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EVALUATING WINDA – A TOOL FOR ASSESSING THE PROBABILITY OF WIND DAMAGE TO FOREST STANDS

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Abstract

WINDA is an integrated system of models for calculating the stand-wise probability of wind damage of trees within a landscape (Blennow & Sallnäs, submitted). It integrates a modified version of the dose/response model HWIND (Peltola *et al*., 1999), the airflow model WASP (Mortensen *et al*., 1998), and a component for calculating the zero-plane displacement and surface roughness. WINDA uses a GIS for geographical computations. The calculations are made point-wise at exposed stand edges and the results are combined for each stand. The likelihood of damage is calculated using extreme value theory. The mechanistic modelling approach makes WINDA useful for evaluating effects on the probability of wind damage of silvicultural treatments and forestry activities as well as of a changed climate. This paper briefly outlines WINDA and evaluates output by comparing predicted damage with observed damage for two landscapes in southern Sweden.

Introduction

Wind is the most important disturbance factor in European forests (Schelhaas et al., submitted). In Sweden, wind and snow damage together represent a cost of about 150 million EUR each year (Valinger & Fridman, 1997) although inter-annual variation is substantial (Blennow & Olofsson, submitted). Because of large spatial variation, the extent of damage done to a particular forest estate may be much larger than average figures for large areas indicate. The need of decision support for management of the risk of wind damage is greater compared to that of other risk factors in forest raw material production (Blennow & Sallnäs, 2002). Because of the complexity of the forest system, computer simulation is a way to provide useful decision support to forest managers with respect to hazards.

During recent years, several models for estimating effects of strong winds on forests were presented (see Blennow & Sallnäs, submitted). These models show that the probability of wind damage is affected by silvicultural treatments and forestry planning activities such as the choice of tree species, thinning regime, length of rotation period and the spatial distribution of different land cover entities. The probability of wind damage, however, also depends on the wind climate. The wind climate at a specific point in a landscape is a result of the regional wind climate interacting with the terrain. A probabilistic and mechanistic modelling approach allows the effects of changes in land cover caused by different management regimes as well as changes in the wind climate to be explored.

In this paper, WINDA, a geographically explicit and integrated system of models for calculating the stand-wise probability of wind damage within a landscape is briefly outlined. The details of WINDA and a sensitivity analysis of output are found in Blennow & Sallnäs (submitted). The performance of WINDA is evaluated by using the model to predict damage caused by a specified weather situation and to compare the predicted damage with observed damage for two landscapes in southern Sweden. Difficulties relating to the availability of suitable data sets for evaluation of this type of model are discussed.

WINDA

A system of models, WINDA, was built for assessing the stand-wise annual probability of wind damage at a landscape level (Blennow & Sallnäs, submitted). Additionally, WINDA may be used for calculating the stand-wise percentage exceedance at of a specified critical windspeed and direction. Using WINDA in this way makes it possible to compare predicand observed ted damage. The system of models was built for conditions such as those found in the south of Sweden where the topography is reasonably level and the forest stands are somewhere between a few to some tens of ha. Norway spruce (*Pices abies* L. Karst.), Scots pine (*Pinus sylvestris* L.), and birch (*Betula* spp.) are the main species. Wind damage is usually concentrated at new forest edges, recently thinned stands, seed trees and shelterwood (*e.g*. Persson, 1975). Strong winds mainly occur in association with the passage of cyclones, *i.e*. in association with large-scale weather systems. We use the term landscape as an area of a few km^2 to a few tens of km^2. A fundamental model assumption is that we assume the weather to be the same within such a landscape, *i.e*. caused by the same weather system. The components of WINDA are described below.

Exposed stand edges: A model component identifies exposed stand edges at least 10 m high. Along these, points for which subsequent calculations are made are determined at 50 m distance from each other. The wind was divided into six direction sections, which corresponds to each point being assumed exposed to wind from directions within ±30º from the direction perpendicular to the edge.

