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Influence of clear-cutting on the risk of wind damage at forest edges: A GIS-based integrated models approach

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Academic dissertation

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ABSTRACT

This study aimed at investigating how forest management affects the wind flow over a forested region and the consequent risk of wind damage at forest edges. For this purpose, a GIS software ArcGIS was used to integrate the models that simulate airflow (WAsP), wind damage (HWIND) and forest growth (SIMA) (Papers II-IV). Heuristics was also used to optimise the temporal schedules and spatial patterns of clear-cuttings regarding the risk management of wind damage and timber harvesting objectives (Paper IV). The integrated models were applied to analyse how clear-cuttings affect the speed and frequency of local winds (Paper I) and the short- (Paper II) and long-term risk of wind damage (Papers III-IV) in a management unit located in central Finland. In papers II and III, the risk of wind damage at current forest edges (Case I) was compared with two alternative situations in which new clear-cuts were carried out if stands reached the minimum acceptable size or age (Case II) or if the stand age exceeded 100 years (Case III). In this study, the risk of wind damage was evaluated in terms of number of stands, their areas and length of vulnerable edges for different critical wind speeds and annual risk probabilities (Papers II-IV).

In Paper (I) it was found that at the regional level the mean wind speed was not affected although the surface roughness changed due to clear-cuttings. However, locally the occurrence of high wind speeds increased. In Paper (II), it was found that, in spite of intensive clear-cuttings (Case II), the short-term risk of wind damage may not necessarily be increased at a regional level. This was because the most vulnerable older stands were cut. Compared to the intensive clear-cutting regime (Case II), it was also found over 20 years simulation period on average only 7% less vulnerable edges in the less intensive clear-cutting regime (Case III) (Paper III). An even flow timber harvesting objective (e.g. every 10 years interval) also affected the temporal and spatial pattern of clear-cuttings over the 30 year simulation period and limited the possibility of minimizing the risk of wind damage at a regional level (Paper IV). However, the risk of wind damage could be reduced by aggregating clear-cuttings and/or avoiding them at the edge of stands with a highest probability to be damaged.

As a conclusion, the integrated models approach presented in this study could, in general, help forest managers to better understand the influence of any forest management options (e.g. new clear-cuttings) on the short- and long-term risk of wind damage both at a stand and a regional level. Moreover, the methodology applied in this study could further help to provide optimal forest management for short- and long-term planning in regard to the risk management of wind damage and timber harvest objectives.

Keywords: airflow, forest growth, forest management, forest planning, genetic algorithm, heuristic optimisation, risk assessment, simulated annealing, tabu search, timber harvest, wind climate

PREFACE

This work was carried out under the Finnish Centre of Excellence Program (2000-2005) at the Centre of Excellence for Forest Ecology and Management (Project No. 64308), led by Academy Prof. Seppo Kellomäki, University of Joensuu, Faculty of Forestry. The work was mainly funded through the SUNARE Research Program promoted by the Academy of Finland (2001-2004) under the project "Silvicultural strategies for managing wind and snow-induced risks in forestry" (SilviRisks, Project No. 52724) and the Finnish-Chinese co-operation project "Responses of the ecosystem processes of high-frigid coniferous forests to climate change: a comparative study of coniferous forests in the boreal region and the subalpine region of western China", funded by the Academy of Finland (Project no. 200013) and the National Science Foundation of China. In addition, it was partly funded by the Finnish Graduate School of Forest Sciences. In the above context, the support from the Academy of Finland, the National Technology Agency (Tekes), the University of Joensuu and the Graduate School of Forest Sciences is acknowledged. Moreover, Forest Centre Pohjois-Savo, is thanked for providing the forest stand data (X-forest-data) for the study areas.

I would also like to thank my supervisors, Prof. Heli Peltola (University of Joensuu), Academy Prof. Seppo Kellomäki (University of Joensuu), Prof. Kaiyun Wang (East China Normal University) and Dr. Ari Talkkari (University of Joensuu) for their valuable suggestions and comments on my work. In addition, my other co-authors, Dr. Ari Venäläinen (Finnish Meteorological Institute), Prof. Timo Pukkala (University of Joensuu) and Mr. Harri Strandman (University of Joensuu) are greatly appreciated for their constructive contribution . Mr David Gritten is acknowledged for checking the English of the manuscripts and summary for PhD thesis.

