the segment volume and green density of each segment in relation to its position (Tamminen 1962, Laasasenaho 1982, Kilkki 1989). The estimation of the crown mass and its vertical distribution is based on the model developed by Oker-Blom et al. (1988). However, it resulted in the dry weight of needles and branches. This had to be converted into green weights with the help of the known relationship between green mass and dry mass for needles and branches (Hakkila 1971, Kärkkäinen 1985, Peltola 1990).

2.3 Total turning moment

The total turning moment at the base of the stem was obtained as the sum of the turning moments determined for each 1-meter-long segment from the wind drag and horizontal deflection of the segment weight. The deflection curve of the tree stem is based on wind loading at the crown centre (Fig. 2). The turning moment is computed at the centre of each segment (Jones 1983), i.e.

$$T(z) = F_1(z) \cdot z + F_2(z) \cdot x(z) \quad (4)$$

where T(z) is the turning moment [Nm], z is the height along stem [m], x(z) is the horizontal displacement of the stem from the upright position [m].

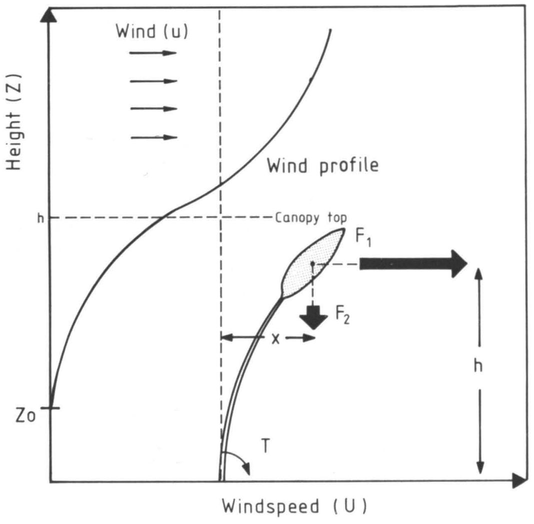

Fig. 2. Forces affecting a tree. Force F_1 (wind) and force F_2 (gravity) cause the total turning moment T at the base of the stem.

The bending of the stem is assumed to be directly proportional to the wind force and inversely proportional to the stem's stiffness (Pennala 1980), i.e.

$$x(z) = \frac{F_1 \cdot a^2 \cdot h \cdot (3 - a/h - 3 \cdot l(z)/h)}{6 \cdot E \cdot I} \quad z \geq a \quad (5)$$

$$x(z) = \frac{F_1 \cdot a^3 \cdot (2 - 3 \cdot (l(z) - b)/a + (l(z) - b)^3 / a^3)}{6 \cdot E \cdot I} \quad z < a \quad (6)$$

where x(z) is in Eq. (5) the horizontal displacement of the stem [m] from the upright position at height z [m] between the crown centre and the tree top, and in Eq. (6) it is the same below the crown centre. F_1 is the total wind force acting on the tree [N], l(z) is the distance from the tree top [m], h is the height of the tree [m] and E is the modulus of elasticity [Pa]. I is the area moment of inertia of the stem [m^4], which equals to $\pi \cdot d_{1.3}^4/64$, where $d_{1.3}$ is the diameter at breast height [cm] (Jones 1983). Parameter a is the distance from ground level to crown centre [m] and b equals the distance between crown centre and the tree top [m].

2.4 Root anchorage

The ability of a tree to resist uprooting is dependent on the total turning moment in relation to the anchorage of the tree, which in turn depends on the root mass, the depth and diameter of the root-soil plate and the properties of the soil. Coutts (1986), for example, showed that initially soil strength (soil resistance) was the most important component of the resistive moment, but that once soil broke, the tension in the windward roots was the crucial factor. Furthermore, when a tree is displaced by the force of the wind, the weight of the roots and the soil helps to hold down the root-soil plate, and thus resist significantly the overturning forces. In addition, further resistance is contributed by the underlying soil and soil around the edges of the plate, as well by the resistance to bending of the roots and soil in the hinge region on the lee side of the tree.

