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A POPULATION APPROACH TO STUDY FOREST STAND STABILITY TO WIND: INDIVIDUAL TREE-BASED MECHANICAL MODELING.

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Abstract

Wind damage is a major disturbance interacting with forest development processes as well in natural forests as in managed forest. Models have been proposed to assess the risk of wind damage either with probabilistic approaches taking into account landscape, stand and tree attributes or with more mechanistic approaches at the scale of the tree. Allowing a precise description of the relations between tree characteristics and breakage or uprooting, mechanistic models are potentially interesting tools for testing the influence of various sylviculture strategies on damage. This work introduces a population model of wind damage based on the mechanical behaviour of all the individual trees in a stand. Using the Transfer Matrix Method of beams, this model allows wind and gravity loads, as well as mechanical state of stems to be well described. Applying the model on populations of Norway spruce trees, we try then to explore how damage is related to wind speed, and how damage at the population level can be predicted from the distribution of individual characteristics.

Introduction

In France, the two 1999 strong storms Lothar and Martin have not only caused high economic losses (wind damage on forests reached as much as 10% of the total standing volume of the country; Wencélius 2002) but they have also sorrowfully reminded us the importance of natural disturbances on forest management. Wind damage is indeed a major disturbance interacting with forest development processes, nevertheless foresters use often empirical methods in order to evaluate stand stability to wind, melting various criteria such as species, slenderness ratio, canopy closure, stand structure and presence of regeneration. In these conditions, it is very difficult to elaborate rigorous sylviculture strategies taking stand stability to wind into account. Field observations after wind storms constitute a first approach to understand the links between stand structure and wind damage (Cucchi et al 2003; Dunham et al 2000). However, their explicative power is limited because of inaccurate knowledge about the stress to which trees have been submitted and because of the small number of sylviculture modalities usually available. Modeling constitutes an interesting approach to investigate further trees and forest stability to wind. Probabilistic models taking into account landscape, stand and/or tree attributes to assess the risk of wind damage have been proposed (Lohmander et al 1987; Valinger et al 1997, 1999; Ni Dhubhain et al 2001). They nevertheless constitute a direct extension of the field approach and suffer from the same drawbacks. Mechanistic models at the scale of the tree are interesting alternatives (Petty et al 1985; Peltola et al 1999; Chiba 2000; Gardiner et al 2000a; Spatz et al 2000). Based on a precise calculation of the relations between tree geometry, wind loading and breakage or uprooting, they allow to understand better which tree characteristics influence stability. In existing studies, the risk of damage in a whole stand is nevertheless usually summarized by the behaviour of only one tree: either the mean tree in regular stands (Peltola et al 1999; Gardiner et al 2000b; Talkkari et al 2000) or the dominant tree in irregular ones (Mason 2002). Wind damage in forest stands appear unfortunately to be far from a whole or nothing process. The classical approach consisting in predicting the critical wind speed above which a given stand will be ruined appears rather poor as it doesn't allow to take into account partial damage. This is especially true in uneven-aged stands where damage are often diffuse and where advanced regeneration and adult trees remaining after disturbance are keys to future forest development (Franklin et al 2002; Zeller 1996).

Adaptations of mechanistic models and of their use are then needed to study in detail the relations between stand structure and wind damage. In this paper, we propose a conceptual shift from the critical wind speed approach, to the characterization of the distribution of damage in a population of trees for a given wind event. Moreover, we show that this approach allows three important questions to be explored: What are the most important individual tree characteristics promoting stability? Does stand structure, i.e. the variability of individual tree characteristics, modify the impact of a storm, both regarding damage amount and stand capacity to recover? Do the damage increase gradually with increasing wind speed or does the stand respond as a whole in relation to a critical wind speed? The strategy we followed was to build an individual tree-based mechanical model allowing to simulate any stand structure and to analyse the stability to wind at the population level. In order to test in future works the impact of sylviculture on long term stand stability, the model presented here, called FOREOLE, was developed in compatibility with an existing individual tree-based stand dynamic model for uneven-aged coniferous mountain forests (Courbaud 2000; Courbaud et al 2001; Courbaud et al 2003). Both were implemented in the software CAPSIS, a computer platform dedicated to the development of stand growth and dynamic models (Dreyfus et al 1996; Coligny (de) et al 2002; Coligny (de) et al in press). The model FOREOLE, its evaluation and applications are detailed in Ancelin et al (submitted).