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Joensuu, February 2006

Hongcheng Zeng

LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following Papers, which are referred to in the text by the Roman numerals I - IV:

I Venäläinen, A., Zeng, H., Peltola, H., Talkkari, A., Strandman, H., Wang, K. and Kellomäki, S. 2004. Simulations of the influence of forest management on wind climate on a regional scale. Agricultural and Forest Meteorology. 123: 149-158. doi: 10.1016/j.agrformet.2003.12.005

II Zeng, H., Peltola, H., Talkkari, A., Venäläinen, A., Strandman, H., Kellomäki, S. and Wang, K. 2004. Influence of clear-cutting on the risk of wind damage at forest edges. Forest Ecology and Management. 203: 77-88. doi: 10.1016/j.foreco.2004.07.057

III Zeng, H., Peltola, H., Talkkari, A., Strandman, H., Venäläinen, A., Wang, K. and Kellomäki, S. 2006. Simulations of the influence of clear-cuttings on the risk of wind damage on a regional scale over a 20 year period. Manuscript in review.

IV Zeng, H., Pukkala, T. and Peltola, H. 2006. The use of heuristic optimization in risk management of wind damage in forest planning. Manuscript in review.

In Paper I, Hongcheng Zeng participated in the writing of the Paper equally with other co-authors, but Dr. Ari Venäläinen was responsible for the airflow simulations. The work involved in Papers II – IV was mainly carried out by Hongcheng Zeng, but Prof. Timo Pukkala was responsible for the optimization work in Paper IV and co-authors of the Papers participated in the formulating of the research tasks and commented the manuscripts.

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1 INTRODUCTION

1.1 Mechanism of airflow and wind damage

Wind can greatly affect the structure and functioning of a forest ecosystem, and the wind-induced damage is a continuous cause of economic loss in forests. Approximately 180 million m^3 of timber was blown down in Europe during storms in December 1999 (UNECE/FAO 2000). While in Finland in November 2001, over 7 million m^3 of timber was damaged in similar circumstances (Pellikka and Järvenpää 2003). The economic impact of wind damage is particularly severe in managed forests, on account of the reduction in the yield of recoverable timber, the increased costs of unscheduled thinning, clear-cutting, and resulting problems in forestry planning. Furthermore, broken and uprooted trees left in the forest can lead to detrimental insect attacks on the remaining trees because of an increase in breeding sites (Ravn 1985). Thus, better understanding of the risk of wind damage could help foresters to manage the forests in a sustainable way.

Gaining a good knowledge of airflow is necessary for a better understanding of the mechanism and the risk for wind damage. The vertical stratification of wind profile was commonly assumed as logarithmic in a flat area with homogeneous roughness (Gloyne 1968, Lyles and Allison 1979, Hagen and Kidmore 1981, Abtew et al. 1989, Mortensen et al. 2002). The trees affect air motions, however. For example, when Zhu et al. (2000) studied Japanese black pine (*Pinus thunbergii* Parl.), they found that wind profile within a single tree crown is greatly influenced by wind direction and the distribution of the needles and branches. While the relative wind speed along the trunk is relatively stable, especially in a low and middle parts of each vertical section. In general, the mean wind profiles follow a well-defined logarithmic pattern above the canopy and an exponential function within the canopy (Raupach and Thom 1981).

McNaughton (1989) also reported that (1) a rapid adjustment is essentially complete by about 10 tree heights from the forest edge, and (2) complex flow structures within the adjustment zone, often with a jet in the trunk space and probably an intermittent rotor above and within the upper canopy. In respect to the influence of topography, over isolated small hills (< 1 km) with moderate slopes (≤ 0.3), wind variations are primarily associated with aerodynamic rather than thermal forcing (Taylor and Lee 1984, Taylor et al. 1987). While in more complex terrain, both local circulations arising from differential heating and cooling (e.g. mountain/valley circulations) and mechanical modifications of the prevailing wind (e.g. channelling and speed up over ridge-tops) are important (Barry 1992, Lee 2000).

