Supporting Management of the Risk of Wind Damage in South Swedish Forestry

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Abstract

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Private forest owners in southern Sweden consider wind damage to be one of the most problematic risks from an economic perspective. A potential climate change also raises the question of the possible impact of such a climate change on the risk of wind damage. Taking into consideration the spatial aspects, and the uncertain occurrence of windstorms over time and in space, this thesis aims at providing information to support the management of the risk of wind damage in south Swedish forestry. Computer models were used to assess the probability of wind damage to forest stands, and to project forest stands within case study landscapes in southern Sweden.

Although the topography is relatively gently in southern Sweden, it significantly influences the probability of wind damage on a landscape scale. A possible cost-effective means to manage the risk of wind damage can be to target risk-reducing forestry measures to topographically induced wind exposed locations. To support the targeting of risk-reducing forestry measures a tool was constructed, accounting for different risk-preferences among forest owners, for the identification of stands with a high probability of wind damage. The results emphasize the possibility to reduce the risk of wind damage by spatial forestry planning, taking wind shelter from topographic features and surrounding stands into consideration.

Based on regional climate change scenarios, it cannot be ruled out that a climate change can lead to an increasing probability of wind damage in southern Sweden. In southernmost Sweden, a climate change very likely can lead to an increasing probability of wind damage. With implications for spatial forestry planning, the probability of strong wind from the sector west to southwest is indicated to remain comparatively high. Shortening the lengths of rotation periods appears to be one possible means for forestry in southern Sweden to adapt to climate change.

Keywords: decision support, uncertainty, probability, wind climate, tree growth, forest management, spatial planning, topography, climate change, adaptation.

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Contents

Appendix

Papers I-IV

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals:

I. Olofsson, E. & Blennow, K. Topographical influences on the probability of wind damage to south Swedish forest landscapes. Manuscript.

II. Olofsson, E. & Blennow, K. 2005. Decision support for identifying spruce forest stand edges with high probability of wind damage. *Forest Ecology and Management 207*, 87-98.

III. Blennow, K. & Olofsson, E. The probability of wind damage in forestry under a changed wind climate. *Climatic Change*. Submitted.

IV. Olofsson, E., Andersson, M., Bergh, J., Blennow, K. & Sallnäs, O. Climate change and the risk of wind damage to forests in a south Swedish landscape – impacts and possibilities for risk reduction. *Canadian Journal of Forest Research.* Submitted.

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In Paper III editorial revisions have been made.

Introduction

Several times during the last century, European forests have been subject to extensive wind damage events, with a trend of increasing damage during the last decades (Schelhaas, Nabuurs & Schuck, 2003). A similar tendency has been found for Sweden, and furthermore such events are more common in southern than in northern Sweden (*e.g.* Nilsson *et al*., 2004). In Europe, windstorms in 1990 and in 1999 blew down approximately 115 and 190 million cubic meters of timber, respectively (UNECE/FAO, 2000), and in southern Sweden in January 2005, a single storm caused damage to an amount of timber corresponding to nearly an entire year's cutting volume for the whole country (Anon., 2006). By the choice of tree species, silvicultural treatments and forestry planning it is possible to actively manage the risk of wind damage (Moore & Quine, 2000). However, in southern Sweden only one third of the private forest owners apply forestry measures with respect to the risk of wind damage, even though they consider wind damage to be one of the most problematic risks from an economic perspective (Blennow & Sallnäs, 2002). The climate is expected to change due to anthropogenic forcing (IPCC, 2001) which could mean stronger or more frequently occurring windstorms (Räisänen *et al.*, 2004), and changes in other climate elements that could affect the resistance of the forests to wind (Quine & Gardiner, 2002). This might have an impact on the future probability of wind damage and have implications for the management. A majority of the private forest owners in Sweden also believe that climate changes might affect their forests, whereas a minority adapt forestry e.g. because of uncertainty about what forestry measures to apply (Petersson, 2004). To support active risk management in south Swedish forestry one way could be to provide information on the probability of wind damage under a present and under a changed climate, and information on possible ways it could be handled.

Forestry in southern Sweden

Southern Sweden corresponds in this thesis to the Götaland region (Fig. 1). Here a comparably gentle topography and a mixture of arable land and forests characterize the landscapes. The main tree species are Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.), and birch (*Betula pendula* Ehrh. and *Betula pubescens* Roth.). The forest land is owned by state organisations, forest companies and private persons. Private holdings, on average about 30 hectares in size, constitute 77% of the productive forest area (Anon., 2005).

Swedish forests have traditionally been seen as a national resource that should be managed for sustainable timber production. The forest industry, including pulp and sawmills, make an important contribution to Swedish economy. The majority of the forestland in southern Sweden has thus been used for timber production, and the standing volume of timber in the forests has increased during the past decades (Anon., 2005). The forestry is characterized by high efficiency and a high degree of mechanization; the clear-felling system is the dominating management system today. In the last revision of the Forestry Act in 1994 it is stated that Swedish forests "shall be managed in such a way as to provide a valuable yield and at the same time preserve biodiversity. Forest management should also take into account other public interests" (Anon., 1994). Legislation, taxes and subsidies are used to direct forest owners' management at the national forestry goal (Anon., 2001a). In the last revision, legislation became less detailed, and forest owners now have more freedom and own responsibility within their forestry.

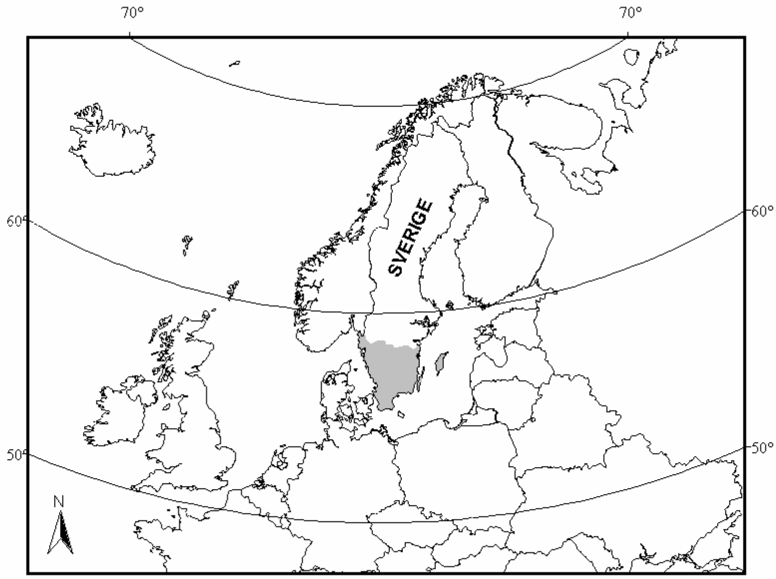

Fig. 1. The Götaland region of Sweden, shaded in grey.

Policy instruments, e.g., education and consultation, are used to support private forest owners' management decisions (Anon., 2001a). For example courses, meetings, magazines and web-pages organized and published by forestry organisations and agencies can provide valuable information. In a survey it was found that about 73% of the private forest owners in the county of Småland in southern Sweden are provided with information on management through forestry counsellors (Blennow, pers. commun., 2006). An important tool supporting management can also be the forest management plan, which is produced by different forestry organisations. A forest management plan gives a picture of the conditions on the property and provides management proposals (Anon., 2001b).

Private forest owners are a heterogeneous group having different and multiple objectives with their forestry. In an enquiry it was found that 77% of Swedish private forest owners considered timber production to be important (Mattson, Boman & Kindstrand, 2003). Apart from timber production they are also concerned with values of conservation and amenities (Mattson, Boman & Kindstrand, 2003; Hugosson & Ingemarsson, 2004). Changes in society and forest ownership structure have resulted in a reduced proportion of private forest owners living on their estates, and in a reduced proportion that are directly dependent on the income from the forest (Törnqvist, 1995).