However, because the contribution from factors other than weight is very complicated, the support provided by roots is modelled by the proportion of the root-soil plate weight of the total anchorage including the above components, i.e. windward roots, root-soil plate mass, hinge and soil resistance (Peltola 1990),

$$RS_{sup} = \frac{g \cdot Mass \cdot RS_{mean}}{A_{rsw}} \quad (7)$$

where RS_{sup} is the supporting moment of the total root-soil plate anchorage [Nm], Mass is the fresh mass of the root-soil plate [kg], g is the gravitational constant [ms^{-2}] and RS_{mean} is the mean depth of the root-soil plate volume [m]. A_{rsw} is a parameter [%] indicating the proportion of the root-soil plate weight of the total belowground anchorage (see Coutts 1986).

In order to calculate the root-soil plate support, the root mass was divided into roots with diameter ≥ 5 cm and roots with diameter 1 to 5 cm. In the former case, the dry root mass was regressed against stem diameter at stump height (Hakkila 1972). The resultant value was multiplied by 1.3 to include the mass of roots with diameter 1 to 5 cm (Hakkila 1972, Mälkönen 1972, Peltola 1990). The dry root mass was converted into green mass assuming that the density of roots was 473 kgm^{-3} on the basis of dry weight and 1000 kgm^{-3} on the basis of green weight (Hakkila 1976, Kärkkäinen 1985).

The width of the root plate [m], representing roots with diameter ≥ 5 cm, was regressed against stem diameter at stump height, but the resultant value was multiplied by 1.3 to take into account roots with diameter 1 to 5 cm (Hakkila 1972). Similarly, the depth of the root system was regressed against stem diameter at stump height (Hakkila 1972). The consequent volume of the root-soil plate (V, m^3) was obtained as $V = 0.333 \cdot \pi \cdot (R^2) \cdot depth$, where depth is the depth of the root-soil plate (m) with the diameter ≥ 5 cm, and R is the length of the longest horizontal root [m]. The soil volume not occupied by roots was converted into the soil mass assuming the fresh density of soil to be 1700 kgm^{-3} on the basis of the mean particle density, proportion of the bulk volume and the water content of sandy soil (Hillel 1982, Grip et al. 1988, Päivänen 1989, Peltola 1990).

2.5 Stem resistance

Stem breakage in strong winds may also occur if the elastic limit (maximum strength) of the stem is exceeded. The ability of a tree to resist stem breakage is (Jones 1983)

$$S = \frac{T \cdot d_{1.3}}{2 \cdot I} \tag{8}$$

where S is the breaking stress of the stem [Pa], T is the total turning moment at the stem base [Nm], $d_{1.3}$ is the stem diameter at breast height [m] and I is the area moment of inertia of the stem [m^4]. Stem breakage could, however, occur at whatever height, not necessarily at breast height.

3 Model parameters and computations

3.1 Wind profile parameters

To estimate the wind profile at the stand edge (Eq. 2), windspeed was measured at four heights at the edge of a Scots pine stand close to Mekrijärvi Research Station, in eastern Finland, in the autumn of 1989 (62° 47' N, 30° 58' E, 145 m a.s.l.). The density of the stand was about 350–400 stems per hectare, and mean stand height was between 18 and 20 m. The measurements represent 26 different three-minute periods over seven days. The measurements were done using cup anemometers connected to an automatic data logging system at the heights of 3.5, 6.0, 10.0 and 16.0 m above ground (Peltola 1990, Peltola et al. 1993).

The best fit with the logarithmic formula of the mean wind profile was obtained using the value 0.20 m for Z_o in Eq. (2). The parameter k (von Karman's constant) was assumed to be 0.41 (e.g. Oliver and Mayhead 1974). Air density (p) in Eq. (1) was taken as 1.2226 kgm^{-3}, and the drag coefficient (C_d) as 0.29 (Mayhead 1973). At stand edge conditions, where the mean wind profile was measured at about 10 m outside the edge, there was no great shift towards the bottom of the wind profile due to the vegetation (see e.g. Oliver 1974). Consequently, the zero plane displacement was neglected in the calculations.

3.2 Other parameters

The modulus of elasticity (Eqs. 5, 6 and 8) was assumed to be 7000 MPa, which is quite typical for green coniferous wood including Scots pine wood (Sunley 1968, Lavers 1969, Petty and Worrel 1981). The value for the bending strength of the stem was assumed to be 32 MPa, which is about 70 % of the breaking stress derived from static tests for clear pine wood in short-term loading (Fons and Pong 1957, Lavers 1969, Petty and Worrel 1981, Petty and Swain 1985).