A mechanical model to calculate the response of every tree in a stand…

The model FOREOLE uses mechanical criteria of vulnerability in order to assess tree stability to wind. Tree structure has to withstand overturning, depending on anchorage resistance, and stem breakage, controlled by stem wood resistance. Resistance to uprooting is given by a critical turning moment at tree base modeled by a simple law and expressed in terms of stem weight, as proposed by Gardiner et al (2000a). This law, issued from pulling experiments on a large number of trees in Great Britain, uses a regression coefficient depending on species and soil conditions. Resistance to stem breakage is based on a critical threshold of compressive stresses (Peltola et al 1999). Indeed, tree response to wind is concerned with the development of internal longitudinal stresses. Highest in the outer fibres of the leeward side of the stem, compressive stresses due to bending and self-weight support are of interest to diagnose stem breakage (Chiba 2000).

Due to the large number of trees to be analysed in the population, mechanical calculations are restricted to tree stem. The response of each stem to wind-induced forces is estimated using the Transfer Matrix Method (TMM), allowing stem mechanics to be computed in a discrete way by a stepwise procedure (Morgan et al 1987; Cannell et al 1988; Milne et al 1989). Here applied on 3D beams, the method is based on the principal functions of a tree-based biomechanical model previously developed in order to evaluate wood quality in growing tree stems at the forest stand scale (Ancelin et al in press). The model FOREOLE allows the stem mechanical state to be calculated under the following loadings: (i) stem self-weight (applied as distributed loads), (ii) crown weight (applied as concentrated loads at the theoretical insertion points of branches into the stem) and (iii) wind drag (principally related to the airflow within the crown). Tree stem, discretized in several beam elements, and crown are described in 3D by species dependent theoretical taper equations. Stem mechanical state is calculated in two steps, applying successively wind drag and overhanging displaced elements weight. Turning moment at tree base is obtained from external loads and lever arms, while compressive stresses along stem in the leeward outer fibers are derived from internal forces provided by the two TMM calculations. Hence, for a given wind intensity, the mechanical state of every tree can be compared to resistance criteria in order to estimate partial wind damage in the population.

… A simple approach to describe wind action…

As in several works on tree stability to wind (e.g. Petty et al 1985; Blackburn et al 1988; Peltola et al 1993, 1999; Gardiner et al 2000a; Gaffrey et al 2002), we use a static approach to model wind forces and consider only horizontal mean wind speed according to height above the ground. Two locations are considered for the population of trees in a greater theoretical forest stand: at stand edge or within stand. From either field or wind tunnel experiments, many authors have proposed theoretical profiles of mean wind speed which can be used at forest edge or inside forest, above and below canopy. The mean wind profile above a rough surface is classically described by a logarithmic law in terms of height (Thom 1971; Oliver et al 1974; Raupach et al 1981; Raupach 1992; Brunet et al 1994). This type of profile is used in the model FOREOLE above the ground at stand edge and above the canopy inside the forest (with different parameters for each surface). Moreover, inside the stand, mean wind speed attenuates rapidly within the canopy so that the profile presents a characteristic inflexion point at canopy top (Thom 1971; Oliver et al 1974; Raupach et al 1981; Brunet et al 1994). It can be approximated by an exponential decreasing (Oliver et al 1974; Raupach et al 1981; Petty et al 1985; Blackburn et al 1988). The model FOREOLE uses these different profiles to determinate the mean mechanical state of trees. A static wind loading could lead to a considerable underestimation of experienced forces because the maximal wind gust speed can reach up to twice its hourly mean speed (Oliver et al 1974). This problem is solved using a gust factor, developed from wind tunnel studies, relating mean wind loading to extreme values (Gardiner et al 1997; Gardiner et al 2000a). Furthermore, as one moves away from stand edge, mean wind loading decrease is translated using an edge factor (Peltola et al 1999; Gardiner et al 2000a). In the end, internal and basal mean bending moments obtained by the TMM calculations are converted into maximum values using these two additional factors, before comparison to tree resistance criteria.

… And some new results on stability to wind at the population level.