The risk of wind damage in southern Sweden

Since the beginning of the 20th century, storm events in 1954, 1969, and in 2005, stand out as being the most extensive ones in terms of the volume timber being damaged in Sweden (Fig. 2). On average 4 million cubic meters of timber are damaged annually by wind and snow (Valinger & Fridman, 1995). As a reference the current annual cutting volume for the whole of Sweden is some 80 million cubic meters of timber (Anon., 2005). The increased number of events of extensive wind damage that have taken place during the past century could be explained by several factors. There is no clear evidence of an increasing frequency of storms during this period (Alexandersson *et al*., 2000). Instead the increasing wind damage can be explained by the changes in the state of the forests: the increased standing volume of timber, and the increased practicing of the clear-felling system (Blennow & Olofsson, 2004), of which the clear-felling system creates forest edges, and wind turbulence (Morse, Gardiner & Marshall, 2002). Furthermore there has been an increased use of Norway spruce, which is relatively vulnerable to wind (Persson, 1975; Peltola *et al*., 2000).

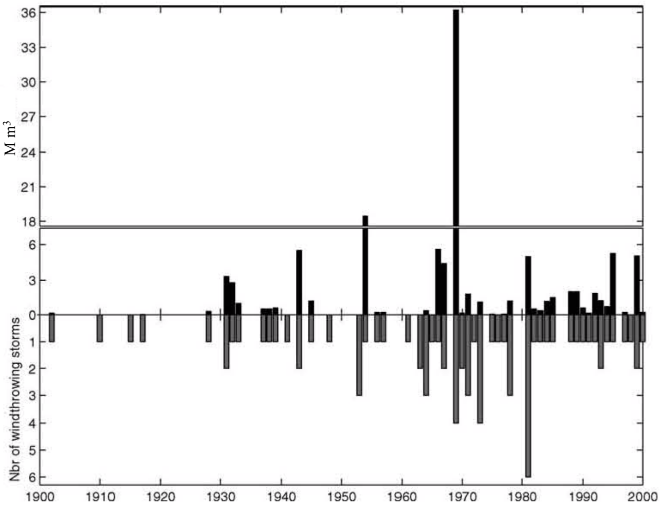

Fig. 2. During the period 1901-2000, the annual total wind damaged volume in cubic meters of timber in the upper part (M m^3), and the annual total number of recorded forest damaging storms in the lower part. Note the break at 7.5 M m^3 on the upper axis. From Nilsson *et al*. (2004).

On the national scale there is a spatial variation in the probability of wind damage. This is partly explained by spatial variation in wind climate, with a pattern of higher probability of high wind speeds in southern Sweden compared to northern Sweden (Raab & Vedin, 1995; Nilsson *et al*., 2004). In southern Sweden weather-systems that may generate strong winds, are more common during autumn and winter, and often associated with easterly moving cyclones. There is also spatial variation in the probability of wind damage on a landscape scale due to variation in wind exposure and forest states. Wind exposure on a site is a result of the wind at ground level being modulated by changes in surface roughness, topography, and forest structures. Forested areas of higher roughness slow down surface wind speed more than do arable land and water. Complex topography can influence wind exposure on different spatial scales (Miller, Quine, & Hunt, 1987). Topographic features cause wind speed-up effects over hills, ridges, and escarpments and on lee-sides there could be increased wind turbulence (Walmsley & Tayler, 1996; Ruel, Pin & Cooper, 1998; Suárez, Gardiner & Quine, 1999), and wind shelter. Locally clear-fellings increase wind exposure of adjacent forest edges (Alexander, 1964; Venäläinen *et al.*, 2004; Zeng *et al.*, 2004). Forests' vulnerability to strong wind varies for example with tree species, tree height, stem taper and stand density (*e.g.* Persson, 1975; Cremer *et al.*, 1982; Lohmander & Helles, 1987; Blackburn & Petty, 1988; Gardiner *et al.*, 1997). Newly thinned stands and stands with newly created edges are especially vulnerable to strong winds (Persson, 1975; Cremer *et al.*, 1982; Lohmander & Helles, 1987).

For forest owners wind damage could have implications for the timber production (Manley & Wakelin, 1989), conservation (Ulanova, 2000), and amenities. Direct effects can be increased harvesting and transportation costs, quality downgrade of saw log (Nieuwenhuis & O'Connor, 2001), and reduced timber prices (UNECE/FAO, 2000; Anon., 2006). It can result in clear-fellings, which compared to standing forests are less appreciated for recreation (Lindhagen, 1996). Windstorms can also hinder electricity supply and communications. Indirectly, extensive wind damage can increase the risk of insect attacks, because of an increased amount of breeding material (Schroeder & Lindelöw, 2002). In Sweden it is possible to partly compensate for this, with insurance for loss of destroyed timber and non-optimal harvests.

The risk of wind damage under a changed climate

The climate is expected to change due to anthropogenic forcing (IPCC, 2001). For Sweden dynamically downscaled regional climate scenarios for the period 2071-2100 have been produced at the Rossby Centre, of the Swedish Meteorological and Hydrological Institute (Rummukainen *et al.*, 2004). They are initialized using boundary conditions from two global climate models (Roeckner *et al.*, 1999; Pope *et al.*, 2000), respectively, and have been run using the forcing from two different greenhouse gas emission scenarios (Nakicenovic *et al.*, 2000). According to these scenarios the Swedish climate will on average be warmer; precipitation is expected to increase during the winter months, whereas the amount of snow and soil freezing is expected to decrease (Räisänen *et al.*, 2004). The characteristics of various extreme weather events are also expected to change, which could mean for example stronger and more frequently occurring windstorms (Räisänen *et al.*, 2004). In Sweden during the period 1991-2000, in line with the scenario results, the annual mean temperature has increased by 0.8°C and precipitation by 6% compared to the period 1961-1990, which is suggested as being an effect of both natural climate variability and anthropogenic forcing (Räisänen & Alexandersson, 2003).

These predicted climatic changes could have an impact on the forest ecosystem and on forestry (Sonesson *et al.*, 2004). Unless the vulnerability of the forests is changed, a changed wind climate could mean increased wind exposure and an increased probability of wind damage. However, a climate change may also influence other climate elements that indirectly could affect the probability of wind damage (Quine & Gardiner, 2002). Furthermore, reduced soil-freezing could result in weaker tree anchorage during frost-free soil conditions. Simulations for Scots pine in Finland indicate an increasing length of the frost-free period (Peltola, Kellomäki & Väisänen, 1999; Venäläinen *et al.*, 2001a, b) increasing the probability of windthrow. As an effect of increased temperature tree growth has been predicted to increase in Sweden (Bergh *et al.*, 2003). This will render trees vulnerable to wind at an earlier age, and could increase the probability of wind damage by the longer time the vulnerable trees are exposed to the wind.

Risk management

Since management decisions involve the future they also involve risks (Kangas & Kangas, 2004). This can be due to incomplete knowledge (Sahlin & Persson, 1994), genuine uncertainty, and due to the uncertainty of what is valued the most from the forest (Blennow & Sallnäs, 2005). Decisions for the management of the risk of wind damage will involve genuine uncertainty, due to the randomness of the occurrence of windstorms. A forest owner may want to decide what tree species to use in a plantation. For example compared to birch, Norway spruce could be expected to result in a higher production (Fries, 1964; Eriksson, 1976; Bergquist *et al.*, 2005), and at the same time a higher risk of production loss due to wind damage (Persson 1975; Peltola *et al.*, 2000). In this situation the forest owner has to weigh the expected utilities and the risks brought about by these two alternatives.

Risk can be valued different by different decision-makers (Weiss, 2001). Valuation of risk is influenced for example by perceived lack of control and catastrophic potential (Slovic, 2000). What level of risk is acceptable is determined by the decision-makers risk-preferences. Due to varying risk-preferences a distinction can be made between risk-seeking, risk-neutral and risk-aversive decision-makers. The risk of wind damage may be considered small at a national forestry scale, since when large areas and long time perspectives are considered, effects of extensive wind damage in terms of destroyed timber and reduced production may be small. For private forest owners who consider smaller areas, and shorter time perspectives (Lönnstedt, 1997), extensive wind damage could be of significant importance and the risk of wind damage may be considered high.