The mean depth of the root-soil plate volume was calculated to be approximately 20 % of the maximum depth of the root system including roots with diameters of at least 5 cm. The supporting moment caused by the weight of the root-soil plate was assumed to be 30 % (A_{rsw}) of the total below-the-surface support (Eq. 7), which is the mean value obtained by Coutts (1986) for Sitka spruce (*Picea sitchensis*) when the area of mineral soil on the failed surface varied between 60 and 100 %.

3.3 Conditions for computations

The model was used to determine the windspeed and turning moment necessary to fell a tree or break the stem of individuals of Scots pine at the stand edge, where trees face the exposed area (e.g. new clear-cut area). The selected tree heights were 12 m, 16 m and 20 m, and the tapers ($d_{1.3}$/h) 1:70, 1:80 or 1:100. The crown weight to stem weight ratio for the trees was 0.3, with the weight arranged over the uppermost 40 % of the stem (Nyyssönen 1954). In addition, a value of 0.5 was also used for trees 20 m in height with the crown distributed over the top 65 % of the tree. The larger crown value describes a tree, which used to grow in the open. Thus, there is a short stem branching out into a large spreading crown, which also has a large wind load. The smaller crown ratio describes a tree, which has grown in a closed stand, i.e. with a small crown, which will have relatively little wind loading (Table 1). Furthermore, the soil was assumed to be a sandy moraine like that on the site where the wind profile was measured.

Table 1. Model tree characteristics.

Tree		Root plate		Mass (kg)				
$d_{1.3}$ (cm)	Height (m)	Depth (cm)	Width (m)	Roots	Stem	Crown	Stem+ Crown	Root-soil plate
12	12	56	0.80	19	63	19	82	620
15	12	63	0.93	32	98	29	127	950
17.1	12	67	1.03	42	127	38	165	1240
16	16	65	0.98	37	139	42	181	1080
20	16	73	1.16	60	217	65	282	1700
22.5	16	77	1.27	77	274	82	356	2150
20	20	73	1.16	60	258	78	336	1700
25	20	80	1.38	96	403	121	524	2670
28.5	20	84	1.54	26	524	164	688	3460
20*)	20	73	1.16	60	258	129	387	1700
25*)	20	80	1.38	96	403	201	605	2670
28.5*)	20	84	1.54	126	524	261	785	3460

*) Crown weight/stem weight ratio 0.50, whereas in other cases it equals 0.30.

4 Results of model computations

The top half of the crown contributed most substantially to the turning moment caused by wind drag (Fig. 3). This is because windspeed decreased quite rapidly from the top of the canopy downward. Most of the turning moment was due to wind drag, but the contributions of stem and crown bending are by no means negligible. However, the effect of wind drag on the stem was negligible when compared to the other forces.

The total turning moment required to uproot or break a tree increased with tree size (Figs. 4, 5), but the windspeed needed to produce this moment decreased with tree size. The resistance increased also more slowly with tree size than did the turning moment. Trees having an equal stem diameter also gained equal support through anchorage, since the amount of anchorage was related to the stem diameter. The turning moment required for uprooting was much smaller than that required for stem breakage.

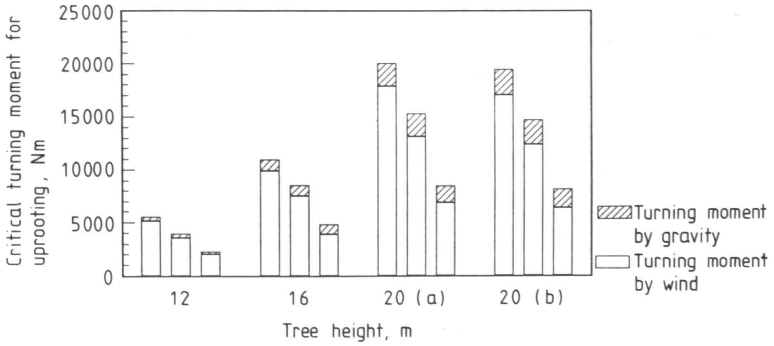

Fig. 3. Contribution to the total turning moment by one meter height increments of a Scots pine tree with a height of 20 m, taper 1:100 and crown/stem weight ratio of 0.3 at a windspeed of 14 ms^{-1}.

