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Mechanical stability of trees under static loads[1]

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Wind affects the structure and functioning of a forest ecosystem continuously and may cause significant economic loss in managed forests by reducing the yield of recoverable timber, increasing the cost of unscheduled thinning and clear-cuttings, and creating problems in forestry planning. Furthermore, broken and uprooted trees within the forest are subject to insect attack and may provide a suitable breeding substrate, endangering the remaining trees. Therefore, an improved understanding of the processes behind the occurrence of wind-induced damage is of interest to many forest ecologists, but may also help managers of forest resources to make appropriate management decisions related to risk management. Using fundamental physics, empirical experiments, and mechanistic model-based approaches in interaction, we can study the susceptibility of tree stands to wind damage as affected by the wind and site and tree/stand characteristics and management. Such studies are not possible based on statistical approaches alone, which are not able to define the causal links between tree parameters and susceptibility to wind damage. The aim of this paper is to review the recent work done related to tree-pulling and wind tunnel experiments and mechanistic modeling approaches to increase our understanding of the mechanical stability of trees under static loading.

Key words: mechanical stability; mechanistic modeling; static loading; stem breakage; tree pulling; uprooting; wind; wind tunnel.

Wind, which can affect the structure and functioning of a forest ecosystem greatly, is a continuous cause of economic loss in forests. For example, in December 1999 approximately 180×10^6 m^3 of timber was blown down in Europe during storms. In 2004, there was again 70×10^6 m^3 of timber blown down in a winter storm, this time mainly in southern Sweden. The economic impact of wind damage is particularly severe in managed forests because of the reduction in the yield of recoverable timber, the increased costs of unscheduled thinning and clear-cutting, and resulting problems in forestry planning. Furthermore, broken and uprooted trees left in forest can lead to detrimental insect attacks on the remaining plants because of an increase in the amount of available breeding material.

The susceptibility of a forest stand and trees within the stand to wind damage is controlled by the properties of the wind climate (i.e., wind speed, duration, and gustiness) and by forest structure and tree/stand and site characteristics such as tree species, tree height and diameter, crown area, rooting depth and width, stand density, soil type, and topography (Cremer et al., 1982; Coutts, 1986; Lohmander and Helles, 1987; Gardiner, 1995; Gardiner et al., 1997; Kerzenmacher and Gardiner, 1998; Peltola et al., 1999, 2000; Mitchell et al., 2001; Hale et al., 2004; Achim et al., 2005a, b; Lanquaye-Opoky and Mitchell, 2005; Scott and Mitchell, 2005). It can be studied based on fundamental physics (i.e., wind and gravity-based forces), empirical experiments (e.g., tree swaying, tree pulling, and wind tunnel experiments) and mechanistic model-based approaches in interaction. In this way, the threshold wind speed (critical wind speed) required to damage a tree within a stand for a given type of tree and stand at a particular location might be predicted.

When analyzing the mechanical stability of trees under static loading, a tree is assumed to have failed when the applied bending moment of a tree exceeds the maximum resistive moment of a tree, which could be defined as the maximum resistance of the tree stem to failure or of the root system to overturning, with the relative strengths of these resistances determining the mode of failure. On the other hand, in response to wind, the trees sway dynamically with consequent short-term vibration or oscillatory motion, and their crowns are streamlined and tree stems deflected (Papesch, 1974; Mayer, 1987; Peltola, 1996; Kerzenmacher and Gardiner, 1998), which should also be taken into account when aiming to predict accurately these threshold wind speeds.

To understand the mechanism of wind-induced damage in trees, researchers in recent decades have investigated the stability of trees to uprooting and/or stem breakage empirically. These studies included static-pulling (e.g., Fraser, 1962; Fraser and Gardiner, 1967; Somerville, 1979; Coutts, 1986; Smith et al., 1987; Frederickson et al., 1993; Papesch et al., 1997; Ray and Nicoll, 1998; Moore, 2000; Peltola et al., 2000; Achim et al., 2005a, b), and dynamic tree-swaying experiments (e.g., Milne, 1991; Gardiner, 1995). The behavior of model trees under wind loading has also been studied in wind tunnel experiments (Fraser, 1962; Raymer, 1962; Walshe and Fraser, 1963; Mayhead et al., 1975; Stacey et al., 1994, Gardiner and Stacey, 1996; Gardiner et al., 1997, 2005; Rudnicki et al., 2004; Vollsinger et al., 2005).

Information on tree-pulling and wind tunnel experiments has also been used in the construction of mechanistic models to describe the behavior of trees in stands under static wind loading in an attempt to predict the threshold wind speeds (critical wind speeds) necessary to uproot or break the trees (e.g., Peltola et al., 1999; Gardiner et al., 2000; Ancelin et al., 2004; Hale et al., 2004; Achim et al., 2005a, b). These models are meant to aid in managing the risk of wind damage related to forest management and forest planning (see, e.g., Dunham et al., 2000; Talkkari et al., 2000; Blennow and Sallnäs, 2004; Zeng et al., 2004, in press; Zeng, 2006). In this context, this

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paper aims to review the recent work done related to the experimental (tree pulling and wind tunnel experiments) and mechanistic modeling approaches toward understanding the mechanical stability of trees under static loads.

THEORETICAL BASIS FOR UNDERSTANDING THE MECHANICAL STABILITY OF TREES UNDER STATIC LOADS

Wind and gravity-based forces acting on trees—There are a number of possible methods for calculating the wind loading on a tree. These include direct calculation using the drag coefficient and crown area of the tree canopy (Jones, 1983), spectral methods using the approach presented by Davenport (1961), or an empirical approach using the measured drag of trees (Mayhead et al., 1975). The first approach is presented here as an example for analyzing the theoretical basis for the mechanical stability of trees under static loading. In this approach, a tree is assumed to deflect to a point of no return as a result of static loading by a wind of constant mean speed and direction. Under these circumstances, mechanical stability of a tree is affected by the horizontal force of the wind and the vertical force of gravity (including the mass of the stem and crown and possibly also snow loading), i.e., based on fundamental physics. Moreover, the resistance of a tree to uprooting depends on its anchorage, and the resistance to stem breakage depends on the modulus of rupture of the stem.

The wind loading and consequently the gravity-based force on a tree can be calculated separately at each height in the canopy based on a predicted wind profile (e.g., at the stand edge) and the vertical distribution of stem and crown mass, which makes it possible to calculate the maximum bending moment and the threshold wind speed at which the tree may be uprooted or its stem broken (Fig. 1).

The total wind-induced force F_1 (in Newtons) summarizes the wind forces acting on the tree at each height (Jones, 1983; Peltola and Kellomäki, 1993):

$$F_1(z) = \frac{1}{2} \cdot C_d \cdot \rho \cdot u(z)^2 \cdot A(z), \quad (1)$$

where $u(z)$ is the mean wind speed (in meters per second) and $A(z)$ is the streamlined projected area of the tree (stem and crown) against the wind (in square meters) at height z (in meters) above the ground, C_d is the drag coefficient (dimensionless), and ρ is the density of the air (in kilograms per cubic meter).

At the stand edge, the wind profile could be assumed to be of the logarithmic form, based on the aerodynamic characteristics of friction velocity (u_*, in meters per second), roughness length (z_0, in meters), zero plane displacement (d, set to 0 m), and von Karman's constant (k, dimensionless) (Oliver and Mayhead, 1974; Smith et al., 1987; Peltola and Kellomäki, 1993),

$$u(z) = \frac{u_*}{k} \cdot \ln\left(\frac{z-d}{z_0}\right). \quad (2)$$

Once any substantial bending of a tree occurs, an additional force due to gravity (F_2, in Newtons) comes into play and is also calculated by dividing the stem and crown into segments (e.g., one meter in length) and by adding all the forces acting on each segment as follows (Jones, 1983; Petty and Swain, 1985; Peltola and Kellomäki, 1993):