This was illustrated by calculations made by Nilsson & Sallnäs (2006). They included the risk of wind damage in calculations of the expected utility (average cash flow) for two spruce, S3 and S1, and one birch, B3, management programmes, respectively, applied within southern Sweden. S3 included three thinnings and final felling at age 75, S1 included one thinning and final felling at age 65, and B3 three thinnings and final felling at age 60. For the whole Götaland region for long-term simulations, and a return period of wind damage of 20 years, S3, in line with present Swedish forestry policy, resulted in the highest expected utility. For smaller areas and for 25-year periods, S3 and S1 resulted in similar aggregated expected utilities and would be about equally good alternatives for risk-neutral decision-makers (Fig. 3). For risk-aversive decision-makers S1 would be a better alternative than S3, and B3, which resulted in the highest minimal expected utility for any 25-year period, would be the best alternative. According to traditional decision theory risk-aversive decision-makers make decisions to maximize the minimal expected utility (Gärdenfors & Sahlin, 1988).

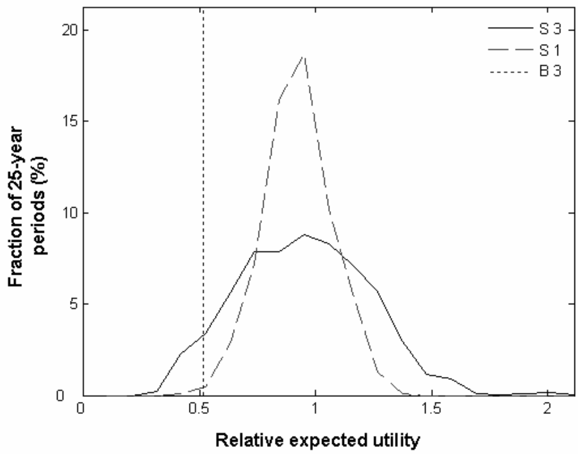

Fig. 3. Fraction of 25-year-periods for different relative expected utilities calculated for the management programmes, S3, S1, and B3, for a return period of wind damage of 20 years, respectively. Based on Nilsson & Sallnäs (2006).

Risk management involves decisions to reach an acceptable level of risk. The risk of wind damage can for example be managed by the choice of tree species, the choice of tree spacing, thinning regime, and the time and order of final fellings (*e.g.* Persson, 1975; Somerville, 1980; Savill, 1983; Lohmander & Helles, 1987; Gardiner *et al.*, 1997; Meilby, Strange & Thorsen, 2001). According to Persson (1975), for Swedish conditions for example the choice of more wind-firm tree species, a reduced density of plantations, the avoidance of thinnings in older stands, and the spatial planning of final fellings considering prevailing wind directions are possible means to reduce the risk of wind damage. A cost-effective method to manage the risk of wind damage could be to target these risk-reducing forestry measures to locations or stands with a high probability of wind damage.

Support for risk management

One way to support management is to provide information on the probability of wind damage to forests, and information on how it could be handled. For example various tools have been developed for the identification of wind exposed sites (*c.f.* Hannah, Palutikof & Quine, 1995), and vulnerable stands (*c.f.* Fraser, 1965; Smith *et al*., 1987). In Britain, the “Windthrow Hazard Classification” (Booth, 1977; Miller, 1985) was developed to help classifying sites with respect to the risk of wind damage, in order to guide decisions on thinning strategies and rotation lengths (Quine, 1995). In Canada, frameworks have been developed for ranking sites in risk classes to guide management (Ruel, 1995; Mitchell, 1998). To provide probability assessments, logistic regression models have been developed (*e.g.* Lohmander & Helles 1987; Jalkanen & Mattila, 2000; Ni Dhubhain, 2001; Scott & Mitchell, 2005), and for Swedish conditions, for assessing the probability of wind and snow (Valinger & Fridman, 1997; Fridman & Valinger, 1998).

Probability assessments can also be provided using a mechanistic approach. Then critical wind speeds that cause damage to trees are predicted (*e.g.* Peltola *et al*., 1999; Ancelin, Courbaud & Fourcaud, 2004; Achim *et al*., 2005). By combining critical wind speeds with wind data, the probability of wind damage to the trees can be assessed (Moore & Somerville, 1998; Gardiner & Quine, 2000; Talkkari *et al*., 2000; Blennow & Sallnäs, 2004; Zeng *et al*., 2004). For example, for British forestry the model ForestGALES (Gardiner, Peltola & Kellomäki, 2000; Gardiner & Quine, 2000) has been developed, and can be used to evaluate the effects of different management strategies (Cucchi *et al*., 2005). DAMS scores provide a measure of the wind exposure at a site (Quine, 2000), and it is being integrated with a GIS to make it possible to use the model on a landscape scale (Gardiner, Suárez & Quine, 2003). For south Swedish conditions WINDA (Blennow & Sallnäs, 2004) was developed for assessing the probability of wind damage to forest stands within landscapes. Wind exposure is estimated with the airflow model WASP (Mortensen *et al*., 1998). It is integrated with a GIS, and it accounts for winds from different direction sectors. Due to the amount of input data required, these types of models in general might be too time-consuming for direct use within small-scale practical forestry.

In Sweden so far, information to support the management of the risk of wind damage has primarily been received from observations of wind damage to forests over relatively short time periods or observations of wind damage to forests of specific storm events (*e.g.* Werner & Årmann, 1955; Carlquist, 1972; Persson, 1975). The extent of wind damage has been attributed e.g. to stand characteristics, and the management has concentrated on stand-level forestry measures to increase the resistance of forest stands to wind (*c.f.* Werner & Årmann, 1955; Persson, 1975). However, in addition to the characteristics of a stand itself, the probability of wind damage depends on the characteristics of its surroundings, which means that in addition to stand-level forestry measures, spatial forestry planning would be a possible means in south Swedish forestry to reduce the risk of wind damage. Furthermore, the management of the risk of wind damage is about to handle the uncertain occurrence of windstorms over time and in space. In this respect, a potential future climate change might have an impact on the occurrence of windstorms, and also on the trees resistance to wind. In order to provide information to support the management of the risk of wind damage in south

Swedish forestry, these aspects could also be considered, and for this the model-system WINDA could provide a useful tool.

Objectives

This thesis aims at providing information to support the management of the risk of wind damage in south Swedish forestry. Specifically, the objectives are to:

- assess topographical influences on the probability of wind damage to forest landscapes in southern Sweden,
- construct a simple-to-use tool, accounting for different risk preferences among decision makers, for the identification of spruce stand edges of high probability of wind damage,
- assess the probability of damaging wind speed over Sweden under a changed climate and its implications for spatial forestry planning,
- assess the probability of wind damage in a south Swedish landscape under a changed climate and,
- evaluate the modifications of the length of the rotation period as one example of how to adapt forestry to climate change.

Materials and methods

Case study landscapes

Four case study landscapes were used representing different wind climates, topography, and forest states in southern Sweden. They were partly selected due to the existence of digitised stand data. Two of the landscapes are located in the southern part of the Götaland region, and two of the landscapes are located in the northern part (Fig. 4). In the Götaland region there is a comparable high probability of high windspeed from the westerly to the southwesterly direction sector (Raab & Vedin, 1995).

The Björnstorp estate (55º37'N/13º24'E) considered in papers I and II covers an area of 2690 hectares of which 45% is forestland. The most common species is Norway spruce. Other important tree species are birch, beech (*Fagus sylvatica* L.), and oak (*Quercus* spp.). The surroundings are predominantly open arable land. Within the landscape a pronounced ridge runs from the north to the south. Wind data for Björnstorp was collected at a meteorological observing station at Sturup Airport (55º54'N/13º37'E) located about 7 km south of the estate (Fig. 4). The wind data consisted of 10 minute average wind speed and hourly wind direction at 10 m above the ground for the period 1972–1991.

The estate of Fulltofta (55º53'N/13º39'E) used in paper I covers an area of about 2060 hectares. About 90% is forested, consisting mainly of stands of Norway spruce, birch, and beech. Forests to the north and to the east cover the surrounding terrain. To the south open arable land and to the west the lake Ringsjön is found. The topography of the landscape is relatively gentle. Wind data was collected at the meteorological observing station at Sturup Airport located about 50 km south of the estate.