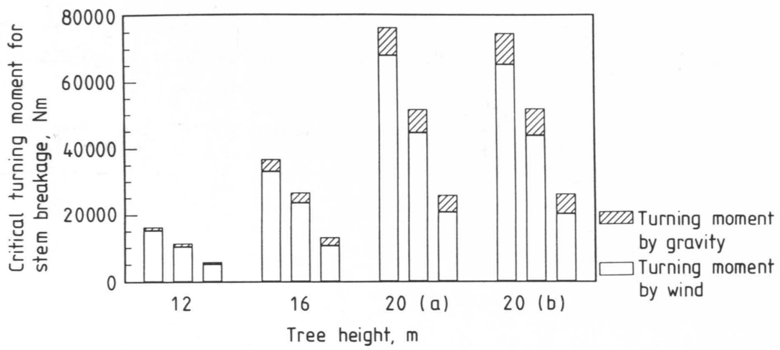

Fig. 4. Turning moment needed to uproot trees of various sizes. (Taper 1:70, 1:80 and 1:100 from left to right, and crown to stem weight ratio (a) 0.3 and (b) 0.5).

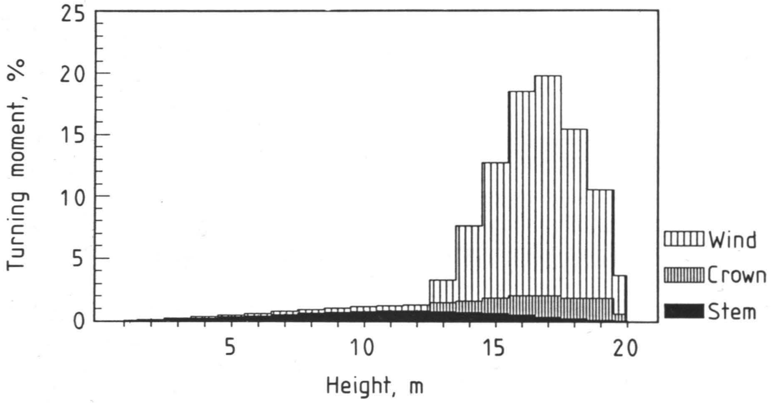

Fig. 5. Turning moment needed for stem breakage of various sizes of trees. (Taper 1:70, 1:80 and 1:100 from left to right, and crown to stem weight ratio (a) 0.3 and (b) 0.5).

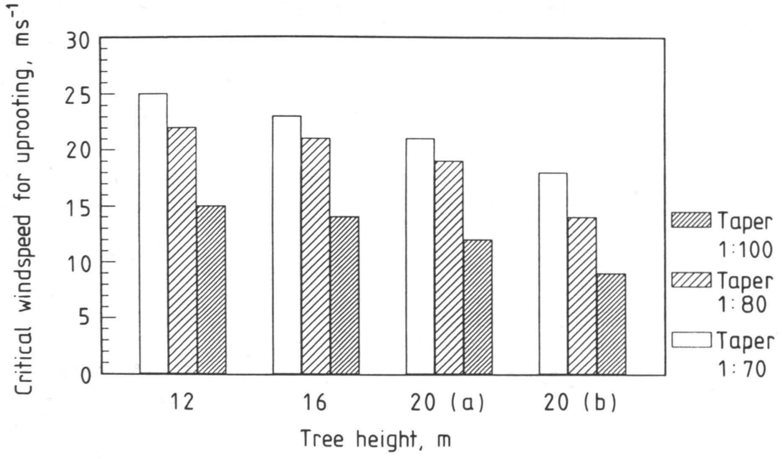

Fig. 6. Critical windspeed for uprooting trees of heights of 12, 16 and 20 m and taper values of 1:70, 1:80 and 1:100 (crown weight to stem weight ratio (a) 0.3 and (b) 0.5).