The model FOREOLE allows stability to wind to be analyzed from the distribution of individual characteristics within the population (Fig. 1) and evolution of partial wind damage to be simulated according to wind speed (Fig. 2). This individual-based population approach offers a new potential particularly interesting for applications to irregular stand structures. In this case, the critical wind speed approach based on a representative tree can be debatable since variability of trees and damages is not taken into account.
Implemented in relation to a stand dynamic model for uneven-aged coniferous mountain forests (Courbaud 2000; Courbaud et al 2001; Courbaud et al 2003), the model FOREOLE allows wind damage and stability to be simulated and analysed from populations of Norway spruce (Picea abies, L. Karst) trees. The results presented here were obtained using field data from a Norway spruce stand located in the French Alps, department of Savoy, locality Séez-Ecudets (here denoted Seez; latitude: 45°38’N, longitude: 6°50’E). The experimental plot was a square of 0.3015 ha containing 189 trees, i.e. 626 stems.ha^{-1}. As often in moun-

tain areas, tree size variability was intermediate between the case of a typically regular stand and a true irregular one.

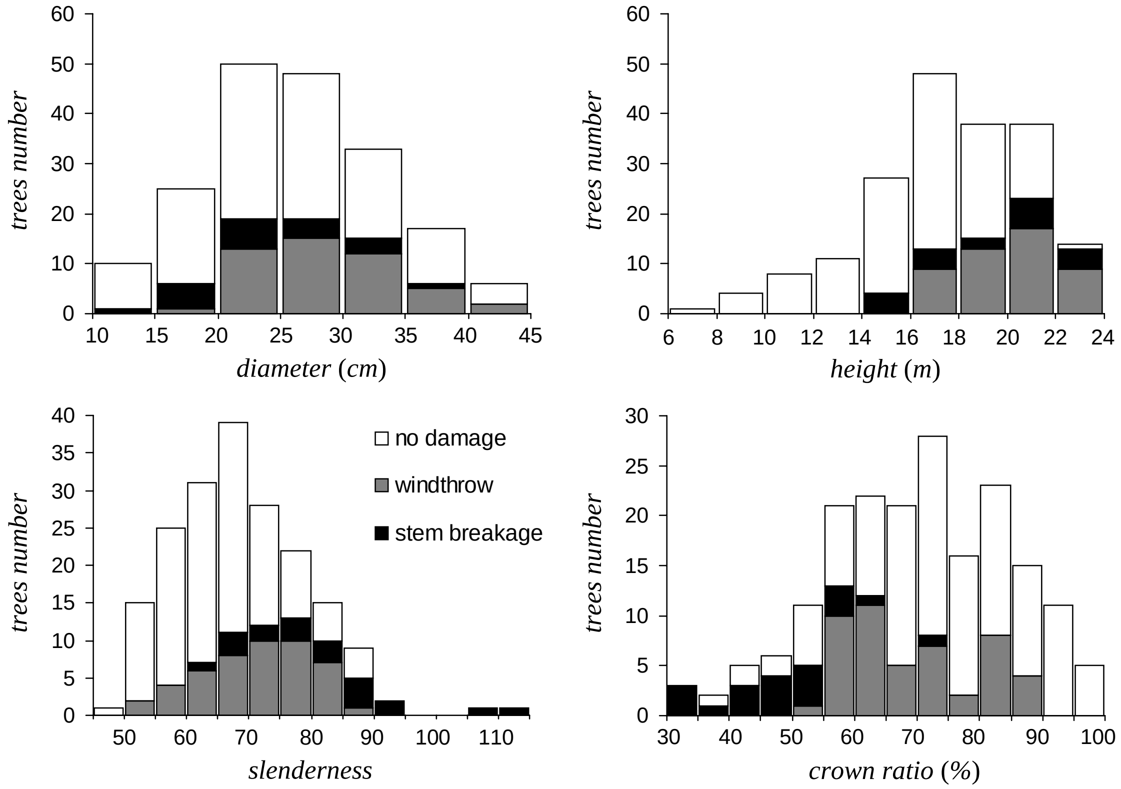

Fig. 1: Damage distribution in the Norway spruce population Seez according to trees characteristics: diameter, height, slenderness and crown ratio. The analysis was made from a simulation within stand with a mean canopy top wind speed of 20 m.s^{-1}. Wind damage represented respectively 36% of tree number and 42% of standing volume.