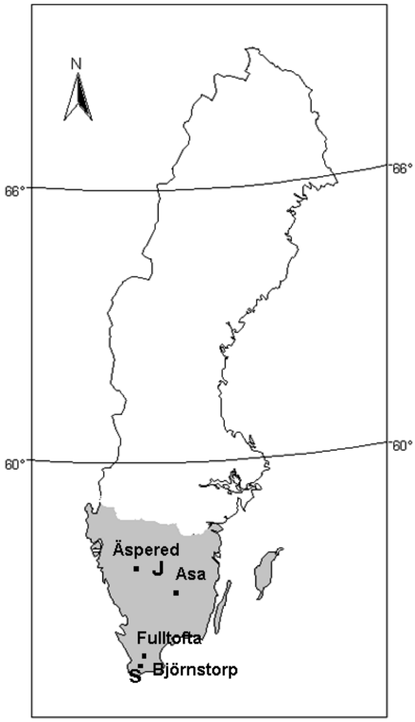

Fig. 4. Location of the case study landscapes and the meteorological observing stations at Sturup Airport (S) and Jönköping Airport (J) within the Götaland region of Sweden.

The landscape of Asa (57º10'N/14º47'E), used in paper I, covers an area of 3300 hectares of about 87% is forestland. Within the landscape of Asa is found Asa Experimental Forest, used in papers II, III, and IV, which covers about 728 hectares of which approximately 90% is forestland. For the whole area the main tree species are Norway spruce, Scots pine, and birch. Forests predominantly cover the surrounding terrain, except to the east where the lake Asasjön is located. Topography is hillier compared to the southernmost landscapes. Wind data was collected from a meteorological observing station at Jönköping Airport (57º75'N/14º07'E) about 70 km northwest of the landscape. The wind data consisted of 10 minute average wind speed and hourly wind direction at 10 m above the ground for the period 1968–1991.

The landscape of Äspered (57º45’N/13º12’E) used in paper I covers an area of about 2600 hectares of which approximately 70% is forestland. The dominating tree species are Norway spruce and birch. The surrounding terrain is predominantly forest covered, except to the east where the lake Tolken is located. Topography is characterized by fissure valleys elongated in the north-east to the south-west direction. Wind data from the meteorological observing station at Jönköping Airport about 50 km west from the landscape was used.

WINDA

The model system WINDA (Blennow & Sallnäs, 2004) was used for assessing the probability of wind damage to forest stands within the case study landscapes. WINDA developed to be used within landscapes of conditions similar to those found in southern Sweden. The term landscape here means an area of a few km^2 to a few tens of km^2. Fundamental assumptions are that within a landscape the weather-system is the same, and that wind damage is being initiated at forest stand edges. So far, WINDA has been evaluated for two landscapes in southern Sweden and compared well with the observed damage (Blennow, Olofsson & Sallnäs, 2003; Blennow & Sallnäs, 2004).

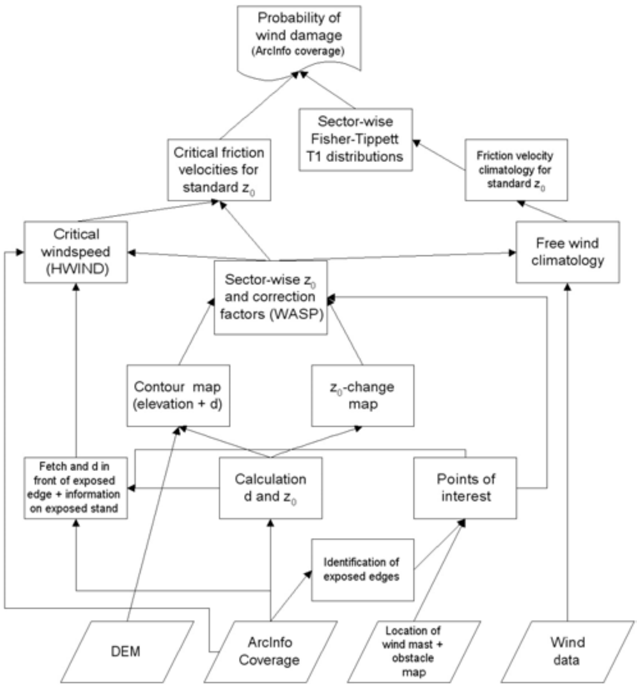

Fig. 5. Schematic structure of WINDA. From Blennow & Sallnäs (2004).

WINDA is integrated with a GIS and consists of a set of model components that assess the risk of wind damage from calculations of tree stability and wind forces at exposed stand edges (Fig. 5). Within a landscape WINDA identifies wind exposed stand edges at least 10 m high. Along these edges points are determined with a distance of 50 m between them. The wind was divided into six direction sectors, which corresponds to each point being assumed to be exposed to wind from directions within ±30º from the direction perpendicular to the edge.

For each point the trees' resistance to uprooting and stem breakage, respectively, is calculated with a modified version of HWIND (Blennow & Sallnäs, 2004), which makes it possible to account for variation in conditions in front of an exposed edge. In HWIND (Peltola *et al.*, 1999) the forces acting upon a tree are divided into a horizontal force due to the wind and a vertical force due to gravity. 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 resistance to uprooting is predicted from an estimate of the root-soil plate weight. A tree is assumed to overturn if the maximum turning moment exceeds the support provided by the root-soil plate anchorage. The maximum turning moment a tree can withstand without stem breakage 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 stem breakage, respectively.

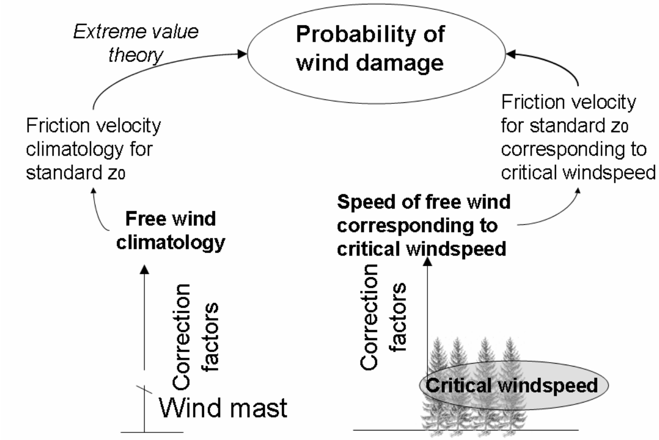

Fig. 6. Conceptual model of the calculation of the probability of wind damage in WINDA. From Blennow & Sallnäs (2004).

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 the effects of obstacles, roughness changes (z_0) and orography (Fig. 6). The cleaning is made using sector-wise values of z_0 and correction factors. The data is then converted from windspeed to friction velocity. The sector-wise values of z_0 and correction factors are used to link the corresponding critical windspeeds and directions to the free-stream wind with the windspeed values and is expressed as friction velocities for a standard roughness length. The annual probability of exceedance for the critical friction velocity is calculated using the extreme value theory according to Gumble (1958). The annual probability of wind damage for each stand is calculated from the sector-wise maximum of the largest of the probabilities of uprooting and stem breakage among the points of the stand.

Wind climate scenario data used in papers III and IV were produced using the RCAO model (Döscher *et al.*, 2002), which does not include a model for the gustiness of the wind and produces values representative for areas rather than points. This means that high windspeeds are underestimated in simulated surface wind compared to observed data (Meier *et al.*, 2006). Gustiness is a feature of the surface wind and not of the wind above the boundary layer, and WINDA was modified in paper III to run on geostrophic windspeed, i.e., the wind above the boudary layer, rather than on surface windspeed. In the modified version of WINDA, the critical windspeeds calculated by HWIND are expressed as critical friction velocities and then subsequently linked to geostrophic windspeeds, according to methods in Kristensen, Rathmann & Hansen (2000). The annual probability of exeeding the critical geostrophic windspeed is calculated, rather than the probability of exceeding the critical friction velocity.