Dose/response: WINDA uses HWIND as a dose/response model component. The details of HWIND are found in Peltola *et al*. (1999). In brief, the forces acting upon a tree are divided into the horizontal force due to the wind and the vertical force due to gravity. The trees are assumed to deflect to a point of no return when acted upon by wind of constant mean velocity and direction. A predicted wind profile at the stand edge is used together with the vertical distribution of stem and crown weights to calculate the mean wind loading and gravity-based forces at each height in the canopy. The predicted wind profile was assumed to be logarithmic. The resistance to uprooting is predicted from an estimate of the root-soil plate weight. A tree is assumed to overturn if the total maximum turning moment exceeds the support provided by the root-soil plate anchorage. The maximum turning moment a tree stem can stand without snapping is calculated from the diameter at breast height and the modulus of rupture of green wood. Critical windspeeds are calculated that correspond to the turning moments required for uprooting and snapping of trees, respectively. These are given as hourly average values at tree top level after adjusting for the streamlining of the crown and the gustiness of the wind using empirical factors. To make it possible to account for variation in conditions in front of an exposed edge HWIND was modified so that z_0 and d in front of the exposed edge were made into variables.

Free-stream wind: The Wind Atlas and Application Program (WASP) (Mortensen *et al*., 1998) is used to calculate the free-stream wind, which is the observed windspeed and direction cleaned from effects of obstacles, roughness changes and orography (Figure 1). The cleaning is made using sector-wise values of z_0 and correction factors. These are linearly smoothed with respect to direction to avoid large jumps in the data series. The data series are converted from windspeed to friction velocity. Assuming geostrophic balance the friction velocity is related to a specified aerodynamic roughness length using to a methodology by Kristensen *et al*. (2000). In this way an observed wind data series may be expressed in terms of a series of free-stream friction velocities for a standard roughness length.

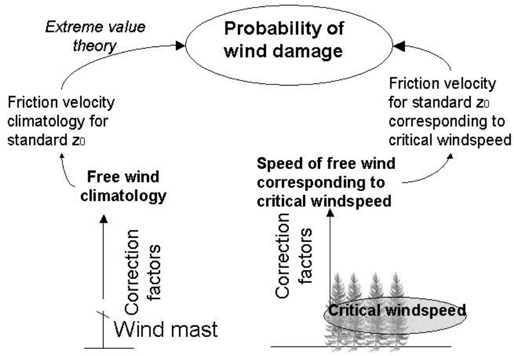

Fig. 1: Conceptual diagram for calculating the probability of wind damage using WINDA. (From Blennow & Sallnäs, submitted.)

Probability of wind damage: The sector-wise values of z_0 and correction factors were calculated using WASP for each point of interest. After linear smoothing as above, these were used to link the corresponding critical windspeeds and directions to the free-stream wind with the windspeed values expressed as friction velocities for the standard roughness length**,** $u_*^{'}$ (Figure 1). The annual probability of exceedance for the critical $u_*^{'}$ is calculated using extreme value theory. For each sector, Fisher Tippett Type I distributions are fitted to the square of the annual maximum of $u_*^{'}$ using the Lieblein corrected Gumble method (Cook, 1985). In order to ensure independency between sectors, furthermore, only the largest data value from each strong wind occasion is retained. This is ensured by at least two days separation between annual maxima for any two sectors. The annual probability of wind damage for each stand is calculated as

$$p = 1 - [(1 - p_1) \cdot, \ldots, \cdot (1 - p_n)] \quad (1)$$

where p_n is the sector-wise maximum of the largest of the probabilities of uprooting and snapping among the points of interest and n is the number of sectors. In addition, the corresponding stand-wise probabilities of uprooting and snapping may be calculated, respectively.

Geographical computations and input data: An ArcInfo polygon coverage (Anon., 2001) and a digital elevation model for the study landscape and its surroundings are used as input together with an obstacle map for a circle centered on the meteorological observing station (Mortensen *et al*., 1998). Forest inventory data used included information on tree species, species-wise average tree height, diameter at breast height, and number of stems per ha and were kept in the table of the ArcInfo coverage together with values of z_0 and d for polygons in the surroundings of the study landscape. The forest inventory data were used to calculate z_0 and d for each stand within the study landscape based on the work by Raupach (1992, 1994). Each stand was then classified into either of four z_0-classes. After merging adjacent stands into polygons of the same class, a map of roughness-change lines separating these polygons is produced by WINDA. Polygons in the surroundings of the study landscape were assigned values of z_0 according to Mortensen *et al*. (1998) and the corresponding values of d are assigned according to 80% of the estimated height based on information from standard topographic maps. Together with a contour map of the sum of the elevation above sea level and d, these maps are input to WASP. A routine in WINDA then identifies d for the polygon in front of the exposed edge and calculates the fetch as the average length of a 30º sector centered on the specified wind direction. Together with fetch, the calculated values of z_0 and d in front of the exposed stand, the forest inventory data are, furthermore, used by HWIND to calculate critical windspeeds for uprooting and breakage, respectively.