Wind damage was calculated assuming the population located well within the stand as was on the field. At a given mean wind speed, histograms of damage distribution, according to individual dimensions, highlight classes of less stable trees (Fig. 1). The amount of trees is used in ordinate to let stand structure appear on the graph even if the relative number of damaged trees would have been more appropriate to quantify the vulnerability of each size class. If tree diameter provides a poor explanation of damage occurrence, height appears as the more important variable at the tree level controlling stability: no damage occurred for trees below 14 m and a constant increase with tree height occurred beyond. Moreover, critical threshold values or ranges for both slenderness and crown ratio can be identified and associated with either windthrow or breakage. At a wind speed of 20 m.s^{-1}, it can be observed that trees with slenderness greater than 85 and with crown ratio less than 55% are the most likely to suffer stem breakage. Trees with slenderness between 70 and 85, and with crown ratio between 55 and 65% are the most likely to suffer overturning. In forest locations suffering from severe climatic conditions, these results could be used in order to elaborate sylviculture strategies limiting the number of trees in size classes at highest risk.
An analysis of the relation between damage amount and wind speed was also carried out with regard to stand structure, using two additional virtual stands following the representative tree approach proposed by Mason (2002). The first one had a normal diameter distribution with a mean tree equivalent to Seez and a standard deviation roughly half of Seez (Virtual Regular Stand: VRS). The second one had an inverse J-shape diameter distribution with a dominant tree equivalent to Seez (Virtual Selection Stand: VSS). Both were built using virtual

stand generation tools developed in the software CAPSIS (Goreaud et al, 1999) and had the same density than Seez. A range of theoretical wind speeds was tested so that damage amount ranged from 0% to 100% of the populations. The percentage of wind damage in each population was computed in the model FOREOLE according both to tree number and cumulated volume (Fig. 2).