For running WINDA, input information on each case study landscape and its surrounding were kept in an ArcInfo polygon coverage (Anon., 2001c). Stand-level data used were tree height, diameter at breast height, and the number of stems per hectare for each species. The surroundings were described by four roughness-length classes by assigning polygons values of z_0 and displacement heights, d. Values of z_0 were assigned according to Mortensen *et al*. (1998) and values of d according to 80% of the estimated height, based on information from standard topographic maps. Observed wind data was input as time series of wind speed and wind direction, collected at the meteorological observing stations, respectively. Wind climate scenario data was provided as gridded model outputs of 49 km resolution. Wind speed at the 850 hPa surface level was used as a proxy of the geostrophic wind speed, while wind direction calculated at 10 m above the ground was used. Additional input was values of z_0 and d of the landscapes of the meteorological observing stations. For all landscapes, information on topography was obtained from digital elevation models of 50 m resolution.

The Forest Time Machine

The empirically based projection model Forest Time Machine (FTM) (Andersson, Dahlin & Mossberg, 2005) was used in papers I and IV, for simulating the development of the forests within the case study landscapes. For Swedish conditions the FTM system was primarily developed to support the evaluation and comparison of management strategies on a landscape scale. The system includes modules for tree growth, regeneration, mortality, decay of dead wood, forestry operations, economics, nutrient balances, and biodiversity indicators. So far, it has for example been used to simulate and evaluate long-term consequences on forest productivity and nature conservation (Agestam *et al.*, 2002; Ask & Andersson, 2002; Andersson, Sallnäs & Carlsson, 2005).

It is a spatially explicit system, which makes it possible to take into account spatial interactions between forest stands. The FTM-system uses the stand as the smallest geographical unit and simulations are made in time-steps of five years (Fig. 7). Depending on which modules to use in the simulations, the FTM system requires different input data. In papers I and IV, the regeneration, tree growth, mortality, and forestry operations modules were used. For any module stand-level data on e.g. site index, vegetation class and soil type is used as input. In addition, stand-level data on age, tree height, diameter at breast height, the number of stems per hectare, basal area, and regeneration method is input for each tree species. The user controls management by specifying management programmes and assigning them to the forest stands in the database. Regeneration, pre-commercial thinning, commercial thinning, final felling, and shelter felling can be applied. In addition, the user can set a number of variables that control the treatments at stand-level, e.g., the proportion of tree species to achieve after thinnings, the intensity of thinnings, and the time of final fellings.

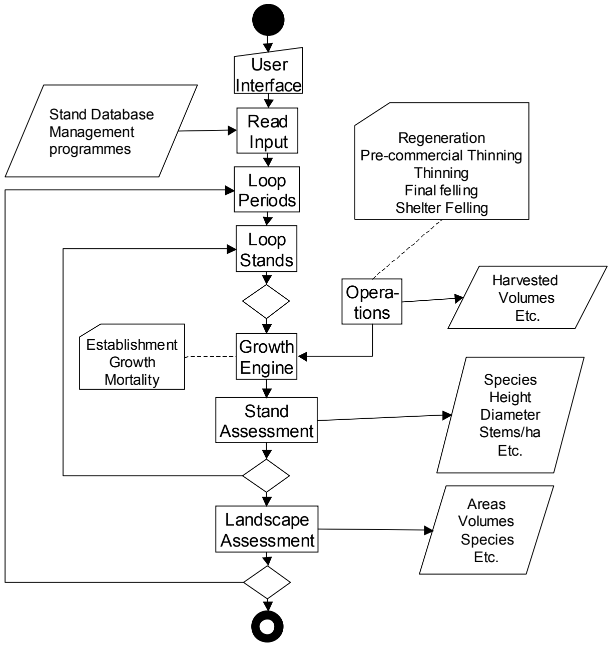

Fig. 7. Schematic structure of the FTM system. Simulations are made in time steps of five years (periods).

Forest stands are divided into different development phases; young forest, wood production, seed/shelter tree, retention tree, or dead tree. For the young forest phase growth is estimated as the time for the trees to reach 8 m. The wood production phase is defined as the period during which trees grows from 8 m in height to final felling. In this phase basal area and volume growth are estimated with a model developed by Ekö (1985), which can handle different tree species and tree species compositions of stands. An important variable for predicting tree growth and management treatments in simulations is site index. For each five-year period in simulations outputs are, on the landscape- and stand-level for example standing volume and species composition. On the stand-level output are age, tree height, diameter at breast height, the number of stems per hectare, and basal area for each tree species.

In paper IV a module was included in the FTM system to make it possible to modify tree growth during simulations, due to a changing climate. In this module the user can for different tree species specify a predicted relative change in productivity for a specified simulation length. The relative change in productivity is used to continuously modify site indices of stands during simulations. Established relationships between site quality and SI for Norway spruce and Scots pine (Hägglund, 1981), birch (Fries, 1964), and beech and oak (Carbonnier, 1971, 1975) were used to link a relative change in productivity with SI. Additionally, in paper IV, sub-models were constructed to link projected forest stands in the FTM system to WINDA for probability assessments.

Climate change scenarios

Regional climate change scenarios were provided from the Rossby Centre at the Swedish Meteorological and Hydrological Institute (Rummukainen *et al*., 2004). They have been produced with the RCAO model (Döscher *et al*., 2002) for a control period 1961–1990 and for the scenario period 2071–2100. Global climate change scenarios have been produced by the two global climate models (GCMs); ECHAM4/OPYC3 (Roeckner *et al*., 1999) from the Max-Planck Institute of Meteorology in Germany and HadAM3H (Pope *et al*., 2000) from the Hadley Centre in the UK (Fig. 8). Regional climate scenarios for Sweden have been made by regionally downscaling of the global climate driven by the two GCMs, respectively. Each of the two GCM driven scenarios has been forced with two different greenhouse gas emission scenarios, respectively. They are denoted SRES B2 and A2 and represent a moderate and a rather high greenhouse gas emission scenario (Nakicenovic *et al*., 2000). The different levels of greenhouse gas emissions are due to differing underlying assumptions on for example technology development, economy, and global population growth rate. The B2 scenario is for a world with an increasing global population, but at a rate that is lower than under A2, lower energy intensity, and a smaller share of coal in primary energy. In general, the magnitude of calculated changes in climate variables increases with the forcing going from B2 to A2.

Global climate models	ECHAM4/OPYC3	HadAM3H
Emission scenarios	B2 A2	B2 A2
Regional climate change scenarios	RE control RE B2 RE A2	RH control RH B2 RH A2

Fig. 8. Matrix of the global climate models and the emission scenarios of the regional climate change scenarios for Sweden.

Summary of the papers

Paper I

This study was performed to assess the topographical influences on the probability of wind damage for south Swedish landscapes. Topographically induced wind exposed locations within landscapes were explored. The four case study landscapes were used (Fig. 4). For the estates of Björnstorp and Fulltofta, and for the landscapes of Asa and Äspered, respectively, the same wind climatology was used.

For each case study landscape, approximately 1000 hectares were selected and used in the analyses. To create similar conditions of the landscapes, each landscape was assigned a similar forest. The existing stand boundaries within the landscapes were kept. The development of an, for south Swedish conditions, ideal Norway spruce stand was simulated for 75 years with the FTM system. A site index (H 100) of 28 m was assumed for the spruce stand, and a management programme was specified including one pre-commercial thinning and two medium intensive commerial thinnings. Outputs of tree height, diameter at breast height, and the number of stems per hectare were then used in regression analyses to fit each of the variables to stand age. Within each landscape, the forest stands were assigned random numbers (new stand ages) between 1 and 75, and the relationships derived in the regression analyses were used to calculate new stand variables of the stands.

To reduce the effects of the spatial distribution of stands of different tree sizes on the probability of wind damage, the stands, i.e., the contents (tree height, diameter at breast height, and the number of stems per hectare) of polygons were spatially randomized. The forest stands were randomised thirty times, and for each of them the annual probability of wind damage of each forest stand was assessed with WINDA. Based on results from the randomizations, under the assumption that wind damage in a stand means that all trees in the stand are damaged, the annual expected relative area of wind damage (RA) was calculated for each landscape. The RA of the estates of Björnstorp and Fulltofta of similar wind climatology was compared, and correspondingly the RA of the landscapes of Asa and Äspered. Topographically induced wind exposure was explored within each landscape by analyzing the forest stands that for at least one of the randomizations were assessed a probability of wind damage higher than 0.1.