Predicted and observed wind damage

Observed wind damage was compared with predictions made by WINDA for two landscapes in southern Sweden. Asa Experimental Forest (57°10'N/14°47'E) is 6.7 km^2 large and is surrounded by mainly coniferous forest-land. Before two storms in January 1993, the forest consisted of 305 forest stands of which 299 were pure or mixed stands of Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.), and birch (*Betula* spp.). The six remaining stands contained various amounts of different deciduous tree species for which the parameter values of birch were used in the computations. WINDA was run on forest inventory data that were collected in 1991 and projected to represent the state of the forest in 1993 before the storms. The wind climatology used was based on an eleven years long time series of one-hour average wind data observed 10m above the ground at the Experimental Forest. An obstacle map for the vicinity of the wind mast was made using aerial photo interpretation and the heights of the obstacles were measured from the ground. Ten or more uprooted or broken trees were observed in 24 forest stands in a ground-based field survey after the storms (Figure 2a). There was a statistically significant difference between the stands for which damage was predicted and a randomly selected set of stands as tested using Fisher's Exact test (p=0.0001) (Table 1 a).

Table 1. Number of stands for which wind damage was observed and predicted by WINDA, respectively, in a. Asa Experimental Forest for two storms in January 1993 (From Blennow & Sallnäs, submitted). Here, a stand was considered damaged if at least ten trees were uprooted or broken. b. Björnstorp Estate for a storm on December 3, 1999.

a

		Predicted damage	
		No damage	Damage
Observed damage	No damage	276	5
	Damage	15	9

b

		Predicted damage	
O b		No damage	Damage
	No damage	155	45
	Damage	16	65

The Björnstorp Estate (55º37'N/ 13º24'E) holds about 1200 ha forest-land. A storm in December 1999 caused damage to 20% of the forest acreage (Blennow & Olofsson, submitted). A standard forest field inventory was made in 1999 before the storm. At this time, 44% of the estate was covered by forest vegetation dominated by Norway spruce (*Picea abies* (L.) Karst.). In the area, the topography is fairly level except from a pronounced ridge in the north-south direction. The surrounding terrain is open in character, predominantly with arable land. Wind data for the landscape was collected at a meteorological observing station at Sturup airport (55º32'N/ 13º22'E). During the peak of the storm no wind data were recorded due to malfunctioning instruments. Because of this, the wind direction was determined from the general direction of the fallen trees as observed in the field. The wind speed at Sturup airport was taken as 25 m^{-1}. During the storm a large number of stands were completely felled. Because of low resolution in input data up-wind of the study area, stands within some 300m of the southern fringe of the Björnstorp Estate were used to provide a belt of detailed information close to the study area. WINDA was run for the remaining stands of the estate for the tree species Norway spruce, Scots pine and birch. Model predictions were then compared with field-inventoried damage after the storm in 1999 (Figure 2b). In order to mimic exposed edges that were created during this severe and lengthy storm, WINDA was run twice. After the first run, stands in which damage was predicted was allowed to affect the input tree cover description for the second run of the model. This was made by complete removal of all trees in stands that were predicted damaged by WINDA. There was a statistically significant difference between the stands for which damage was predicted and a randomly selected set of stands as tested using Fisher's Exact test (p=0.0001) (Table 1b).