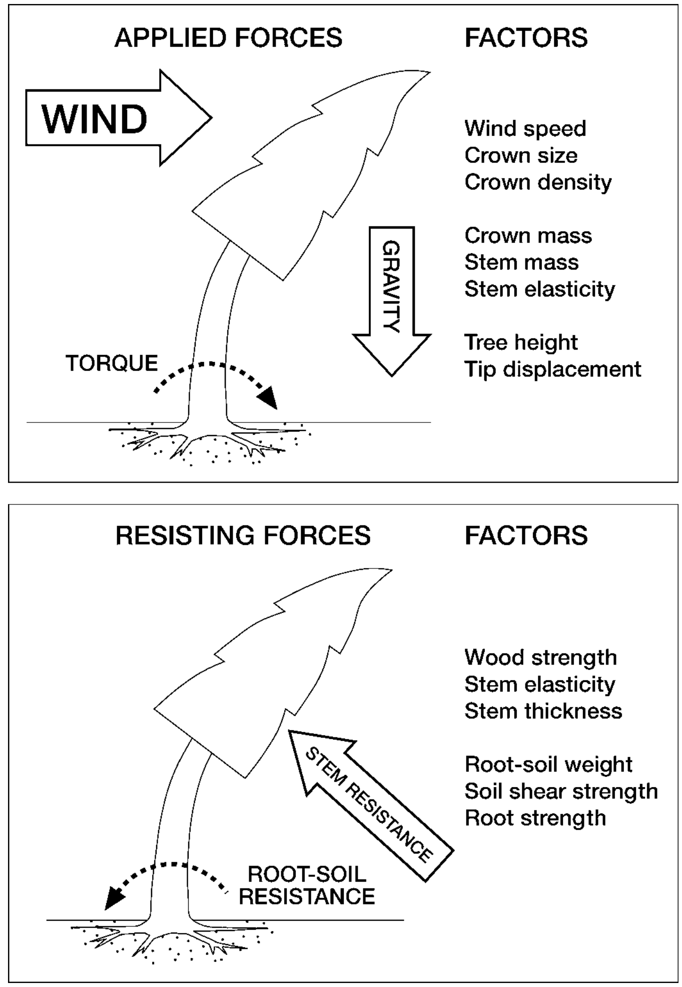

Fig. 1. Mechanism of wind damage in a tree in terms of applied and resistive forces and factors behind them.

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

where $M(z)$ is the mass of the stem and crown (possibly also snow loading) and g is the gravitational constant (in meters per square second).

Bending moment caused by wind and gravity-based forces—As a result of total wind-induced force F_1 and gravity-based force F_2, the total bending moment due to mean wind (and snow and ice) loading $BM_{max}(z)$ (in Newton meters) applied at any point along the stem or in the root system could be expressed as follows:

$$BM_{max}(z) = F_1(z) \cdot z + F_2 \cdot x(z), \quad (4)$$

where z is the height on the stem (in meters) and $x(z)$ is the horizontal displacement of the stem from the upright position (in meters), which is assumed to be directly proportional to the wind force acting on the tree and inversely proportional to the stiffness of the stem (Peltola and Kellomäki, 1993).

Resistance to uprooting—The resistance to uprooting can be estimated based on tree-pulling experiments by determining regressions between the maximum resistive bending moment and various tree physical characteristics (such as root depth, root mass, stem mass and combinations of parameters such as tree height multiplied by the square of the breast height diameter) for each species and soil type (e.g., Fraser, 1962; Fraser and Gardiner, 1967; Somerville, 1979; Coutts, 1986; Smith et al., 1987; Frederickson et al., 1993; Papesch et al., 1997; Ray and Nicoll, 1998; Moore, 2000; Peltola et al., 2000; Achim et al., 2005a, b). Alternatively, the resistance to uprooting can also be described using the estimate for the weight of the root–soil plate to derive a resistive moment as demonstrated by Peltola et al. (1999). In this latter approach, a tree is assumed to be uprooted if the total maximum bending moment (Eq. 4) exceeds the support provided by the root–soil-plate anchorage (Eq. 5), which in turn is expected to depend, e.g., on the root–soil-plate weight, the depth and diameter of the root–soil plate, and the properties of the soil (Coutts, 1986; Peltola and Kellomäki, 1993; Achim et al., 2005a, b). In reality, the total anchorage includes the components such as the root-soil plate mass, the strength of the windward roots, the strength of the root hinge, and the soil strength at the base of the root-soil plate (Coutts, 1986). However, because the contribution of factors other than the root-soil plate mass is very complicated to take into account, the support provided by roots (RS_{sup}) could even be simplified as a proportion of the root–soil plate weight of the total anchorage (A_{rsw}), as was suggested earlier by Peltola and Kellomäki (1993):

$$RS_{sup} = \frac{g \cdot Mass \cdot RS_{mean}}{A_{rsw}} \tag{5}$$

where RS_{sup} is the supporting moment of the total root–soil-plate anchorage (in Newton meters), Mass is the mass of the root–soil plate (RS, in kilograms), g is the gravitational constant (meters per square second), and RS_{mean} is the mean depth (in meters) of the RS volume (cone) based on the width and depth of the RS. A_{rsw} is a parameter (in percentage) indicating the proportion of the root–soil plate weight of the total belowground anchorage (dimensionless) (Coutts, 1986).

Resistance to stem breakage—The resistance of a tree stem to stem breakage is based on the assumption that the wind-induced stress in the outer fibers of the tree stem is constant at all points between the base of the canopy and the butt as well as at the stem base (Morgan and Cannell, 1994). This allows the stress to be calculated, e.g., at breast height ($z = 1.3$ m) or at another height, and when it exceeds the modulus of rupture (MOR) for green timber the stem will break (e.g., Sunley, 1968; Petty and Worrell, 1981; Petty and Swain, 1985; Peltola et al., 2000). The maximum bending moment ($STEM_{res}$) that a tree stem can stand without breakage, for example, at breast height, can be calculated from the diameter at breast height (dbh) and knowledge of the modulus of rupture of green wood (MOR) (Jones, 1983; Morgan and Cannell, 1994),

$$STEM_{res} = \frac{\pi}{32} \cdot MOR \cdot dbh^3. \tag{6}$$

A tree stem is assumed to break when the total maximum bending moment (Eq. 4) exceeds the stem resistance calculated as a function of MOR and dbh (Eq. 6).

Calculation of threshold wind speeds for wind-induced damage—The threshold wind speeds can be calculated by defining the wind speed (e.g., the mean speed over 1 h at the canopy top) at which the maximum bending moment exceeds the resistive moment for uprooting or stem breakage (Fig. 2).

Fig. 2. Example of occurrence of wind-induced damage observed in boreal conditions in eastern Finland as a result of strong wind in 1998 (Photo by Heli Peltola).

These threshold wind speeds to uproot trees or break stems of trees within the stand are affected by characteristics of the tree/stand and the site (see, e.g., Peltola et al., 1999; Ancelin et al., 2004; Achim et al., 2005a,b).

ESTIMATION OF MECHANICAL STABILITY OF TREES UNDER STATIC LOADS BASED ON TREE-PULLING EXPERIMENTS

In a tree-pulling system, the uprooting forces are simulated by pulling trees over with a winch and cable system. First, the simulated static wind force causes deflection of the stem (Fig. 3). The leaning stem then assists in uprooting the tree because its centre of gravity moves over the hinge point in the root system (Ray and Nicoll, 1998). Thus, the second uprooting force is provided by the mass of the deflecting stem and the crown. However, the uprooting moment is resisted by bending of the tree stem and various components of root anchorage. If the uprooting moment exceeds the resistive bending moment of the tree at a particular angle of deflection, the tree will deflect

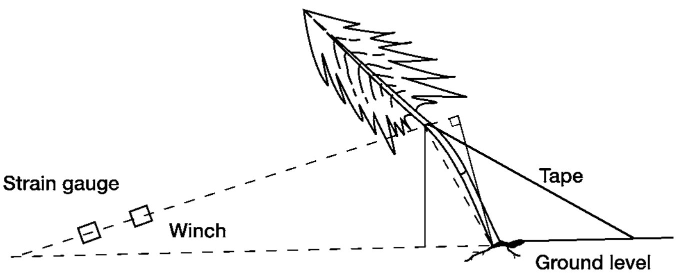

Fig. 3. Principle of tree pulling.

further and finally uproot. It may also happen that the stem will break. In these circumstances, the relative strengths of the stem and roots will determine the mode of failure. The resistance to uprooting can be estimated based on recorded forces by determining regressions between the maximum resistive bending moment (usually calculated at the stem base) and various tree characteristics such as root depth, root mass, stem mass and combinations of parameters such as tree height multiplied by the square of the breast height diameter, separately for each species and soil type.