The RA of the estate of Björnstorp (2.7%) was significantly larger than that for Fulltofta (0.8%) ($p<0.0001$), and RA for the landscape of Asa (0.5%) was significantly larger than that for Äspered (0.3%) ($p=0.006$). The relative area of a high probability of wind damage was larger, and the relative number of stands was higher within the estate of Björnstorp compared to Fulltofta. The relative area of a high probability of wind damage was larger, whereas the relative number of stands was lower within the landscape of Asa compared to Äspered. The relative number of stands with a high probability of wind damage, was found in general to increase with increasing relative elevation.

The results indicate, that although topography of southern Sweden is relatively gentle, it significantly influences the probability of wind damage on a landscape scale. However, the difference in RA between the landscapes of Asa and Äspered was also partly explained by differences in forest structure between these landscapes. Spatial variation in topographically induced wind exposure means that for a given acceptable risk-level, different efforts to reduce the risk of wind damage could be needed within different landscapes. In southern Sweden, spatial forestry planning is a possible means to reduce the risk of wind damage. For example in locations of high probability of wind damage, e.g., upper parts of hills and ridges, and locations oriented in the west to the southwesterly direction sector, risk-reducing forestry measures would have best effects.

Paper II

To support the targeting of risk-reducing forestry measures within a forest estate, on stands where they would be most effective, a simple-to-use tool was constructed for the identification of spruce stand edges of a high probability of wind damage. It was designed by constructing a set of decision trees, using the classification and regression tree methodology (Breiman *et al*., 1984) for separating stand edges with a high probability of wind damage from those with a low probability. To take into account varying risk preferences among decision makers, decision trees for different threshold probability values (0.05, 0.1, and 0.2) for separating stand edges with a high probability of wind damage from those with a low probability were constructed. In addition, different decision trees were constructed considering differing preferences regarding misclassification rates.

WINDA was used to assess the probability of wind damage to spruce stand edges within the estate of Björnstorp and within Asa Experimenal Forest (Fig. 4). For each threshold probability value each edge was dichotomously classified as having either a high or a low probability of wind damage. Using readily available variables describing stand edges, the surrounding terrain, topography, and wind directions, decision trees were constructed on data for the estate of Björnstorp. The final decision trees were selected by means of cross-validation analysis. The decision trees were then evaluated by applying them to data from Asa Experimental Forest some 250 km north of the Björnstorp estate and comparing the results with values of probabilities assessed using WINDA.

In spite of the simple variables used the decision trees correctly identified 64–71% of the high-probability stand edges within the estate of Björnstorp. The misclassification rate for the low-probability stand edges was 12–26%. Among the most explanatory predictor variables that were included in the decision trees were the stem taper of the trees in stand edges, gap size in front of stand edges, the orientation of wind exposure, and topographical exposure. The performance of the decision trees established for Björnstorp was however substatially lower for Asa

Experimental Forest. Within this landscape the decision trees identified 44–50% of the high-probability stand edges, respectively. Decision trees minimizing misclassification rates of high-probability stand edges at Björnstorp identified 0–83% of the high risk stand edges in Asa Experimental Forest, respectively. For the evaluation landscape, using the Fisher exact test (alpha=0.001) a statistically significant difference between classifications made by the decision tree approach and a set of randomly classified stand edges was obtained for four out of nine decision trees.

The relatively poor performance was explained by the high degree of complexity of the underlying processes, limitations in the parameterization data set, and differences between the landscapes and wind climates involved. It was shown that the characteristics both of the spruce stands and of their surroundings are important for the identification of spruce stand edges of a high probability of wind damage. The decision trees could provide valuable help in practical forestry within and nearby the landscape used for the construction of the decision trees. Extrapolating the decision trees which contain variables specifically fitting to the conditions of the parameterization landscape, such as the predominant direction of wind exposure at Björnstorp, to other conditions involves a risk of failure. However, due to their intuitive use the methodology employed appears to be suitable for the development of decision support tools of broad applicability.

Paper III

In this study the probability of damaging wind speeds by the end of the 21st century was analysed, based on regionally downscaled climate change scenarios over Sweden. An approximate estimate for damaging geostrophic wind speed was determined by running WINDA for Asa Experimental Forest. Wind observed at the meteorological observing station at Jönköping Airport during the period 1968–1990 was used to calculate the geostrophic wind. The geostrophic wind was used to calibrate RCAO model outputs of the control period for the closest pixel using wind speed data for the 850 hPa level as a proxy for the geostrophic wind. The differences between the RCAO modelled and the calculated data from observations were small and were ignored in the subsequent calculations.

Compared to the RE control scenario, the RH control scenario resulted in a significantly higher calculated probability of wind damage within Asa Experimental Forest. While the RE scenarios resulted in an increasing probability of wind damage with increasing greenhouse gas forcing (going from control to B2 to A2), the RH scenarios resulted in a reduced probability of wind damage. The threshold geostrophic wind speed for damaging winds was set to 30 m/s. All of the wind climate scenarios indicated that the current pattern of higher probability of strong wind in southern Sweden, compared to northern Sweden, would also remain under a changed climate. The magnitude and sign of differences of damaging wind speeds between the RE and RH scenarios varied spatially over Sweden. For the southernmost location, all scenarios indicated an increasing probability of damaging wind speeds, except for the northwesterly to westerly wind direction sector in RH A2. The climate scenarios also indicated some shifts in wind direction. In general, the probability of strong wind from the sector west to southwest is suggested to remain comparatively high, and the probability of strong wind from the sector south-west to the south-east will increase in many places. For the southernmost location an increase in the probability of strong wind from the northwesterly to westerly sector is suggested.

Despite an ambiguity in the results between the climate scenarios, useful information about the wind climate can be extracted from them in terms of regional patterns in wind speed and wind direction with implications for spatial forestry planning under a changing wind climate. For forestry this suggests, that avoiding forest edges facing west to south-westerly directions will in the future continue to be a way to reduce the probability of wind damage, and that the incentive to avoid edges facing southerly directions will increase in many places. For southernmost Sweden, for which all but one scenario suggests increasing windiness, avoiding forest edges facing west to south-westerly directions is suggested to remain as a possibility to reduce the probability of wind damage, and the incentive to avoid edges facing north-west to westerly as well as southwest to south-easterly directions increases.

Paper IV

In this study RCAO regional climate change scenarios for the period 2071–2100 were used to assess the probability of wind damage within Asa Experimental Forest under a changed climate. The effects of both a changed wind climate and changed tree growth were accounted for. The RE B2 scenario was used to evaluate the modifications of the length of the rotation period as one example of how to adapt forestry to climate change.

Based on RCAO modeled climate data the process-based model BIOMASS (McMurtrie, Rook & Kelliher, 1990; Bergh, McMurtrie & Linder 1998) predicted the relative change in net primary production of Norway spruce and Scots pine for the study landscape. The predicted change in tree growth of the tree species was used to gradual adjust the site indices of the forest stands within the study landscape in simulations with the FTM system. The study landscape was projected without any effect of climate change on NPP, and with effects of climate change on NPP according to each of the four different climate change scenarios. The corresponding modelled wind climate was then used for probability assessments with WINDA. In addition, the predicted change in wind climate or the predicted change in tree growth was included in simulations under the RE B2 scenario. To accommodate for the age class distribution within the study landscape, an alternative age class distribution in 2071-2100 was evaluated under the RE B2 scenario. To evaluate the effects of the modification of the length of the rotation periods, different criterion for final felling was applied in different simulations. As the base criterion a final felling was carried out when the volume growth rate of the stand in the last simulated 5-year period went below 3% of its standing volume. This threshold value was increased to 3.5, 4, 4.5, and further to 5%, and applied in separate simulations. In each simulation the study landscape was projected forward for 110 years. The annual probability of wind damage of the forest stands was in the period 2071-2100 assessed at six occations, i.e., once for each five-year period in the FTM system. The six observations were used to calculate for each stand the probability that a stand is damaged by wind during the 30-year period.