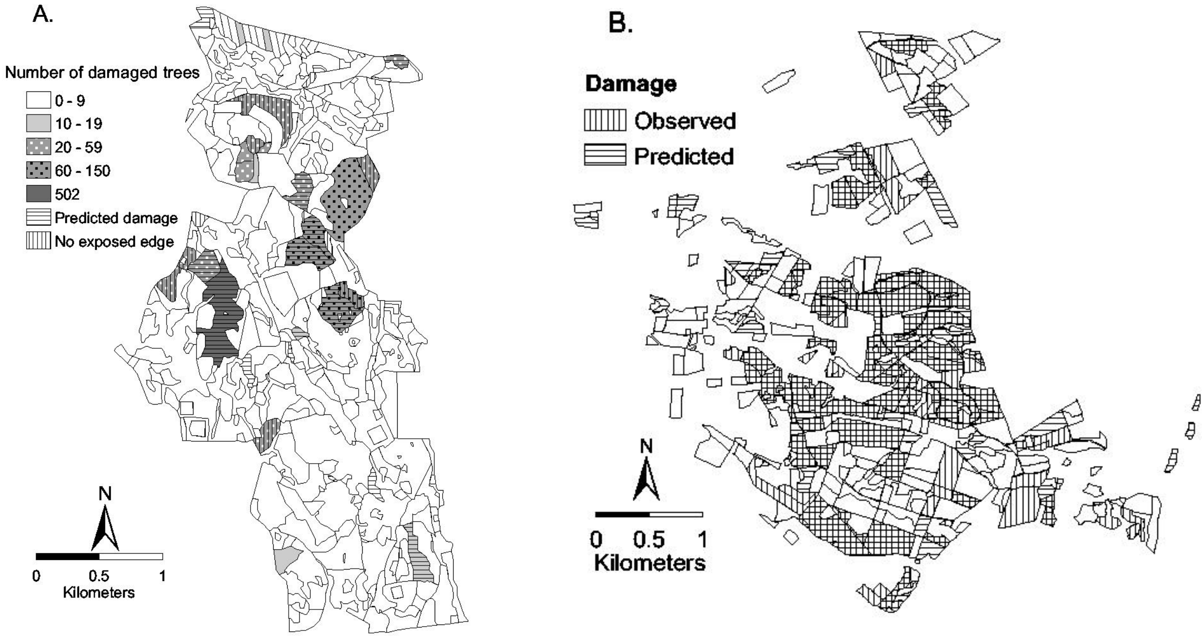

Figure 2: WINDA-predicted damage compared with observed damage for two landscapes in southern Sweden. a. Asa Experimental Forest after two storms in January 1993 (From Blennow & Sallnäs, submitted). B. The Björnstorp Estate before the storm on December 3, 1999, where only stands holding Norway spruce, Scots pine or Birch are included.

The probability of wind damage

The annual probability of wind damaged was calculated using WINDA for Asa Experimental Forest. A factor of 0.91 (Rathmann pers. commun., 2001) was used to compensate for a ten-minute averaging time for observed windspeed and to make these values compatible with the corresponding one-hour average values of critical windspeeds output by HWIND (Figure 3). The state of the forest in 1993 was used as above. Twenty-four years of wind data collected at Jön-köping Airport (57˚45'N/14˚04'E) were used. No obstacles were found in the vicinity of the mast according to a detailed airport map.

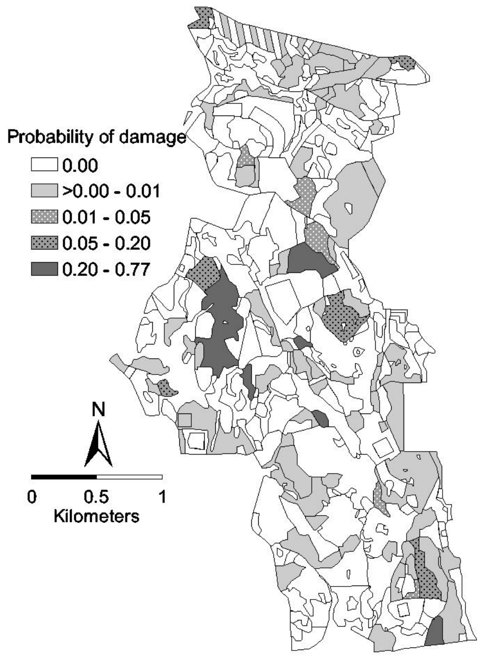

Figure 3. WINDA-calculated stand-wise probability of wind damage for Asa Experimental Forest, southern Sweden. (From Blennow & Sallnäs, submitted.)

Discussion

The mechanistic modelling approach allows both the input land-cover and wind climate to be manipulated in WINDA. This makes WINDA useful for evaluating effects on the probability of wind damage of silvicultural treatments and forestry activities as well as of a changed climate. WINDA differs in several respects to previous wind damage models. First, compared to the GALES model (Gardiner & Quine, 2000), WINDA is more general and can be applied to any landscape with reasonably level terrain such as that found in southern Sweden. Secondly, rather than using gridded output from an airflow model as Talkkari et al. (2000) did, or for conditions inside a stand, the wind climate predictions in WINDA are specifically made for points at exposed stand edges. This was motivated by the wind-load being highest at the stand edges and by the high sensitivity of airflow model output to the spatial resolution used, respectively (Walmsley & Taylor, 1996; Suàrez *et al*., 1999). Thirdly, WINDA uses the Gumble extreme value theory in calculating the probability of exceedance (Cook, 1985). This is preferable to using the parent distribution when estimating extreme values since this admits the use of a shorter time series of wind data for extreme-value estimation.