Fraser (1962) and Fraser and Gardiner (1967) were among first to have measured the static forces required to pull trees (*Picea sitchensis* Bong Carr.) over in the field in tree-pulling experiments (i.e., with a cable attached near the center of gravity of the tree). In these studies, a significant linear relationship was found between the maximum resistive bending moment acting approximately at ground level (BM_{max}) and the stem mass for Sitka spruce (Table 1). But BM_{max} was also affected by the rooting depth and soil type. In addition, infection of trees by the root rot fungus (*Heterobasidium annosum*) reduced BM_{max} significantly.

Other previous tree-pulling studies have also shown significant relationships between BM_{max} and various tree characteristics such as stem volume, dbh, and tree height in addition to stem mass (see Table 1), e.g., in loblolly pine (*Pinus ponderosa*), radiata pine (*P. radiata*), Scots pine (*P. sylvestris*), Norway spruce (*Picea abies*), birch spp. (*Betula* spp.), and balsam fir (*Abies balsamea*) (Frederickson et al., 1993; Papesch et al., 1997; Moore, 2000; Peltola et al., 2000; Achim et al., 2005a, b). In addition, Moore (2000) showed in radiata pine and Peltola et al. (2000) in Scots pine, Norway spruce, and silver birch that trees with higher taper (lower ratio of tree height to dbh), had higher BM_{max} than trees with low taper with same tree height. According to Peltola et al. (2000), highly tapering trees were also more susceptible to stem breakage than uprooting and vice versa.

Moore (2000) was also able to demonstrate that root plate diameter and root plate depth also were significantly associated with BM_{max}. In fact, stem volume, tree height to dbh ratio and root plate width together explained >91% of the variation found in BM_{max} in uprooted radiata pines. Similarly, Coutts (1986) and Ray and Nicoll (1998) suggested that a positive relationship could be expected between maximum resistive bending moment and rooting depth in Sitka spruce trees, because the strength of the root anchorage influences the mode of failure. However, they failed to demonstrate any significant relationship between maximum resistive bending moment and root plate diameter.

Gardiner et al. (1997) and Peltola et al. (2000) also suggested that the stem volume (i.e., height × dbh^2) predicted best the BM_{max} for uprooting regardless of tree species, whereas the third power of dbh best predicted the BM_{max} for stem breakage. Peltola et al. (2000) ranked different species in the following order of decreasing resistance in podzolic soils: Scots pine > birch > Norway spruce (i.e., decreasing order) for uprooting and birch > Scots pine > Norway spruce for stem breakage. To some degree, the lower resistance of a Norway spruce to uprooting and stem breakage compared to an equivalently sized Scots pine (or birch) grown in similar site conditions (Peltola et al., 2000) reflects the shallower rooting and/or lower stem resistance of this species, which is in line with earlier findings reported in the literature (Kalela, 1949; Lavers, 1969; Hakkila, 1972).

According to Fraser and Gardiner (1967), the relative instability of trees on poorly drained soils may be at least partly due to the shallow root systems compared to soils with good natural drainage, where the major part of the root system consists of sinker roots, and, thus, the mean rooting depth is nearly double of that in poorly drained soils. Somerville (1979) also found that radiata pine growing in deep rips tended to fail by stem breakage rather than by uprooting. Thus, the root architecture may be more important than root plate size as such (e.g., its volume) in defining the overall root anchorage strength. Measurements of root–soil plate depth and width give, on the other hand, only rough estimates of tree stability, because many roots break during tree pulling and the exact

TABLE 1. Linear regressions between different tree and site characteristics (stem mass, tree height, breast height diameter (Dbh), stem volume, root depth and width, and soil type) and maximum resistive bending moment (BM_{max}) for different tree species with a level of effect detected: weak (+), strong (++), no effect (–), not analyzed (na).

		Linear regressions between BM_{max} and different variables						
Reference	Tree species	Stem mass	Tree height	Dbh	Stem volume	Root depth	Root width	Soil type
Fraser (1962)	Sitka spruce, Douglas fir	++	na	na	na	+	na	++
Fraser and Gardiner (1967)	Sitka spruce	++	na	na	na	na	na	++
Somerville (1979)	Radiata pine	na	na	na	na	++	na	++
Coutts (1986)	Sitka spruce	na	na	na	na	++	–	na
Smith et al. (1987)	Black spruce	na	++	na	na	na	na	na
Frederickson et al. (1993)	Loblolly pine	++	na	na	na	na	na	na
Papesch et al. (1997)	Radiata pine	na	na	++	++	na	na	na
Ray and Nicoll (1998)	Sitka spruce	na	na	na	na	++	–	na
Moore (2000)	Radiata pine	++	++	++	++	++	++	++
Peltola et al. (2000)	Scots pine, Norway spruce, birch spp	na	+	++	++	+	–	na
Achim et al. (2005a, b)	Balsam fir	++	na	na	na	na	na	–

dimensions are difficult to measure (Peltola et al., 2000). Uprooting has also been found to be the most typical mode of failure under unfrozen soil conditions, which indicates that root anchorage is usually less pronounced relative to stem strength (e.g., Coutts, 1986; Moore, 2000; Peltola et al., 2000), whereas, under frozen soil conditions stem breakage has been the dominant mode of failure as demonstrated, for example, in Scots pine by Peltola et al. (2000).

Coutts (1986) was one of the first to investigate the components of the root anchorage of trees, i.e., tensile strength of windward roots, weight of the root–soil plate, resistance of leeward roots to bending at the hinge region, and the resistance to failure of the soil underneath the root–soil plate in shallowly rooted Sitka spruce. He found that soil resistance was the largest component in the early stages during the course of uprooting but when the bending moment due to the applied force was maximum, the components of anchorage were in the order: windward roots > weight > hinge > soil resistance. The major effect of the windward roots on anchorage highlighted the importance of lateral root development in these shallow root systems (Coutts, 1986). However, in hybrid larch (*Larix europea* × *japonica*) growing on a freely draining soil, Crook and Ennos (1996) found that approximately 75% of the anchorage strength was provided by the windward sinkers and tap root, i.e., indicating that strong tap roots may increase the strength of root anchorage in these circumstances.

It was reported earlier that the modulus of rupture (MOR) of the broken stems, as derived from the BM_{max} for stem breakage, was significantly lower on average based on tree pullings of living trees than the values reported for clear wood specimens (e.g., Lavers, 1969; see Peltola et al., 2000). Comparison with the values measured indirectly for MOR reveals large differences in MOR between knot-free wood and whole trees. The modulus of rupture measured for Scots pine, for example, was on average 85% of that of the typical value for knot-free wood (Peltola et al., 2000). The effect of knots on the overall strength of the stem (reduced wood strength) coupled with a breakdown in the assumption of a uniform stress distribution (due to the possible difference in cable attachment height compared to the point of action of the wind) has led to differences between the results of winching experiments and those of theoretical calculations (see Wood, 1995).

The Forestry Commission in the UK maintains a tree-pulling database for almost 2000 trees representing different species (with various tree characteristics) and soil types from different regions and countries. This database will provide useful information on mechanical stability of these various tree species under static loading with regard to uprooting and stem breakage. This information can be used in mechanistic modeling to estimate the maximum resistive bending moment of trees needed to predict the threshold wind speeds for uprooting and stem breakage for trees. On the other hand, simulating static loading is not enough to explain alone the mechanical stability of trees, although these real-size tree experiments are useful in stability research. This has been demonstrated also previously, for example, by Oliver and Mayhead (1974), who showed that the wind speeds that actually blew trees down were much lower than those calculated based purely on the BM_{max} derived based on static tree pullings (see, e.g., Fraser, 1964). Instead, for example, streamlining of tree crowns (which reduce the drag area) and dynamic swaying of trees due to high wind speeds and wind gusts should also be examined in addition to the response of trees to static loading. Moreover, the effects of forest management, such as thinning and new clear-cuts on the wind loading of trees at the margins of these clear-cut areas, should be studied, i.e., based both on model stands and real field conditions, for further understanding of the stability of trees under static and dynamic wind loading.