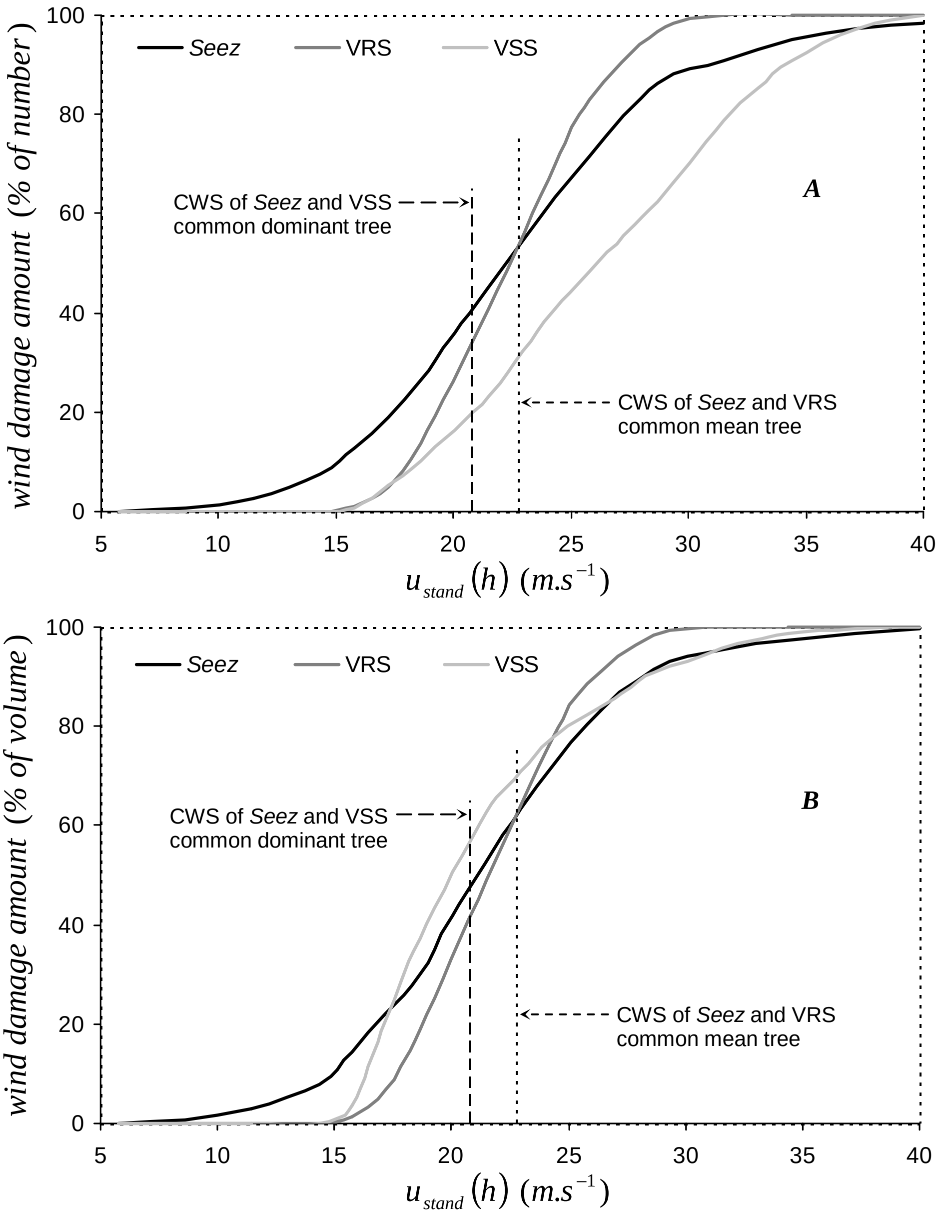

Fig. 2: Evolution of damage amount according to mean wind speed at canopy top within stand. Results for the Norway spruce population Seez, the virtual regular stand VRS and the virtual selection stand VSS. The percentage of damage is given according to: A/ the total number of trees; B/ the total volume of trees. The critical wind speed (CWS) of representative trees is indicated.

As a function of wind speed, the damage evolution is proved to be a sigmoid function with a slow damage increase for small wind speeds, an abrupt variation at intermediate speeds and a slow progression towards complete damage at high speeds. The relation is then smoother than hypothesized in the classical critical wind speed approach which separates a domain without quantified damage for slow speeds and a domain of stand ruin for high speeds (Gardiner et al 2000b; Talkkari et al 2000; Mason 2002). Moreover, during the step of rapid increase of damage, the slope of the relationship between damage and wind speed depends directly on stand structure: the more heterogeneous the stand, the milder the slope and the larger the range of wind speed concerned.

Not only the population approach allows to analyze how partial damage increases with wind speed in a stand, but it also allows to disconnect volumes and tree numbers. Stand structure appear to be influent on the relation between the relative number of damaged trees and their relative volume. The difference between these two percentages remains quite small for regular stand structures, whereas it is found very important for irregular ones. In this case, intermediate wind speeds lead to a relative damaged volume sometimes more than twice greater than the relative number of trees (Fig. 2). Overall, biggest trees are proved to be the more likely to wind damage. The results of such analysis would be very interesting to assess the reduction of value recovery resulting from a storm, as explored by Nieuwenhuis et al (2002). The population approach could allow storm consequences to be investigated according different points of view. In some cases, wind effect may be prejudicial for wood production, because of the important volume of suddenly damaged wood, whereas future stand dynamics may be preserved by the relatively large number of survivors and the resilience of the stand.

Conclusion

The presented modeling approach allows the forest stands resistance to wind to be qualitatively estimated with an individual tree-based model which takes into account inner stand variability. This population approach offers a new potential for quantifying the risk of wind damage in forest stands in relation to stand structure, particularly interesting for applications on irregular stands with regard to some actual stand-based models. The possibility to analyze damage both in volume and tree number allows the reduction of value recovery to be discussed in a more complete way. Furthermore, this work on stand stability to wind constitutes a new step in the integration of natural disturbances into forest stands dynamic models. The model FOREOLE could allow to estimate the long term impact of wind disturbance on stand dynamics as well as to build sylviculture strategies improving long term stand stability. A complete coupling with the forest stand dynamic model is currently in development for this purpose. This innovative tool should allow us to progress on the understanding of the complex feed-back processes between disturbance, stand resistance, resilience and dynamics.

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References

Ancelin, P., Courbaud, B., Fourcaud, T., submitted: "Predicting partial wind damage in a population of trees using an individual based mechanical model", Annals of Forest Science.