A major difficulty in evaluating WINDA is to find suitable data. First, digital forest inventory data may be difficult to find. To reduce errors from projecting forest inventory data, furthermore, the forest inventory data used must have been collected fairly close to the point in time when the storm occurred. Detailed mapping of the damage caused is needed and this must have been made shortly after the storm. The extent of damage should not be too large in order to test the predictive ability of WINDA. For fairly extensive damage such as that at the Björnstorp Esate, WINDA had to be run twice in order to mimic the formation of new edges during the storm. Although a shorter time series of wind data is required for predicting damage after a specific storm event, the requirements on wind data are in several ways higher than for calculating the probability of wind damage. This is because during a specific storm event spatial variation is present within the weather system causing the storm. Because of this, the meteorological observing station should be located close to the study landscape. These requirements may be hard to fulfill. So far, WINDA was evaluated for two landscapes.

WINDA was able to predict wind damage that compared reasonably well with observed wind damage for the two landscapes in southern Sweden. (Figure 2). For Asa Experimental Forest, the system of models was able to predict damage in all but one of the most severely damaged stands, *i.e*. in stands with 60 or more trees damaged. No statistically significant differences were found between observed and predicted damage for any of the two landscapes. This was the result although the shape of the wind profile was assumed logarithmic (Peltola *et al*., 1999). In reality, the shape of the wind profile at the forest edge depends on the permeability of the exposed forest (*e.g*. McNaughton, 1989). Although several different commercially available airflow models perform well and produce similar results, some differences remain between airflow model output and measured data, especially in steep and complex terrain (*eg*. Suárez *et al*., 1999). This is because in complex and steep terrain detachment of the airflow is expected to occur. Because of this, airflow models such as WASP are expected to perform even better in reasonably level terrain, such as that in southern Sweden. Fairly close correlations between observed extensive and predicted wind damage were found even if the distributed output from WASP for a specific strong wind occasion cannot be expected to be as good as that for a longer period of time (Suarez et al. 1999), such as the time period used in the calculations of probability. However, this could help explain some of the difference between observed and predicted damage (Figure 2).

Additionally, some differences between predicted and observed damage may be explained by the use of standard forest inventory data as input. Such data consists of representative values for whole stands. A particular stand may, however, have an uneven spatial distribution of trees and may include individual trees that are well or poorly represented by these data. In particular, at old stand edges, trees that are less well represented by the data can be found (Persson, 1975). Because of this, WINDA is expected to perform better in actively managed forests than in natural forests. The resistance to wind loading of individual trees may, furthermore, be reduced by fungal infection, and vary because of within-stand variation of rooting conditions *etc*. (Persson 1975). Parameter values for describing the anchorage of the trees in podzolic soil (moraine formation) have been used throughout the study landscape although variation in soil conditions is present. These variations were not accounted for as parameter values for these soil types were lacking. For Asa Experimental Forest, furthermore, the calculations were made on projected forest inventory data. This procedure inevitably introduces some errors in the description of the forest. In spite of these factors WINDA performed reasonably well and was able to correctly predict damage for all but one of the forest stands at Asa Experimental Forest in which extensive wind damage was observed.

In general, WINDA calculated higher probability of uprooting than of breakage (Figure 3). This is in accordance with windthrow being more common than breakage of trees in Sweden (Persson, 1975). In a test presented in Blennow & Sallnäs (submitted) WINDA output was most sensitive to increasing tree height, reduced diameter at breast height and the internal parameter critical windspeed.

To better be able to use WINDA to evaluate different silvicultural treatments and forestry activities and to produce decision support, it will be coupled with a dynamic landscape projection model. This model includes components such as a forest growth model, which is sensitive to different specified forest management programmes (Andersson & Dahlin, 2003). It will be run for a period of time of a few rotation periods. In this way we will explore if and how much the probability of wind damage can be reduced and what it costs. Tentative methods for reducing the probability of wind damage are choice of species, location, age at final felling, and felling order, and thinning regime. Furthermore, WINDA will be used for evaluating effects of climate change on the probability of wind damage. This will be done by feeding, WINDA with high-resolution climate change scenario data (SWECLIM, 1998) and compare with results of present day climate (Blennow *et al*. 2000).