ESTIMATION OF MECHANICAL STABILITY OF TREES UNDER STATIC LOADS BASED ON WIND TUNNEL EXPERIMENTS

An alternative approach to estimating the static forces on trees by tree pulling is that of wind tunnel modeling, in which scale models of trees are exposed to wind and the forces on them are measured using a suitable balance or strain gauge. One of the problems associated with this method is the question of suitable scale, i.e., how to select proper wind speed in relation to the scale factor of the model in order to produce the results applicable to field conditions. However, the comparison of the wind tunnel data with full scale experiments (e.g., Stacey et al., 1994) suggests that the wind tunnel could simulate conditions of the real forest very successfully (Gardiner and Stacey, 1996). In this system, the applied bending moments of model trees (see Fig. 4) due to the wind are measured using, e.g., a moment balance, and they represent the torque (force × distance) at the base of the model tree created by wind pressure on the canopy (Gardiner et al., 2005).

Fraser (1962) and Raymer (1962) were among first ones to investigate the static forces acting on real trees in a wind tunnel. Raymer (1962) showed that the wind force acting on trees was approximately linearly related to wind speed above $10\ m \cdot s^{-1}$. Moreover, resulting bending moments could also be clearly expressed by tree mass, and the bending moments determined in this way were very close to those measured by static tree pulling. Before these first wind tunnel experiments, the wind force was expected to increase with the square of velocity, although in reality, and especially at higher wind speeds, the tree crowns were known to become streamlined, exposing less area to the wind than expected.

Based on wind tunnel measurements, Fraser (1962) and Raymer (1962) determined the drag coefficient for different tree species, i.e., using trees of 3.8–11.6 m tall for Norway spruce, Scots pine, Douglas fir (*Pseudotsuga taxifolia*) and western hemlock (*Tsuga heterophylla*). Later, Mayhead (1973) continued this work and determined drag coefficients for various British forest tree species. Recently, Rudnicki et al. (2004) and Vollsinger et al. (2005) also studied the relationship between crown streamlining and drag in a wind tunnel in several young hardwood species such as black cottonwood (*Populus tricocarpa*), red alder (*Alnus rubra*) and paper birch (*Betula papyrifera*), and juvenile conifers such as western red cedar (*Thuja plicata*), western hemlock and lodgepole pine (*Pinus contorta*). Both these studies confirmed that drag was proportional to the crown mass and wind speed regardless of species studied, but it was also proportional to the wind speed squared and wind speed specific frontal area (i.e. area of the tree projected against wind).

Fraser (1962), Raymer (1962), and Walshe and Fraser (1963) also investigated bending moments in a wind tunnel within a model forest (e.g., using 0.3-m high model trees) using a fixed wind speed of $16\ m \cdot s^{-1}$, which corresponded to a drag

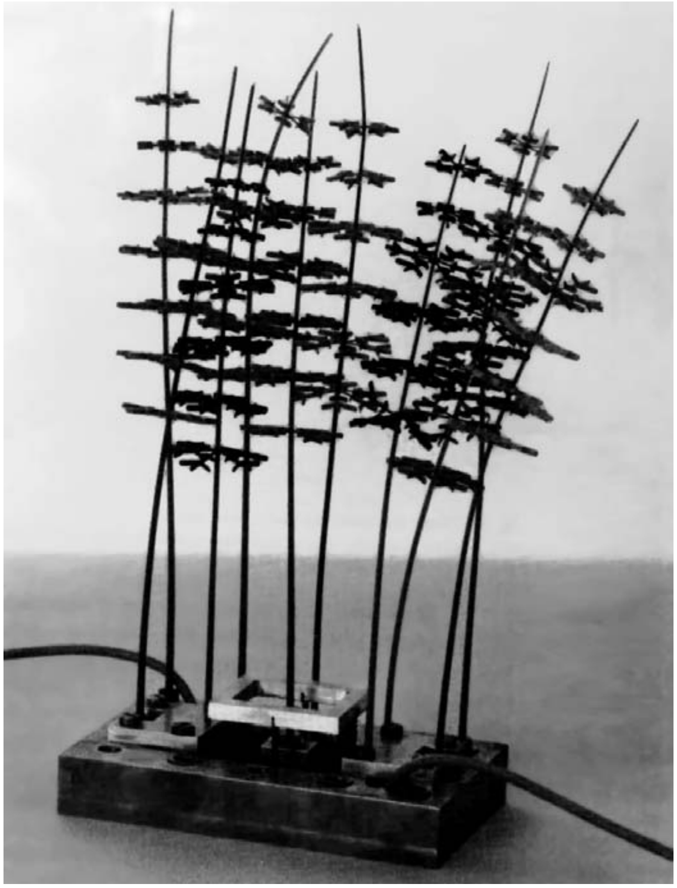

Fig. 4. Model trees (1/75th scale) designed by Prof. Barry Gardiner (Forestry Commission, UK) for wind tunnel simulations (reprinted from Stacey et al., 1994, p. 316, fig. 4, original copyright 2006, Kluwer Academic Publishers, with kind permission of Springer Science and Business Media; original photo taken by Rex Belcher, University of Oxford).

coefficient, C_d, of 0.71 for real trees. As a result, Walshe and Fraser (1963) found a rapid decrease in the bending moment in the first four rows of a regular model plantation. However, in the rest of the plantation the bending moment distribution was not uniform, and some locations had quite high bending moments (possibly due to the pattern of airflow over the model forest). In addition, the lowest bending moments were obtained throughout the plantation when tree spacing at the margin was denser. Walshe and Fraser (1963) also found that the bending moment was doubled on the immediately leeward side of the gap if individual model trees were removed, emphasizing the importance of forest uniformity. However, according to Fraser (1962), widely spaced trees at the margins eliminated the zone of fluctuating forces behind the front, without appreciably increasing the general level of forces over the rest of the forest.

Recently, Stacey et al. (1994), Gardiner and Stacey (1996), and Gardiner et al. (1997, 2005) have conducted wind tunnel tests (in the 4×2 m Oxford University boundary layer tunnel) on a 1:75 scale model of Sitka spruce forest in a correctly scaled turbulent boundary layer flow. This Sitka spruce forest consisted of 12 000 flexible tree models. These model trees were built so that their mass, flexibility, and aerodynamic drag characteristics were dynamically similar to typical 15-m tall Sitka spruce trees in a 30 $m \cdot s^{-1}$ storm. The uprooting moments were measured directly by a sensitive, high-frequency balance designed especially for that purpose. Based on these findings, they were the first to determine a relationship ($Gust_{factor}$) between mean ($Gust_{mean}$) and extreme ($Gust_{max}$) bending moments (i.e., $Gust_{factor} = Gust_{max}/Gust_{mean}$) on trees in regard to tree height, tree spacing, and distance from the stand edge (see Eqs. 7 and 8 for $Gust_{mean}$ and $Gust_{max}$), but also the effect of gap size (i.e., Gap_{factor}) on wind load of trees at the downwind edge of the clearing (see Eqs. 9 and 10) (Eqs. 7–10 published in Gardiner et al., 2000),

$$Gust_{mean} = [0.68 \cdot (s/h) - 0.0385] + [-0.68 \cdot (s/h) + 0.4785] \cdot [1.7239 \cdot (s/h) + 0.0316]^{x/h} \quad (7)$$

$$Gust_{mean} = [2.7193 \cdot (s/h) - 0.061] + [-1.273 \cdot (s/h) + 0.9701] \cdot [1.1127 \cdot (s/h) + 0.0311]^{x/h}, \quad (8)$$

where s is the spacing between trees (in meters), h is the mean tree height (in meters) and x is the distance from the forest edge (in meters), and $0.075 < s/h < 0.45$ (Gardiner et al., 2000). In this context, an infinite upwind open area ahead of the forest is assumed. Therefore, to take into account the effect of any gap size on wind loading, a so-called Gap_{factor} was determined, representing the ratio of the mean wind loading (Gap_{mean}) to extreme values (Gap_{max}), i.e., Gap_{factor} ($= Gap_{max}/Gap_{mean}$) as a function of gap size (size of the upwind gap in tree heights), based on Eqs. 9 and 10:

$$Gap_{mean} = \frac{0.001 + 0.001 \cdot \text{gap size}^{0.562}}{0.00465} \quad (9)$$

$$Gap_{max} = \frac{0.0072 + 0.0064 \cdot \text{gap size}^{0.3467}}{0.0214}. \quad (10)$$

In the wind tunnel tests by Stacey et al. (1994), these extreme bending moments were nearly 10 times the mean values. Moreover, the trees at the windward edge of a model stand were exposed to significantly higher wind speeds than those trees further to the interior of the model forest. Gap size also significantly affected the amount of wind loading at the downwind edge (see, e.g., Stacey et al., 1994; Gardiner and Stacey, 1996). Gardiner and Stacey (1996) suggested that trees at forest edges become inherently more stable over time than trees within the forest because the form of those at the forest edges has adapted to the increased wind exposure. On the other hand, recently exposed edge trees will be much more vulnerable because of their lack of adaptation. However, the wind loading and, thus, their vulnerability will decrease as distance increases from the windward forest edge, i.e., when the applied bending moment of trees decreases in these conditions (Gardiner and Stacey, 1996). The level of decrease is, however, dependent also on stand density to some degree, i.e., the wind loading will decrease more quickly in a dense edge (Gardiner et al., 1997). Moreover, upwind gap size will affect significantly the level of wind loading at these forest edges (Stacey et al., 1994; Gardiner et al., 1997).