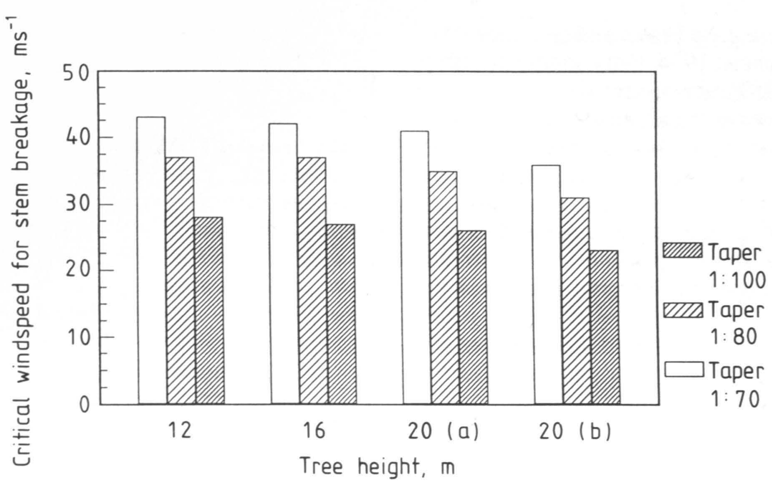

Fig. 7. Critical windspeed for stem breakage for trees of heights of 12, 16, 20 m and taper values of 1:70, 1:80 and 1:100 (crown weight to stem weight ratio (a) 0.3 and (b) 0.5).

The taper of the model trees also affected most the windspeed necessary to uproot a tree. For example, a taper of 1:100 required windspeeds of 15, 14 and 12 ms^{-1} (10 m above ground level) to overturn trees 12, 16 and 20 m in height, respectively (Fig. 6). For a taper of 1:70, the critical windspeeds were 25, 23 and 21 ms^{-1}. The model computations, thus, show that harmful windspeed decreases with decreasing taper and increasing height.

The taper of trees also had a great effect on the windspeed needed to break a stem. For example, stem taper of 1:100 required windspeeds of 28, 27 and 26 ms^{-1} to cause stems breakages in trees 12, 16 and 20 m in height, respectively (Fig. 7), whereas a taper of 1:70 called for critical windspeeds of 43, 42 and 41 ms^{-1}. In the case of stem breakage, decreasing taper or increasing tree height also reduce the windspeed required to break a tree. The windspeed was, however, much greater than that needed to overturn a tree, but the differences between various tree heights were not great. The crown to stem weight ratio also affected the windspeed required to overturn or break a tree, i.e. tall and slender trees with a large crown systems are more susceptible to wind-induced damage than otherwise similar trees with smaller crowns.

5 Discussion

5.1 Model evaluation

The main requirement for predicting wind-induced damage is knowledge of the wind forces; these can be estimated by physical equations or empirical formulas. Mayhead et al. (1975), for example, derived an empirical relationship, which related the drag force on windspeed and canopy weight (see also e.g. Fraser 1962, 1964). However, foliage flexibility and density, as well as the weight distribution and shape of the crown, all affect wind drag, because of the effect on streamlining capacity of the crown (see e.g. Papesh 1974). In this study, the physical approach was used (e.g. Grace 1977, Smith et al. 1987), although it, too, has some limitations; e.g. the actual value for C_d and streamlined crown area as a function of windspeed are not precisely understood (e.g. Mayhead 1973).

The study deals with stand edge conditions where the wind force on trees is mainly due to the mean wind (e.g. Papesh 1974). Thus, the static approach (e.g. by Fraser and Gardiner 1967, Oliver and Mayhead 1974, Petty and Swain 1985, Smith et al. 1987) was used instead of the dynamic one. Trees were assumed to deflect to a point of no return in a wind of constant velocity and direction. This made it possible to calculate the maximum windspeed a tree can withstand when the rooting resistance and the breaking strength of the stem were known. The model ignores the effect of tree swaying on uprooting, although prolonged swaying of a tree by strong winds obviously loosens the roots in the soil and may cause a root failure equally on well-drained sandy soils and on peaty soils (Hutte 1968, Oliver and Mayhead 1974). The support by the crown contact with neighbouring trees was also excluded from the model, but this is not of equal importance at the edge of a stand as it is within a stand (e.g. Grace 1977).