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References

Andersson, M. & Dahlin, B., 2003. The forest time machine – a multi purpose forestry projection model system. In Vacik H. et al [eds.]: Decision support for multiple purpose forestry. A transdisciplinary conference on the development and application of decision support tools for forest management, April 23-25, 2003, Univ. Natural Resources and Applied Life Sciences, Vienna, Austria, CD-Rom Proceedings.

Anonymous, 2001. ArcInfo 8.1. ESRI Inc. Redlands, CA, USA.

Blennow, K., & Olofsson, E., submitted. Strong wind as hazard in forestry – a European perspective. Invited contribution to the IGU Commission on Climatology book on extreme winds.

Blennow, K., & Sallnäs, O., 2002. Risk perception among non-industrial private forest owners. Scandinavian Journal of Forest Research 17: 472–479.

Blennow, K., & Sallnäs, O., submitted. WINDA – a system of models for estimating the probability of wind damage to forest stands within a landscape. Submitted to *Ecological Modelling*.

Blennow, K., Rummukainen, M. & Sallnäs, O., 2000. Modelling the risk of windthrow in forestry under changing climatic conditions. In W. Cramer, R. Doherty, M. Hulme, and D. Viner (Editors) Proceedings of the workshop ECLAT-2, 'Climate scenarios for agricultural, ecosystem and biological impact', Potsdam, Germany, October 13-15, 1999. pp. 98–100.

Cook, N.J., 1985. The Designer's Guide to Wind Loading of Building Structures, Part 1. Butterworths, London. 371 pp.

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 and Management 135, 261–277.

Gardiner, B. A., Peltola, H., & Kellomäki, S., 2000. The development and testing of two models to predict the critical wind speeds required to damage coniferous trees. Ecological Modelling 129, 1–23.

Kristensen, L. Rathmann, O., & Hansen, S.O., 2000. Extreme winds in Denmark. Journal of Wind Engineering and Industrial Aerodynamics 87, 147–166.

Lieblein, J., 1974. Efficient methods of extreme-value methodology. Report NBSIR 74-602, National Bureau of Standards, Washington, DC., 31 pp.

Mortensen, N. G., Landberg, L., Troen, I. & Petersen, E. L., 1998. Wind Atlas Analysis and Application Program (WASP). Ris∅ National Laboratory, Roskilde, Denmark.

McNaughton, K.G., 1989. Micrometeorlogy of shelter belts and forest edges. Philosophical Transactions of the Royal Society of London, Series B, 324, 351–368.

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, 647–661.

Persson, P., 1975. Stormskador på skog – Uppkomstbetingelser och inverkan på skogliga åtgärder. (Windthrow in forests – It's causes and the effect of forestry measures. In Swedish, English summary.) Department of Forest Yield Research, Royal College of Forestry, Stockholm. Research Notes 36.

Quine, C.P., 2000. Estimation of mean wind climate and probability of strong winds for wind risk assessment. Forestry 73, 247–258.

Raupach, M. R., 1992. Drag and drag partition on rough surfaces. Boundary-Layer Meteorology 60, 375–395.

Raupach, M. R., 1994. Simplified expressions for vegetation roughness length and zero plane displacement as functions of canopy height and area index. Boundary-Layer Meteorology 71, 211–216.

Schelhaas, M-J., Nabuurs, G-J., Schuck, A., submitted. Natural disturbances in the European forests in the 19th and 20th centuries.

Suárez-Minguez, J.C., Gardiner, B.A. and Quine, C.P. 1999. A comparison of methods for predicting wind speeds in complex forested terrain. Meteorological Applications 6, 1-14.

SWECLIM, 1998. Regional climate simulations for the Nordic region – first results from SWECLIM. Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.

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 and Management 135, 303–313.

Valinger, E. & Fridman, J., 1997. Modelling probability of snow and wind damage in Scots pine stands using tree characteristics. Forest Ecology and Management, 97, 215–222.

Walmsley, J.L., & Taylor, P.A., 1996. Boundary-layer flow over topography: impacts of the Askervein study. Boundary-Layer Meteorology 78, 291–329.