Gardiner et al. (2005) have also compared wind speeds and turbulence within and above the model forests and the wind loading on model trees based on four different silvicultural systems, i.e., even-aged, single-tree selection, shelterwood/group selection, and strip felling. They showed that the profiles of different mean wind and turbulence characteristics above the forests were remarkably similar when vertical heights were normalized by the height of the tallest tree, but differences existed within the canopy. The presence of smaller subcanopy trees reduced wind loading on the main canopy trees either by providing support and increasing damping or by absorption of energy from canopy-penetrating gusts (see Gardiner et al., 2005). Although wind tunnel experiments in general have obvious limitations and the derived results are only strictly applicable under similar conditions, the forces measured are of the right magnitude and should thus provide a reasonable basis for the design of mechanistic models, similar to the static tree-pulling experiments.

MECHANISTIC MODELING AS AN APPROACH TO PREDICT TREE STABILITY UNDER STATIC LOADING

Until recently, studies on wind-induced forest damage have been mainly statistical and have indicated how the properties and the position of a tree stand are related to the frequency and size of damage (e.g., Laitakari, 1952; Neustein, 1965; Alexander, 1967; Neustein, 1971; Persson, 1975; Miller, 1985; Laiho, 1987; Lohmander and Helles, 1987). However, by understanding the behavior of trees in strong winds (e.g., Mayer, 1987; Gardiner, 1995; Peltola, 1996; Blackburn, 1997; Gardiner et al., 1997) and the mechanisms of root anchorage (Deans and Ford, 1983; Coutts, 1986; Ray and Nicoll, 1998), we are able to develop mechanistic models to predict the critical wind speeds for damage and how these critical wind speeds change with the properties of the trees within the stand. Such an approach would allow us to predict the impact of silvicultural operations on tree stability and even to design silvicultural strategies to reduce wind-induced damage. Such predictions and designs are not possible with only statistical approaches, because the causal links between tree parameters and susceptibility to wind damage are not defined, unlike in a mechanistic approach (Gardiner et al., 2000).

In recent years, mechanistic models such as HWIND (Peltola et al., 1999), GALES (Gardiner et al., 2000), and FOREOLE (Ancelin et al., 2004) have been developed based on the properties of tree and forest stand, i.e., to predict the threshold (critical) wind speeds needed for uprooting trees or causing stem breakage. The basic structures of the different mechanistic models developed so far, i.e., HWIND (Peltola et al., 1999), GALES (Gardiner et al., 2000), and FOREOLE (Ancelin et al., 2004), are very similar. The major differences lay in the method for calculating the values at each stage of the model (for details see, e.g., Gardiner et al., 2000; Ancelin et al., 2004). When both the GALES and FOREOLE models were designed originally to calculate the critical wind speed (mean speed for 1 hour) within the forest, the HWIND model was designed to calculate the critical wind speed (mean speed for 1 hour) at the stand edge (Fig. 5). Moreover, while the wind loading on a tree is calculated directly from the knowledge of the drag coefficient and crown area in the HWIND model (based on Eqs. 1–4), an alternative method is to use the relationship between the drag of the air on the surface and the aerodynamic roughness of the surface, as done in the GALES and FOREOLE models.

Moreover, in the HWIND model the resistance to uprooting is predicted using the estimate of the root–soil plate mass to derive a resistive moment, while the resistance to stem breakage relies on values for the modulus of rupture determined for different species of timber (based on Eqs. 5–6). A tree is thus assumed to be uprooted in the HWIND model if the total bending moment exceeds the support provided by the root–soil plate anchorage. Similarly, a tree is assumed to break if the breaking stress acting on the stem exceeds a critical value of the modulus of rupture. In that context, the dynamic wind loading is taken into account based on Eqs. 7–10. The example predictions by the HWIND model (see Peltola et al., 1999) show that the wind speed needed to cause uprooting or stem breakage of trees will decrease as the tree height or the tree height to dbh ratio increases or the stand density decreases (Fig. 6). Moreover, trees are more liable to suffer damage at newly created stand edges compared to further inside the stand (Fig. 7). According to Peltola et al. (1999), large clear-cuts also decrease the critical wind speeds needed to cause damage of trees at their margins compared to smaller ones (Fig. 7).

Compared to the HWIND model, in the GALES model (see Gardiner et al., 2000), the aerodynamic roughness provides a measure of the stress (force per unit area) imposed on the canopy as a function of wind speed, and the zero-plane displacement provides a measure of the mean height on the tree at which the wind acts within a stand. Together they allow a calculation of the bending moment imposed on the tree for any wind speed. Moreover, data from almost 2000 trees uprooted during pulling experiments and destructive sampling of green wood allows the prediction of the maximum resistive bending moment and, further, the critical wind speed at which the tree will be uprooted or break for a number of coniferous trees. The GALES model assumes a linear relationship between tree stem mass and the maximum resistive moment that can be provided by the root system. It assumes also that the stress in the outer fibres of the stem induced by the wind is constant with height. Like HWIND, GALES predicts the wind firmness of forest stands based on the calculation of the critical wind speed above which the mean tree of a stand is uprooted or broken.

This approach used in HWIND and GALES (mean tree at risk) is well adapted to regular stands, but in heterogeneous stands, not all the trees are necessarily damaged at the same time. Thus, models used to analyze the distribution of damage within a population of trees could offer a good alternative in this respect. Ancelin et al. (2004) presented the FOREOLE model, which was developed for predicting critical wind speed of individual trees within a coniferous stand. FOREOLE is based on a numerical description of tree structure, allowing both wind and self-weight loads to be calculated at every height of the stem, as well as the bending moment at the tree base and mechanical stresses along the stem. Similar to the HWIND and the GALES models, the FOREOLE uses a static approach to model wind forces in which the turbulent aspect of wind is accounted for with the gust factor. Stem breakage or uprooting is then predicted from comparisons to failure criteria: critical bending moment (as in GALES, also called Forest-Gales) and critical compressive stress (which was not assumed to be constant along the stem, unlike in GALES and HWIND). In model comparisons by different authors (e.g., Gardiner et al., 2000; Ancelin et al., 2004), the FOREOLE model outputs (e.g., critical wind speeds needed to uproot or break the trees at stand edge conditions) were in reasonable agreement with similar models (GALES and HWIND, Fig. 8). This agreement was

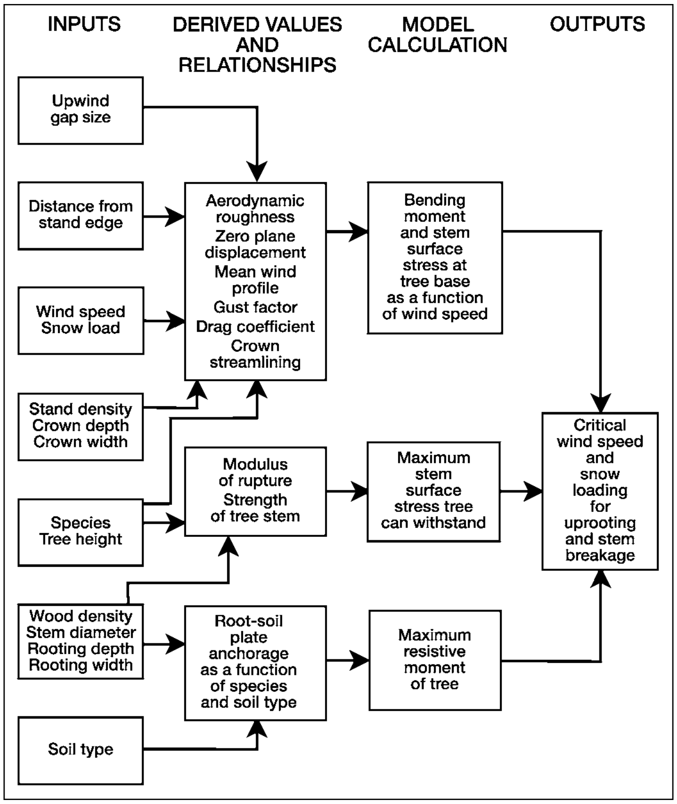

Fig. 5. Principle of mechanistic modeling: HWIND model as an example.

also found previously between GALES and HWIND by Gardiner et al. (2000).