In the present model, wind force and total turning moment are expected to increase nearly linearly as a function of the windspeed between 10 to 20 ms^{-1} because of crown streamlining (Raymer 1962, Walshe and Fraser 1963). If the reduction in frontal area as the windspeed increased was not accounted for, the trees would have been blown down or the stems broken more easily. Papesh (1974) and Mayhead (1973), for example, have suggested that drag increases in proportion to the square of the windspeed for larger trees (i.e. branches are stiff and do not streamline). This differs from the approach used in this study.

It was also supposed that the weight of the roots and soil in the root-soil plate gives 30 % of the total below-ground support as Coutts (1986) found for Sitka spruce, when area of mineral soil on failed surface varied between 60 and 100 %. The rest of the support was given by windward roots (54 %), soil resistance (7 %) and hinge (9 %). Sitka spruce is, however, a flat rooting tree, whereas Scots pine has a deep-going root system. In addition, the contribution from root and soil weight might be more important in Scots pine because pine roots are significantly weaker than spruce roots. For example, a 10 % increase in A_{rsw}, would cause an equal decrease in total anchorage. This means that the trees would have been uprooted even more easily than the present results suggest. However, since experimental measurements for Scots pines are still lacking, the extent of this bias cannot be estimated. On the other hand, Wood et al. (1961) have also suggested that the resistance to soil failure is generally greater when failure occurs in mineral soils, i.e. the degree of penetration of roots into mineral soil affects tree stability more than it does the total depth of rooting (see also Coutts 1986).

The value of 32 MPa was used for stem breakage. On the average, this is 70 % of the breaking stress derived from static tests for pure pine woods under short-term loading (e.g. Fons and Pong 1957, Lavers 1969, Petty and Worrel 1981, Petty and Swain 1985). Green wood will, however, fail under sustained loading at stress levels of even 50 % below those observed in short-term tests if sustained for a longer period (Brown et al. 1952, Petty and Worrel 1981, Petty and Swain 1985). Thus, even the value of 16 MPa could be acceptable, because defects such as knots result in lower values. However, the value of 32 MPa is very near the value for green wood estimated from wood density, which is the most important factor for stem strength (Kärkkäinen 1985).

5.2 Evaluation of the results

In this study, the total turning moment increased as a function of tree size, and it was smaller for windthrow than for stem breakage. For example, a tree 16 m in height (taper 1:100) was uprooted, if the total turning moment exceeded 4.6 kNm (windspeed 15.7 ms^{-1} at the top of the canopy) and the bending of the stem apex was about 5 degrees (i.e. 1.3 m from the upright position). A similar tree broke, if the turning moment was 12.9 kNm (windspeed at the top of the canopy 30.2 ms^{-1}) and the bending of the stem apex about 3.7 m. A similar tree with a stem diameter of 22.5 cm was uprooted and broke if the turning moment was 10.9 kNm and 36.5 kNm (stem apex bending 0.9 m and 3.0 m) respectively.

The present results concerning uprooting are supported by the results of Somerville (1979), who found that the angle under maximum load was within ten degrees of the vertical before uprooting occurred in *Pinus radiata*. Also, Oliver and Mayhead (1974) found that Scots pine on sandy soil was very near maximum load when the crown deflected about 7 degrees from vertical. On the other hand, Sitka spruce was found to bend by up to 20 to 25 degrees before uprooting occurred on peaty gley soils (Fraser and Gardiner 1967, Coutts 1986). On well-drained soils (e.g. in brown earth), it uprooted when the angle of maximum deflection was 10 degrees (Fraser and Gardiner 1967). The current model may underestimate stem deflection to some degree, because it does not precondition any taper in the stem shape. In addition, the contribution from the overhanging branch mass is not included, and this has been found to lead to underestimate of bending of up to 20 %; at least in spruce plantations (Gardiner and Wood 1992). However, the crown area and its distribution were taken into account in calculation of the wind load on tree, and this may compensate for the above underestimation.

The critical turning moments found in the present study for stem breakage are similar to the results of Petty and Swain (1985), i.e. a Scots pine 16 m in height ($d_{1.3}$ 15 cm) breaks if the turning moment exceeds 12 kNm. Similarly, a tree 16 m in height, with a stem diameter of 22.5 cm, breaks if the turning moment is about 40 kNm. Also Coutts (1986) has suggested that overturning usually took place before breakage, as was found in this study. However, the turning moment required to uproot trees has in some studies been near that required to break the stem (e.g. Somerville 1979, Petty and Worrel 1981, Cremer et al. 1982). This has been claimed to be due to the fact that the roots and stem develop in some sort of allometric balance. Were the value of 16 MPa used in this study as the value of stem strength (see e.g. Petty and Worrel 1981), the results of stem breakage would have been much closer to those for uprooting.