The RE scenarios resulted in an increasing probability of wind damage going from the control to the B2 scenario, and from the control to the A2 scenario. There was no significant difference between the RH control scenario and the RH A2 scenario, whereas the RH B2 scenario slightly reduced the probability of wind damage compared to the control. For the alternative age class distribution in 2071–2100, the probability of wind damage increased going from the RE control to the RE B2 scenario. The probability of wind damage increased going from the RE control to the RE B2 scenario when effects of climate change in terms of either the wind climate or tree growth was applied. For the RE B2 scenario the annual expected area of wind damage within the study landscape was in general reduced with increasing threshold value for the volume growth rate triggering final felling, i.e., with shortened rotation length. A shortening of the rotation length on the landscape scale by approximately 10 years, resulted in a significantly smaller annual expected area of wind damage under the RE B2 scenario compared to the control scenario.

In this study both a changed wind climate and increased forest productivity were accounted for in the assessments of the probability of wind damage in 2071–2100. All climate change scenarios predicted an increase in tree growth within Asa Experimental Forest. The predicted increase in tree growth of the RE B2 scenario, which was moderate compared to that of the other scenarios, resulted in an increasing probability of wind damage. This indicates that although there is some ambiguity between the climate scenarios in terms of future wind speeds (Paper III), it can not be ruled out, however, that a changed wind climate and an increased tree growth can lead to an increasing probability of wind damage in southern Sweden. A shortening of the rotation periods on a landscape scale by about 10 years was found to compensate for the increased probability of wind damage as was predicted for the RE B2 scenario. For forestry in southern Sweden it may therefore be possible to modify the length of the rotation periods as one means to adapt to a climate change.

Discussion

Private forest owners in southern Sweden consider wind damage to be one of the most problematic risks from an economic perspective (Blennow & Sallnäs, 2002). In accordance with the results of previous studies (*e.g.* Somerville, 1980; Savill, 1983; Persson, 1975; Lohmander & Helles, 1987; Gardiner *et al.*, 1997; Moore & Quine, 2000; Meilby, Strange & Thorsen, 2001) it is possible to actively manage the risk of wind damage. In Swedish forestry, according to Persson (1975), possible forestry measures to increase the resistance of the trees to wind include for example the choice of a more wind-firm tree species, a reduced density of plantations, and the avoidance of thinnings in older stands.

In this thesis four case study landscapes in southern Sweden were studied (Fig. 4), representing conditions found in the southern, as well as in the northern part of the Götaland region. When assessing the probability of wind damage to forest stands, analyses were made on the landscape scale to take into account also the characteristics of the surrounding terrain and of the topography. The assessed probability values in absolute terms depend on the characteristics of the case study landscapes (Paper I–V), and on the modelled wind climate and predicted tree growth of the RCAO grid covering Asa Experimental Forest (Paper III and IV). However, the assessed probability values in relative terms could be expected to found within other landscapes in southern Sweden. The studies were made using computer models. This made it possible to assess the probability of wind damage, taking into account both the spatial and uncertain aspects, and to make simulations of the development of the forests (Paper I and IV). At the same time models are simplifications of reality. Furthermore, they are syntheses of present knowledge and there are always areas of scientific uncertainty.

The randomness of the occurrence of windstorms makes it uncertain where and when they will occur. The choice of a more wind-firm tree species or shortened rotation period for example could be expected to reduce the production loss due to wind damage (Persson 1975; Peltola *et al*., 2000), while they at the same time themselves could be expected to result in production loss (Fries, 1964; Eriksson, 1976; Meilby, Strange & Thorsen, 2001; Bergquist *et al.,* 2005). A possible cost-effective way to manage the risk of wind damage, i.e., the uncertain occurrence of windstorms, can be within a forest estate to by spatial forestry planning target the risk-reducing forestry measures to locations or forest stands, for which the probability of high wind speeds would be the highest, and/or the trees' resistance to wind loading is low (Paper I and II). Although topography in southern Sweden is relatively gentle (Anon., 1984), it was found to significantly influence the probability of wind damage on a landscape scale (Paper I). Furthermore, the topography influences the probability of wind damage within south Swedish landscapes. Within the case study landscapes it was also found that the fraction of stands with a high probability of wind damage in general increased with increasing relative elevation. Compared with previous studies (*e.g*. Miller, Quine, & Hunt, 1987; Ruel, 1998; Ruel, 2000), topographically induced wind exposed locations, can be identified e.g., in upper parts of hills and ridges, and in southern Sweden locations facing the west to the southwesterly direction sector. For example in these locations risk-reducing forestry measures would have best effects (Paper I).

Topographically induced wind exposed locations with a high probability of wind damage within two landscapes located in southern Sweden are illustrated in Fig. 9 (Paper I). The landscapes hold similar forests consisting of Norway spruce stands of site index 28 m. The management includes two medium intensive thinnings and final felling at age 75. It is shown that spatial differences in topographical influences on the probability of wind damage mean that different efforts for reducing the risk of wind damage could be applied for different landscapes and within a landscape to reach the same level of risk-taking. In Paper I, it was not accounted for spatial variation within landscapes for example in terms of forest productivity, tree species distributions, and soils. In reality, for example, lower tree heights at upper part of hills and ridges, can reduce the probability of wind damage in these locations (Persson, 1975; Lohmander & Helles, 1987), as can a larger proportion of for example birch in the lower parts of the terrain (Peltola *et al*., 2002). On a landscape scale the distribution of stand sizes, and the fragmentation in terms of the spatial distribution of open land and forests also appears to influence the probability of wind damage.

To support the targeting of risk-reducing forestry measures within practical forestry, an attempt was made to construct an easy-to-use tool, taking into account decision-makers' risk preferences for the identification of spruce stands with a high probability of wind damage (Paper II). In accordence with previous studies it was shown that not only the characteristics of the target stand are of importance, but also the characteristics of its surroundings (Persson, 1975; Lohmander & Helles, 1987; Meilby, Strange & Thorsen, 2001). This emphasizes the possibility to reduce the risk of wind damage of forest stands by using shelter effects of topographic features and neighbouring stands. This tool could provide valuable help within practical forestry within and nearby the landscape used for constructing it. So far, however, its perfomance was substantially lower in an evaluation landscape.

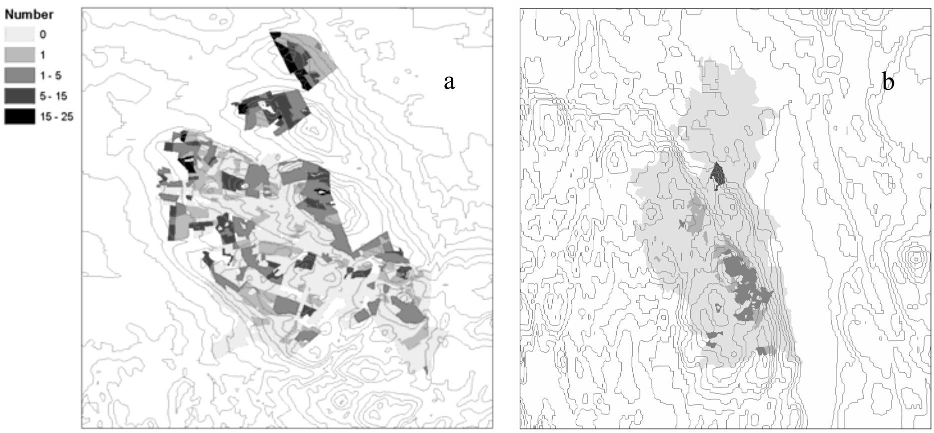

Fig. 9. The number of times forest stands were assessed a high probability of wind damage (p>0.1), based on the results of thirty spatial randomisations of contents of forest stands within the estate of a) Björnstorp and b) the landscape of Asa (Paper I).