In general, the mechanistic models discussed are quite sensitive to parameter changes (Peltola et al., 1999; Gardiner et al., 2000; Ancelin et al., 2004). However, these models are expected to facilitate simulations on bending moments and critical wind speeds needed to cause uprooting or stem breakage in agreement with the corresponding outputs of regression equations for tree-pulling data and with wind speeds known to cause actual damage to similar kinds of trees. However, any inaccuracies in the input tree characteristics (e.g., dbh, height, crown depth and width) and parameters that control the magnitude of the wind loading (e.g., gust factor, drag coefficient, crown streamlining) or the resistive bending moments of trees can have a large influence on the predicted critical wind speed for uprooting and stem breakage (Peltola et al., 1999; Gardiner et al., 2000; Ancelin et al., 2004).

DISCUSSION

Because wind affects the structure and functioning of a forest ecosystem continuously and results in significant economic loss annually in managed forests, an improved understanding of the processes behind the occurrence of wind-

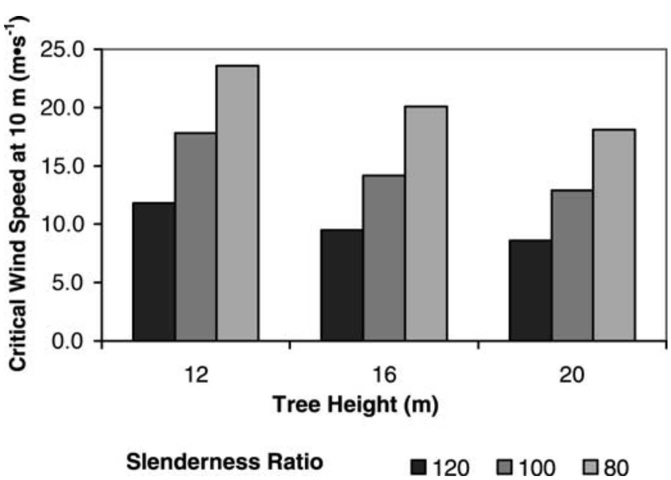

Fig. 6. Example predictions by the HWIND model of the critical wind speed needed for uprooting of Scots pine with different mean tree and stand characteristics at the stand edge conditions with gap size of 10 tree heights. Stand density is height-specific, i.e., 1280 stems·ha^{-1} for 12-m high stand, 860 stems·ha^{-1} for 16-m high stand, and 690 stems·ha^{-1} for 20-m high stand; and slenderness ratio (height to dbh ratio) varies from 80 to 120.

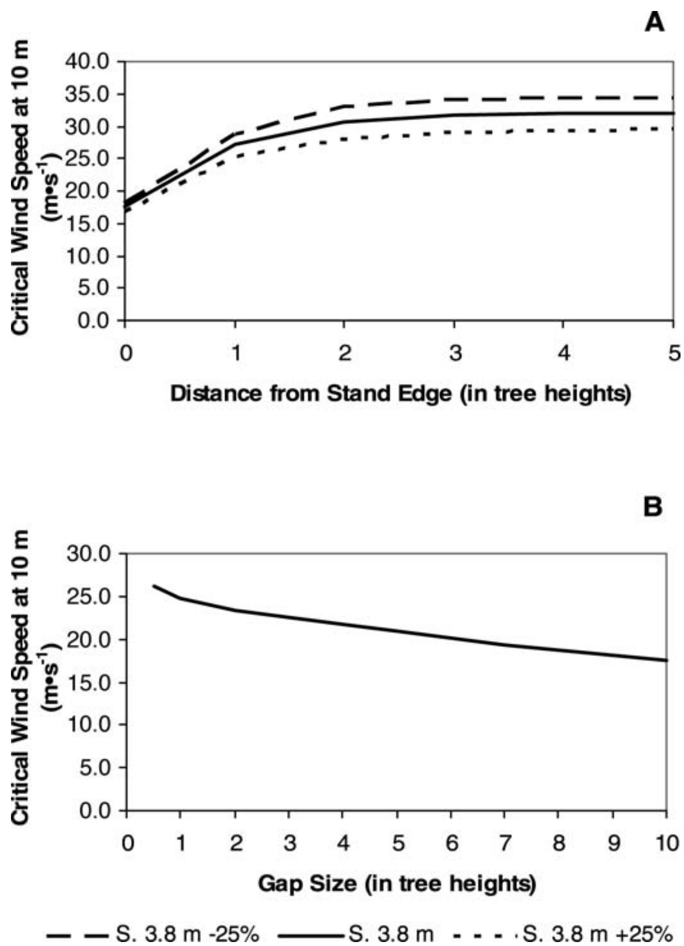

Fig. 7. Example predictions by the HWIND model of the critical wind speed needed for uprooting of Scots pine with height of 20 m and dbh 20 cm. (A) Critical wind speeds at various distances from the stand edge within the stand, when spacing (S) is 3.8 m and 3.8 m ± 25% and gap size is 10 tree heights. (B) Critical wind speeds at the stand edge with varying gap sizes (in tree heights), when spacing (S) is 3.8 m, respectively.

induced damage is of interest to many forest ecologists and managers of forest resources. In an effort to increase this understanding, a number of approaches have been adopted to date to study the stability of forests; e.g., field experiments on the effects of thinning and fertilization on the risk of damage, measurements of wind and the response of trees to it, wind tunnel measurements predicting the stability of tree stands, static tree-pulling tests and mechanistic modelling approaches. These previous studies have added to our understanding regarding the behavior of trees in strong winds and the mechanisms of root anchorage. The results of this research suggest that tree/stand and ground characteristics such as tree species, tree dimensions, stand density, soil type, position of the tree in a stand and gap size will determine the critical wind speed at which damage will occur. However, the local wind and snow/ice extremes and the topography will determine how probable such a wind speed and/or snow load is.

In this context, tree-pulling tests have had an important role in providing valuable information on mechanical stability of trees of varying size and tree species and soil types under static loading in regard to uprooting and stem breakage. This information is also useful in mechanistic modeling when estimating the maximum resistive bending moment of trees needed to predict the threshold wind speeds (critical wind speeds) for uprooting and stem breakage of trees. On the other hand, simulation of static loading alone by tree pulling is not enough to explain the mechanical stability of trees, although these real-size tree experiments are useful in stability research. This has been demonstrated also previously, for example, by Oliver and Mayhead (1974), who showed that the wind speeds that actually blew trees down were much lower than those calculated based purely on the BM_{max} derived from static tree-pulling experiments (see, e.g., Fraser, 1964). This could be explained by the fact that in response to wind, the trees sway dynamically with consequent short-term vibration or oscillatory motion. Moreover, any streamlining of tree crowns under wind loading should also be considered when aiming at predicting threshold wind speeds properly.

Similar to static tree-pulling experiments, wind tunnel experiments may also have some obvious limitations, and, therefore, results derived based on wind tunnel experiments may also be only strictly applicable under similar conditions. On the other hand, they could be expected to provide a reasonable basis for design of mechanistic models, e.g., with regard to modeling the effect of gap size and distance from stand edge on the total bending moment and the threshold wind speed needed to damage trees within a stand. Such a mechanistic approach would thus allow predictions of the impact of management on tree stability and even the design of management strategies for reducing wind-induced damage.