Ancelin, P., Fourcaud, T., Lac, P., in press: "Modelling the biomechanical behaviour of growing trees at the forest stand scale. Part I: development of an Incremental Transfer Matrix Method and application to simplified tree structures", Annals of Forest Science.

Blackburn, P., Petty, J.A., 1988: "Theoretical calculations of the influence of spacing on stand stability", Forestry, 61(3), pp. 235-244.

Brunet, Y., Finnigan, J.J., Raupach, M.R., 1994: "A wind tunnel study of air flow in waving wheat: single-point velocity statistics", Boundary Layer Meteorology, 70, pp. 95-132.

Cannell, M.G.R., Morgan, J., Murray, M.B., 1988: "Diameters and dry weights if tree shoots: effects of Young's modulus, taper, deflection and angle", Tree Physiology, 4, pp. 219-231.

Chiba, Y., 2000: "Modelling stem breakage caused by typhoons in plantation Cryptomeria japonica forests", Forest Ecology Management, 135(1/3), pp. 123-131.
Coligny (de), F., Ancelin, P., Cornu, G., Courbaud, B., Dreyfus, P., Goreaud, F., Gourlet-Fleury, S., Meredieu, C., Orazio, C., Saint-André, L., 2002: "CAPSIS: Computer-Aided Projection for Strategies In Sylviculture: an open source simulator for stand dynamics models", In IUFRO Working Party S5.01-04 conference, Harrison, British Columbia, Canada.
Coligny (de), F., Ancelin, P., Cornu, G., Courbaud, B., Dreyfus, P., Goreaud, F., Gourlet-Fleury, S., Meredieu, C., Orazio, C., Saint-André, L., in press: "CAPSIS: Computer-Aided Projection for Strategies In Sylviculture: advantages of a shared forest modelling platform", In Modelling forest systems Eds. Amaro, A., Reed, D., Soares, P., CABI publishing, Wallingford, UK.
Courbaud, B., 2000: "Comparing light interception with stand basal area for predicting tree growth", Tree Physiology, 20, pp. 407-414.
Courbaud, B., Coligny (de), F., Cordonnier, T., 2003: "Simulating light distribution in a heterogeneous Norway spruce forest on a slope", Agricultural and Forest Meteorology, 116, pp. 1-18.
Courbaud, B., Goreaud, F., Dreyfus, P., Bonnet, F.R., 2001: "Evaluating thinning strategies using a Tree Distance Dependent Growth Model: Some examples based on the CAPSIS software "Uneven-Aged Spruce Forests" module", Forest Ecology Management, 145, pp. 15-28.
Cucchi, V., Bert, D., 2003: "Wind-firmness in Pinus pinaster Ait. stands in Southwest France: influence of stand diversity, fertilisation and breeding in two experimental stands damaged during the 1999 storm", Annals of Forest Science, 3, in press.
Dreyfus, Ph., Bonnet, F.R., 1996: "CAPSIS (Computer-Aided Projection of Strategies in Silviculture): an interactive simulation and comparison tool for tree and stand growth, silvicultural treatments and timber assortment", In Proc. Connection between silviculture and wood quality through modelling approaches and simulation software, IUFRO WP S5.01-04 second workshop, Berg-en-Dal, Kruger National Park, South Africa, August 26-31, 1996, pp. 57-58.
Dunham, R.A., Cameron, A.D., 2000: "Crown, stem and wood properties of wind-damaged and undamaged Sitka spruce", Forest Ecology Management, 135(1/3), pp. 73-81.
Franklin, J.F., Spies, T.A., Van Pelt, R., Carey, A.B., Thornburgh, D.A., Rae Berg, D., Lindenmayer, D.B., Harmon, M.E., Keeton, W.S., Shaw, D.C., Bible, K., Chen, J., 2002: "Disturbances and structural development of natural forest ecosystems with silvicultural implications, using douglas-fir forests as an example", Forest Ecology and Management, 155, pp. 399-423.
Gaffrey, D., Kniemeyer, O., 2002: "The elasto-mechanical behaviour of Douglas fir, its sensitivity to tree-specific properties, wind and snow loads, and implications for stability – a simulation study", Journal of Forest Science, 48(2), pp. 49-69.
Gardiner, B.A., Peltola, H., Kellomäki, S., 2000: "Comparison of two models for predicting the critical wind speeds required to damage coniferous trees", Ecological Modelling, 129, pp. 1-23.
Gardiner, B.A., Quine, C.P., 2000: "Management of forests to reduce the risk of abiotic damage - a review with particular reference to the effects of strong winds", Forest Ecology Management, 135(1/3), pp. 261-277.
Gardiner, B.A., Stacey, G.R., Belcher, R.E., Wood, C.J., 1997: "Field and wind-tunnel assessments of the implications of respacing on tree stability", Forestry, 70(3), pp. 233-252.
Goreaud, F., Courbaud, B., Collinet, F., 1999: "Spatial structure analysis applied to modeling of forest dynamics: a few examples", In Empirical and Process Based Models for Forest Tree and Stand Growth Simulation, Eds. Amaro, A., Tomé, M., Salamandra, Lisboa, pp. 155-171.
Lohmander, P., Helles, F., 1987: "Windthrow probability as a function of stand characteristics and shelter", Scandinavian Journal of Forest Research, 2, pp. 227-238.
Mason, W.L., 2002: "Are irregular stands more windfirm?", Forestry, 75(4), pp. 347-355.
Milne, R., Blackburn, P., 1989: "The elasticity and vertical distribution of stress within stems of Picea sitchensis", Tree Physiology, 5(2), pp. 195-205.
Morgan, J., Cannell, M.G.R., 1987: "Structural analysis of tree trunks and branches: tapered cantilever beams subject to large deflections under complex loadings", Tree Physiology, 3, pp. 365-374.
Ni Dhubhain, A., Walshe, J., Bulfin, M., Keane, M., Mills, P., 2001: "The initial development of a windthrow risk model for Sitka spruce in Ireland", Forestry, 74(2), pp. 161-170.
Nieuwenhuis, M., Fitzpatrick, P.J., 2002: "An assessment of stem breakage and the reduction in timber volume and value recovery resulting from a catastrophic storm: an Irish case study", Forestry, 75(5), pp. 513-523.