The critical windspeed for windthrow and stem breakage in the present study was of about the same magnitude as that suggested by Oliver and Mayhead (1974) as the result of field observations, and by Petty and Swain (1985) in connection with model calculations for Scots pine. The critical windspeed required to uproot trees in the present study was also much smaller than that required to break stems. A windspeed of even 13 ms^{-1} has been found to uproot Sitka spruce (Coutts 1986), but speeds of over 20 ms^{-1} have also been presented (Fraser and Gardiner 1967). In Finland, gusting speeds of the 24 ms^{-1}, have been found to uproot trees if the soil is unfrozen (Solantie 1986). On the other hand, there may also be a great discrepancy between results obtained in theoretical calculations and those following field observations. Oliver and Mayhead (1974), for example, found that a windspeed of 18 ms^{-1} at the tree top was enough to uproot Scots pines in field conditions. On the basis of theoretical calculations, they suggested that the trees would have required a wind of about 40–45 ms^{-1} at the centre of pressure to have been blown down.

In the present study the critical windspeed for windthrow and stem breakage was found to decrease when tree height increased. As in many other studies, the risk of wind-induced damage has been found to increase with increasing height and increasing crown weight to stem weight ratio. Trees have usually been found to be vulnerable to damage when their height exceeds 12 m (Laitakari 1929, Persson 1975, Savill 1976, Lohmander and Helles 1987). On the other hand, all trees are vulnerable to wind damage if the wind is strong enough, but at about the above height the likelihood of damaging winds occurring also increases. In the present study, increasing diameter was found to reduce most of all the risk of wind-induced damage, i.e. greater windspeed was needed for uprooting and stem breakage. These results are supported by those of Petty and Swain (1985), who found taper to be probably one of the most important factors affecting tree stability (see also e.g. Lohmander and Helles 1987).

Obviously, the risk of wind-induced damage can be reduced through thinnings, which enhances radial growth with a consequent decrease in the height/breast height diameter ratio (see e.g. Schretzenmayer et al. 1974, Cremer et al. 1982, Savill 1983). Similarly, root mass and strength of roots will increase following thinning. On the other hand, increasing taper though wider spacing (e.g. thinning or planting widely) does not always increase stability, i.e. wind is able to penetrate deeper into the canopy with a consequent increase in the wind load on trees. A widely spaced stand may also provide less wind protection (Lohmander and Helles 1987), unlike dense stands, which can be quite stable owing to their ability to dissipate incoming winds and the added stability of interlocking root systems and crown contacts. Furthermore, an increase in crown size is evident with increasing space causing a large wind load. Thus, heavy thinnings in older stands could be extremely detrimental as well as in unthinned stands.

The probability of windthrow has been found to increase with an increase in the relative thinning volume (Lohmander and Helles 1987). Thus, we need to grow trees approximately at the usual spacing with higher taper. Fortunately, trees are able to adapt to increased exposure to wind after thinning, especially in younger and more vigorous stands (Hutte 1968, Persson 1975). The probability of windthrow decreases, thus, with time since the most recent thinning (Lohmander and

Helles 1987). Models such as those discussed in this study could be useful tools in investigating many aspects of tree stability. One possibility is in the evaluation of various silvicultural treatments, such as thinnings.

Acknowledgements: This study is funded by the Academy of Finland within the Finnish Research Programme on Climate Change (Silmu). The support of the Faculty of Forestry, and the Mekrijärvi Research Station, the University of Joensuu, is also acknowledged. We also wish to extend our thanks to Prof. Timo Pukkala, Dr. Pauline Oker-Blom and Prof. Hannu Mannerkoski for their valuable comments concerning the manuscript. Thanks are also to Dr. Barry Gardiner and Dr. Claus Mattheck who have rechecked the manuscript and have given valuable comments and criticism. Furthermore, we thank Riitta Honkanen for drawing the figures of this study and Erkki Pekkinen for revision of the English text.

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