However, only a few systematic efforts have been attempted so far to analyze the effects of forest management on the risks of wind damage in stands either in the short or the long term and especially at the regional level based on these mechanistic approaches (see, e.g., Dunham et al., 2000; Talkkari et al., 2000; Blennow and Sallnäs, 2004; Zeng et al., 2004, in press; Zeng, 2006). Any long-term risk assessment would provide the integration of component models at the tree, stand, and regional levels such as for tree growth and yield, mechanistic wind damage, and airflow models. In this respect, Dunham et al. (2000) were the first to present the research in this area; they integrated GALES together with the climate model DAMS and the yield class model to estimate annual damage of stands at different time steps. FOREOLE, as implemented in the software called CAPSIS (see Ancelin et al., 2004), also allows wind firmness to be simulated both in measured and virtual tree populations of trees in coniferous forests. Recently, Zeng et al. (2004, in press) also used HWIND to study the immediate and long-term effects of different clear-cutting options on the risk of wind damage at a regional level in Finland. On the other hand, HWIND, GALES, or FOREOLE models have so far not taken into account the swaying of trees under dynamic loading and the possible support given by the neighboring trees. Moreover, for example, HWIND and GALES models could also be developed in the future so that they could predict the risk of damage for any individual tree in the stand, as FOREOLE does, instead of using mean stand characteristics in these computations. However, the behavior of these improved models should then also be tested and validated properly against real wind damage.

To conclude, the interactive effects of wind, site, tree/stand characteristics and management on the susceptibility of tree stands to wind damage can be studied based on fundamental physics, empirical experiments, and mechanistic model-based approaches. As a result, the threshold wind speeds necessary to damage the trees within a stand can be estimated. In this context, especially the use of a mechanistic approach would allow predictions of the impact of management on tree stability, which would not be possible with statistical approaches alone. On the other hand, the dynamic swaying of trees in addition to the streamlining of their crowns in response to wind should be accurately taken into account in predictions of these threshold wind speeds. With a better understanding of the interactions of wind, tree/stand characteristics and management both in the short and long term, more appropriate silvicultural decisions could be made to decrease the harmful effects of wind-induced damage on forests. Thus, although our understanding has substantially advanced in recent years, we need still to continue this stability research in order to fully understand the processes behind the occurrence of wind-induced damage.

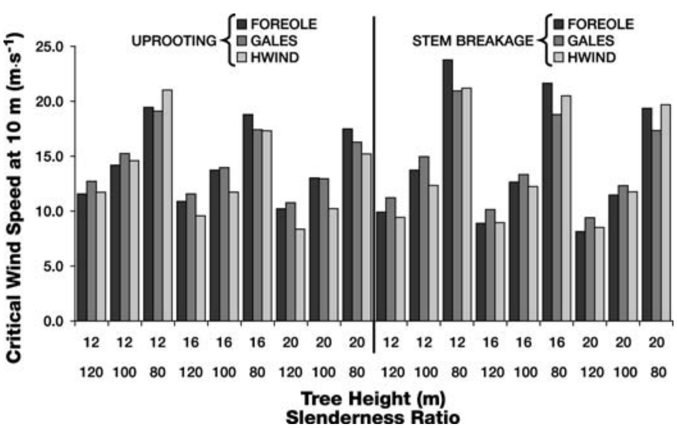

Fig. 8. Comparison of model outputs by FOREOLE, GALES, and HWIND in terms of critical wind speeds (at 10 m above the ground) required to damage Norway spruce trees of different sizes (i.e., tree height from 12 to 20 m and slenderness ratio (height to dbh ratio) from 80 to 120) at stand edge conditions, assuming a gap size of 10 tree heights (reprinted from Ancelin et al. [2004], p. 110, fig. 4, with permission from Elsevier).

LITERATURE CITED

ACHIM, A., J.-C. RUEL, AND B. A. GARDINER. 2005a. Evaluating the effect of precommercial thinning on the resistance of balsam fir to windthrow through experimentation, modeling, and development of simple indices. *Canadian Journal of Forest Research* 35: 1844–1853.

ACHIM, A., J.-C. RUEL, B. A. GARDINER, G. LAFLAMME, AND S. MEUNIER. 2005b. Modelling the vulnerability of balsam fir forests to wind damage. *Forest Ecology and Management* 204: 35–50.

ALEXANDER, R. R. 1967. Windfall after clearcutting on Fool Creek,Fraser Experimental Forest, Colorado. USDA Forest Service Research Note RM-92, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, USA.

ANCELIN, P., B. COURBAUD, AND T. FOURCAUD. 2004. Development of an individual tree-based mechanical model to predict wind damage within forest stands. *Forest Ecology and Management* 203: 101–121.

BLACKBURN, G. R. A. 1997. The growth and mechanical response of trees to wind loading. Ph.D. dissertation, Manchester University, Manchester, UK.

BLENNOW, K., AND O. SALLNÄS. 2004. WINDA: a system of models for assessing the probability of wind damage to forest stands within a landscape. *Ecological Modelling* 175: 87–99.

COUTTS, M. P. 1986. Components of tree stability in Sitka spruce on peaty gley soil. *Forestry* 59: 173–197.

CREMER, K. W., C. J. BOROUGH, P. H. MCKINNEL, AND P. R. CARTER. 1982. Effects of stocking and thinning on wind damage in plantations. *New Zealand Journal of Forestry Science* 12: 244–265.

CROOK, M. J., AND A. R. ENNOS. 1996. The anchorage mechanics of deep rooted larch, *Larix europea* × *japonica*. *Journal of Experimental Botany* 47: 1509–1517.

DAVENPORT, A. G. 1961. The application of statistical concepts to the wind loading of structures. *Proceedings of Institution of Civil Engineers* 19: 449–471.

DEANS, J. D., AND E. D. FORD. 1983. Modelling root structure and stability. *Plant and Soil* 71: 189–195.

DUNHAM, R. A., B. A. GARDINER, C. P. QUINE, AND J. C. SUÁREZ. 2000. ForestGALES. A PC-based wind risk model for British forests, version 1.3. User's guide. Forestry Commission, Forest Research, Northern Research Station, Roslin, Midlothian, UK.

FRASER, A. I. 1962. The soil and roots as factors in tree stability. *Forestry* 35: 117–127.

FRASER, A. I. 1964. Wind tunnel and other related studies on coniferous trees and tree crops. *Scottish Forestry* 18(1): 84–92.

FRASER, A. I., AND J. B. H. GARDINER. 1967. Rooting and stability in Sitka spruce. *Forestry Commission Bulletin* 40:1–28. Forestry Commission, Her Majesty's Stationery Office, London, UK.

FREDERICKSON, T. S., R. L. HEDDEN, AND S. A. WILLIAMS. 1993. Testing loblolly pine windfirmness with a simulated wind stress. *Canadian Journal of Forest Research* 23: 1760–1765.

GARDINER, B. A. 1995. The interactions of wind and tree movement in forest canopies. *In* M. P. Coutts and J. Grace [eds.], Wind and trees, 41–59. Cambridge University Press, Cambridge, UK.

GARDINER, B., B. MARSHALL, A. ACHIM, R. BELCHER, AND C. WOOD. 2005. The stability of different silvicultural systems: a wind-tunnel investigation. *Forestry* 78: 471–483.

GARDINER, B. A., H. PELTOLA, AND S. KELLOMÄKI. 2000. Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. *Ecological Modelling* 129: 1–23.

GARDINER, B., AND G. STACEY. 1996. Designing forest edges to improve wind stability. Forestry Commission Technical Paper 16. Forestry Commission, Edinburgh, UK.

GARDINER, B. A., G. R. STACEY, R. E. BELCHER, AND C. J. WOOD. 1997. Field and wind tunnel assessments of the implications of respacing and thinning for tree stability. *Forestry* 70: 233–252.

HAKKILA, P. 1972. Mechanized harvesting of stumps and roots. A subproject of the joint Nordic research programme for the utilization of logging residues. *Communicationes Instituti Forestalis Fenniae* 77(1): 1–71.

HALE, S. E., P. E. LEVY, AND B. A. GARDINER. 2004. Trade-offs between seedling growth, thinning and stand stability in Sitka spruce stands: a modelling analysis. *Forest Ecology and Management* 187: 105–115.

JONES, H. G. 1983. Plants and microclimate: a quantitative approach to environmental plant physiology. Cambridge University Press, Cambridge, UK.

KALELA, E. 1949. Männiköiden ja kuusikoiden juurisuhteista. [Summary: On the horizontal roots in pine and spruce stand.] *Acta Forestalia Fennica* 57(2): 1–79.