Oliver, H.R., Mayhead, G.J., 1974: "Wind measurements in a pine forest during a destructive gale", Forestry, 47(2), pp. 187-194.
Peltola, H., Kellomäki, S., 1993: "A mechanistic model for calculating windthrow and stem breakage of Scots pines at stand edge", Silva Fennica, 27(2), pp. 99-111.
Peltola, H., Kellomäki, S., Väisänen, H., Ikonen, V.-P., 1999: "A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce and birch", Canadian Journal of Forest Research, 29, pp. 647-661.
Petty, J.A., Swain, C., 1985: "Factors influencing stem breakage of conifers in high winds", Forestry, 58(1), pp. 75-85.
Raupach, M.R., 1992: "Drag and drag partition on rough surfaces", Boundary Layer Meteorology, 60, pp. 375-395.
Raupach, M.R., Thom, A.S, 1981: "Turbulence in and above plant canopies", Annual Review of Fluid Mechanics, 13, pp. 97-129.
Spatz, H.C., Bruechert, F., 2000: "Basic biomechanics of self-supporting plants: wind loads and gravitational loads on a Norway spruce tree", Forest Ecology Management, 135(1/3), pp. 33-44.
Talkkari, A., Peltola, H., Kellomäki, S., Strandman, H., 2000: "Integration of component models from the tree, stand and regional levels to assess the risk of wind damage at forest margins", Forest Ecology Management, 135(1/3), pp. 303-313.
Thom, A.S., 1971: "Momentum absorption by vegetation", Quarterly Journal of the Royal Meteorological Society, 97(414), pp. 414-428.
Valinger, E., Fridman, J., 1997: "Modelling probability of snow and wind damage in Scots pine stands using tree characteristics", Forest Ecology Management, 97, pp. 215-222.
Valinger, E., Fridman, J., 1999: "Models to assess the risk of snow and wind damage in pine, spruce, and birch forests in Sweden", Environmental Management, 24, pp. 209-217.
Wencélius, F., 2002: "Tempêtes de décembre 1999 : évaluation des dégâts forestiers par l'Inventaire Forestier National", Revue Forestière Française, LIV, pp. 20-30.
Zeller, E., 1996: "Résoudre des problèmes en forêt de montagne : reboiser, stabiliser, rajeunir, assainir", Ecole intercantonale de gardes forestiers, Maienfeld, p. 30.