Forestry in southern Sweden has experienced an increasing number of events of extensive wind damage during the past century (*e.g.* Nilsson *et al.*, 2004), which has been explained by changes in the state of the forests (Blennow & Olofsson, 2004). In the light of a potential future climate change, this raises the question of the possible impact of such a climate change on the forest ecosystem and forestry in Sweden (Sonesson *et al.*, 2004), not least with respect to the risk of wind damage. The probability of wind damage under a changed climate would however not only depend on changes in the wind climate, but also on changes in the state of the forests that in turn is affected by forest management.

The frequency and magnitude of windstorms will depend on if, and how the climate might change (Paper III). The emission of greenhouse gases depends among other things on the global population growth rate and on the development of technology facilitating the use of other sources than coal as primary energy (IPCC, 2001). There is scientific uncertainty of how different climate processes respond to increasing levels of greenhouse gases in the atmosphere (Rummukainen, 2005). Uncertainty of future greenhouse gas emissions, as well as scientific uncertainty, was depicted (Paper III and IV) by using the four regional climate change scenarios produced for Sweden (Rummukainen *et al.*, 2004) (Fig. 8). The RE B2 scenario was selected for additional analyses in paper IV. However, none of the four scenarios can be regarded as more likely than any of the others (Rummukainen pers. commun., 2005). In terms of future wind speeds, the magnitude and sign of changes varied between the four climate scenarios and also spatially over Sweden (Paper III). For southernmost Sweden, however, the climate scenarios were comparably consistent. In this region all scenarios indicate an increasing probability of damaging wind speeds, except for the north-westerly to the westerly wind direction sector in the scenario RH A2. For southern Sweden and especially for southernmost Sweden, it thus cannot be ruled out that the probability of damaging wind speeds could increase.

A possible reduction in soil-freezing could result in weaker tree anchorage (Peltola, Kellomäki & Väisänen, 1999; Venäläinen *et al.*, 2001a, b) and increase the probability of wind damage. This effect was accounted for in Papers III and IV by assuming non-frozen soils in the assessments of the probability of wind damage, by relying on the highest of the calculated probabilities of uprooting and stem breakage, respectively. As an effect of an increased temperature tree growth has been predicted to increase in Sweden (Bergh *et al.*, 2003). There was shown an increasing tree growth within Asa Experimental Forest for all available regional climate change scenarios (Paper IV). It was shown for the RE B2 scenario, which predicts a moderate increase in tree growth compared to the other three scenarios that this affected the resistance of the forest in a way that resulted in an increasing probability of wind damage. This was also shown for the RH A2 scenario, which resulted in a reduced probability of wind damage under changed wind climate

(Paper III), whereas when both a changed wind climate and an increased tree growth was accounted for, the probability of wind damage was unchanged (Paper IV). For southern Sweden, in spite of some ambiguity between the climate scenarios in terms of future wind speeds, it cannot however be ruled out that the effects of a changed wind climate and increased tree growth can lead to an increasing probability of wind damage. For southernmost Sweden these changes are likely to lead to an increasing probability of wind damage. The probability of wind damage could be expected to vary spatially in southern Sweden also as an effect of spatial variation in tree growth response (Bergh *et al*., 2003). Furthermore, the predicted probability of wind damage can be altered by factors not accounted for in Paper IV (Sonesson *et al*., 2004). For example the predicted tree growth can be hampered by the wind damage itself, or by other calamities such as an increased risk of root rot and insect attacks (Redfern & Stenlid 1998; Evans, Straw & Watt, 2002).

How climate change is responded to will have an impact on the risk of wind damage. Responses to climate change can be considered in terms of mitigation efforts, with the aim of reducing greenhouse gas emissions (MacIver & Wheaton, 2005). Possibly, for forestry this could mean a larger focus on the production of forest fuels. The main part of the responses to climate change is also in terms of adapting forestry to changing conditions. In this context for example the potential of the forests to reduce atmospheric CO_2 has been explored (Hoen & Solberg, 1994). With respect to the predicted impact of a climate change on the probability of wind damage in southern Sweden (Paper III and IV), this could mean that more efforts on risk-reducing forestry measures need to be made to reach the same level of risk-taking. In Paper IV it was found that an increased probability of wind damage under a changed climate could be compensated for on the landscape scale by modifying the length of the rotation periods. Within Asa Experimental Forest the increase in the probability of wind damage under the RE B2 scenario was compensated for by a shortening of the rotation periods on the landscape scale on average by 10 years. For forestry in southern Sweden it thus appears that a modification of the length of the rotation periods might be one possible means to adapt to a climate change. A shortening of the rotation periods by on average 10 years reduced the expected area of wind damage in 2071–2100 from approximately 37 to 4 hectares (Paper IV). It also meant that some forest stands had to be felled before the current Swedish allowable ages for final felling (Anon., 1994). The effects of shortened rotation periods would be expected to be larger on a landscape scale, if spatial considerations of topographically induced wind exposure, and wind shelter of surrounding stands are made (Alexander, 1964; Lohmander & Helles, 1987; Paper I; Paper II).

The climate scenarios indicated some shifts in wind direction (Paper III). In general the probability of strong wind from the sector west to southwest is suggested to remain comparatively high. For southernmost Sweden an increase in the probability of strong wind from the north-westerly to the westerly sector is suggested (Paper III). For southernmost Sweden this could mean an increase in topographically induced wind exposure in locations facing the north-westerly to the westerly direction sector. Avoiding forest edges facing the west to the southwesterly directions is suggested also in the future to be a way to reduce the probability of wind damage. For southernmost Sweden the incentive to avoid forest edges facing the north-westerly to the westerly direction is suggested to increase (Paper III).

Conclusions

WINDA provides a tool that makes it possible to take into consideration the spatial aspects, and the uncertain occurrence of windstorms over time and in space, in order to provide information to support the management of the risk of wind damage in south Swedish forestry. Coupled with the Forest Time Machine it is possible to evaluate the effects of different management strategies on the probability of wind damage, and furthermore together with regional climate change scenarios, it is possible to evaluate the effects of a potential climate change on the probability of wind damage.

In addition to stand-level forestry measures, it is possible to reduce the risk of wind damage in southern Sweden by spatial forestry planning. The topography in southern Sweden significantly influences the probability of wind damage on a landscape scale and within landscapes. Spatial differences in topographical influences on the probability of wind damage mean that, for a given acceptable level of risk-taking, different efforts to reduce the risk of wind damage could be needed for different landscapes. A possible cost-effective means to reduce the risk of wind damage is to target risk-reducing forestry measures to for example topographically induced wind exposed locations, and locations oriented in the west to the southwesterly direction sector, and/or to forest stands with a low resistance to wind. The identification of such locations or stands can be facilitated with easy-to-use tools.

The management of the risk of wind damage concerns the uncertain occurrence of windstorms both over time and in space. In this respect, it is motivated to evaluate the impact of a potential climate change on the probability of wind damage. Studies on climate change are not without uncertainty, but using different climate change scenarios the uncertainties involved can be depicted, and useful information can be extracted from them.

Based on the regional climate change scenarios, it cannot be ruled out that a climate change can lead to an increasing probability of wind damage in southern Sweden. In southernmost Sweden, a climate change very likely can lead to an increasing probability of wind damage. The probability of strong wind from the sector west to southwest was predicted to remain comparatively high. This indicates that in the future as well, avoiding forest edges and considering topographic shelter from this direction could be a possible means to reduce the risk of wind damage.

With respect to the predicted impact of a climate change on the probability of wind damage, more efforts on risk-reducing forestry measures might be needed to reach the same level of risk-taking. Shortening the lengths of rotation periods appears to be one possible means for the forestry in southern Sweden to adapt to climate change. Short rotation lengths could also be a way to handle the uncertainty of the future climate, since this would make it possible to make a new choice of tree species sooner, when new experience and information about the climate has been gained.

Future research

Continued work is suggested on the development of easy-to-use tools supporting forest owners managing the risk of wind damage in practical forestry. With respect to changing growing conditions it is suggested that to facilitate adaptation new or modified tools supporting management in practical forestry are needed. The further evaluation of management strategies is suggested in order to guide forest owners adapt to climate change.

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