KERZENMACHER, T., AND B. A. GARDINER. 1998. A mathematical model to describe the dynamic response of a spruce tree to the wind. *Trees* 12: 385–394.

LAIHO, O. 1987. Metsiköiden alttius tuulituhoille Etelä-Suomessa. [Summary: Susceptibility of forest stands to windthrow in southern Finland.] *Folia Forestalia* 706: 1–24.

LAITAKARI, E. 1952. Myrskyistä ja myrskyn tuhoista Suomessa vv. 1911–50 [On storms and storm damage in Finland during the period 1911–50]. *Communicationes Instituti Forestalis Fenniae* 40(30): 1–29.

LANQUAYE-OPOKY, N., AND S. J. MITCHELL. 2005. Portability of stand-level empirical windthrow risk models. *Forest Ecology and Management* 216: 134–148.

LAVERS, G. M. 1969. The strength properties of timbers. Forest Products Research Laboratory Bulletin 50, 2nd ed. Her Majesty's Stationery Office, London, UK.

LOHMANDER, P., AND F. HELLES. 1987. Windthrow probability as a function of stand characteristics and shelter. *Scandinavian Journal of Forest Research* 2: 227–238.

MAYER, H. 1987. Wind induced tree sways. *Trees* 1: 195–206.

MAYHEAD, G. J. 1973. Some drag coefficients for British forest trees derived from wind tunnel studies. *Agricultural Meteorology* 12: 123–130.

MAYHEAD, G. J., J. B. H. GARDINER, AND D. W. DURRANT. 1975. A report on physical properties of conifers in relation to plantation stability. Forestry Commission, Forestry Commission Research and Development Division, Northern Research Station, Edinburgh.

MILLER, K. F. 1985. Windthrow hazard classification. Forestry Commission Leaflet 85. Her Majesty's Stationery Office, London, UK.

MILNE, R. 1991. Dynamics of swaying of *Picea sitchensis*. *Tree Physiology* 9: 383–399.

MITCHELL, S. J., T. HAILEMARIAM, AND Y. KULIS. 2001. Empirical modeling of cutblock edge windthrow risk on Vancouver Island, Canada, using stand level information. *Forest Ecology and Management* 135: 105–114.

MOORE, J. 2000. Effects of soil type on the root anchorage strength of *Pinus radiata*. *Forest Ecology and Management* 135: 63–71.

MORGAN, J., AND M. G. R. CANNELL. 1994. Shape of tree stems: a re-examination of the uniform stress hypothesis. *Tree Physiology* 14: 63–74.

NEUSTEIN, S. A. 1965. Windthrow on the margins of various sizes of felling area. Report on forest research for the year ended March 1964. Forestry Commission, Her Majesty's Stationery Office, London, UK.

NEUSTEIN, S. A. 1971. Damage to forests in relation to topography, soil and crops. *In* B. W. Holtam [ed.], Windthrow of Scottish forests in January 1968. Forestry Commission Bulletin 45: 42–48. Forestry Commission, Her Majesty's Stationery Office, London, UK.

OLIVER, H. R., AND G. J. MAYHEAD. 1974. Wind measurements in a pine forest during a destructive gale. *Forestry* 47: 185–194.

PAPESCH, A. J. G. 1974. A simplified theoretical analysis of the factors that influence windthrow of trees. Fifth Australasian conference on hydraulic and fluid mechanics, 1974, 235–242. University of Canterbury, Christchurch, New Zealand.

PAPESCH, A. J. G., J. R. MOORE, AND A. E. HAWKE. 1997. Mechanical stability of *Pinus radiata* trees at Eyrewell Forest investigated using static tests. *New Zealand Journal of Forestry Science* 27: 188–204.

PELTOLA, H. 1996. Swaying of trees in a response to wind and thinning in a stand of Scots pine. *Boundary-Layer Meteorology* 77: 285–304.

PELTOLA, H., AND S. KELLOMÄKI. 1993. A mechanistic model for calculating windthrow and stem breakage at stand edge. *Silva Fennica* 27: 99–111.

PELTOLA, H., S. KELLOMÄKI, A. HASSINEN, AND M. GRANANDER. 2000.

Mechanical stability of Scots pine, Norway spruce and birch: an analysis of tree pulling experiments in Finland. *Forest Ecology and Management* 135: 143–153.

PELTOLA, H., S. KELLOMÄKI, H. VÄISÄNEN, AND V. P. IKONEN. 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. *Canadian Journal of Forest Research* 29: 647–661.

PERSSON, P. 1975. Stormskador på skog: uppkomstbetingelser och inverkan av skogliga åtgärder. Skogshögskolan. Institutionen för skogsproduction. [Summary: Windthrow in forests: its causes and the effect of forestry measures] Swedish University for Agriculture Science, Department of Forest Management, Sweden. *Rapporter och Upsatser* 36: 1–294.

PETTY, J. A., AND C. SWAIN. 1985. Factors influencing stem breakage in conifers in high winds. *Forestry* 58: 75–84.

PETTY, J. A., AND R. WORRELL. 1981. Stability of coniferous tree stems in relation to damage by snow. *Forestry* 54: 115–128.

RAY, D., AND B. C. NICOLL. 1998. The effect of soil water-table depth on root-plate development and stability of Sitka spruce. *Forestry* 71: 171–182.

RAYMER, W. G. 1962. Wind resistance of conifers. *National Physical Laboratory Aeronautical Report* 1008: 1–20. Aerodynamics Division, London, UK.

RUDNICKI, M., S. J. MITCHELL, AND M. D. NOVAK. 2004. Wind tunnel measurements of crown streamlining and drag relationships for three conifer species. *Canadian Journal of Forest Research* 34: 666–676.

SCOTT, R. E., AND S. J. MITCHELL. 2005. Empirical modeling of windthrow risk in partially harvested stands using tree, neighbourhood, and stand attributes. *Forest Ecology and Management* 218: 193–209.

SMITH, V. G., M. WATTS, AND D. F. JAMES. 1987. Mechanical stability of black spruce in the clay belt region of northern Ontario. *Canadian Journal of Forest Research* 17: 1080–1089.

SOMERVILLE, A. 1979. Root anchorage and root morphology of *Pinus radiata* on a range of ripping treatments. *New Zealand Journal of Forest Science* 9: 294–315.

STACEY, G. R., R. E. BELCHER, C. J. WOOD, AND B. A. GARDINER. 1994. Wind and wind forces in a model spruce forest. *Boundary-Layer Meteorology* 69: 311–334.

SUNLEY, J. G. 1968. Grade stresses for structural timbers. *Forest Products Research Bulletin* 47: 1–18. Her Majesty's Stationery Office, London, UK.

TALKKARI, A., H. PELTOLA, S. KELLOMÄKI, AND H. STRANDMAN. 2000. Integration of component models from the tree, stand and regional levels to assess the risk of wind damage at forest margins. *Forest Ecology and Management* 135: 303–313.

VOLLSINGER, S., S. J. MITCHELL, K. E. BYRNE, M. D. NOVAK, AND M. RUDNICKI. 2005. Wind tunnel measurements of crown streamlining and drag relationships for several hardwood species. *Canadian Journal of Forest Research* 35: 1238–1249.

WALSHE, D. E., AND A. I. FRASER. 1963. Wind tunnel tests on a model forest. National Physical Laboratory Aeronautical Report 1078. Aerodynamics Division, London, UK.

WOOD, C. J. 1995. Understanding wind forces on trees. *In* M. P. Coutts and J. Grace [eds.], Wind and trees, 133–164. Cambridge University Press, Cambridge, UK.

ZENG, H. 2006. Influence of clear-cutting on the risk of wind damage at forest edges: a GIS-based integrated models approach. Dissertationes Forestales 16. Faculty of Forestry, University of Joensuu. Joensuu,-Finland.

ZENG, H., H. PELTOLA, A. TALKKARI, H. STRANDMAN, A. VENÄLÄINEN, K. WANG, AND S. KELLOMÄKI. In press. Simulations of the influence of clear-cuttings on the risk of wind damage on a regional scale over a 20 year period. *Canadian Journal of Forest Research.*

ZENG, H., H. PELTOLA, A. TALKKARI, A. VENÄLÄINEN, H. STRANDMAN, S. KELLOMÄKI, AND K. WANG. 2004. Influence of clear-cutting on the risk of wind damage at forest edges. *Forest Ecology and Management* 203: 77–88.