In response to wind loading, the trees sway with consequent short-term vibration or oscillatory motions of the stems resulting in their crowns being transformed and stems deflected (Papesch 1974, Mayer 1987, 1989, Peltola 1995, Kerzenmacher and Gardiner 1998). The swaying of trees is reinforced when the pattern of wind gusts becomes coupled to the natural swaying frequency of the trees (Milne and Brown 1990, Milne 1991). If the movement of the swaying exceeds a certain extent, the tree may be uprooted or its stem broken (Peltola 1996a). However, the susceptibility of trees of a stand to wind damage is controlled by not only the properties of the wind (i.e. wind speed, duration, and gustiness; see Mayer 1989), but also the tree and stand characteristics such as tree species, tree height, tree diameter, crown area, rooting depth and width, and stand density (Coutts 1986, Gardiner 1995, Gardiner et al. 1997, Lee and Black 1993, Kerzenmacher and Gardiner 1998, Peltola et al. 1999a, 2000, Dunham and Cameron 2000). The probability of wind damage will increase, for example, with the increment of tree height, age, and decrease with the increment of taper (DBH/height), root depth and width (Lohmander and Helles 1987, Peltola 1999a).

Moreover, large differences in the risk of wind damage can be observed between regions and locations that differ in topography and/or forest structures at a regional level (Copeland et al. 1996, Peltola et al. 1999b, Quine 2000, Proe et al. 2001). Forests located on the hills or higher altitudes are on average most vulnerable to damage (Talkkari et al. 2000). Gaps within the forest enable increased within-canopy wind speeds and consequently increase the risk of wind damage, particularly for the trees located at newly created edges (Peltola 1999a).

However, not only the tree and stand characteristics, but also forest structure at a regional level, will change along with forest growth as a result of forest management. Therefore the risk of wind damage will also change over time (Neustein 1965, Lohmander and Helles 1987, Gardiner et al. 1997). For example, the highest risk of wind damage is most likely to be found where there are sudden changes in wind loading to which the trees are not acclimatised, as in stands adjacent to recently clear-felled areas or in stands that have recently been heavily thinned (Neustein 1965, Lohmander and Helles 1987, Peltola 1996a, 1996b, Gardiner et al. 1997, Peltola et al. 1999a, Gardiner et al. 2000).

Neustein (1965) found that small clearings can reduce the sweep of wind within them compared to large clearings. On the other hand, the extent of susceptible edges per hectare of felled area increases rapidly as the size of clear-cutting areas diminishes. Thus, the reduced amount of wind damage at the edges of small clearings that might be expected from the observed reduction in wind speed compared with larger ones can be outweighed by the much greater length of the perimeter at risk (Alexander 1964, 1967, Neustein 1965, Elling and Verry 1978). Savill (1983) suggested that it is usually safest to fell right up to “permanent” edges or open ground if possible and proceed with felling against the direction of the prevailing wind. The susceptibility of tree stands to wind damage in thinned stands and at newly created forest edges will decrease to some degree over time when the trees left in the forest stands after thinning or located at new forest edges, develop more tapering stems (DBH/height) (Papesch 1974, Hill 1979, Slodicak 1995). A better understanding would, however, be needed on how any changes in the forest structure, as a result of growth and management, may affect local wind conditions and consequently short- and long-term risk of wind damage at both stand and regional level.

1.2 Models for wind damage, airflow and forest growth and heuristic optimization techniques

Based on the properties of the tree and stand, mechanistic wind damage models have been recently developed which can predict the minimum wind speeds (critical wind speeds) needed for uprooting or breaking the tree stems (Peltola et al. 1999a, Gardiner et al. 2000, Ancelin et al. 2004). On the other hand, airflow models have also been built to predict local wind conditions based on wind measurements at a specific site (Walmsley et al. 1993, Mortensen et al. 2002). Meanwhile, statistical and process-based growth and yield models have also been made available to simulate forest growth and dynamics under certain environmental and management conditions (e.g. Kellomäki et al. 1992, Matala et al. 2003).

However, only a few attempts have been made so far to integrate the models described above, i.e. to extend the use of the mechanistic wind damage model in order to provide more detailed information for forest decision makers of the risk of wind damage related to forest management. Talkkari et al. (2000), for example, were the first to integrate the mechanistic wind damage model HWIND (Peltola et al. 1999a) and airflow model MS-Micro/3 (Walmsley et al. 1993) with GIS in order to identify actual damaged stands at forest margins under Finnish conditions. Subsequently, Blennow and Sallnäs (2004) integrated HWIND and the airflow model WAsP (Mortensen et al. 2002), with GIS under Swedish conditions for a similar purpose. However, Dunham et al. (2000) were the first to integrate mechanistic wind damage model ForestGALES together with the wind climate model DAMS and the Yield Class Model to estimate annual damage of stands at different steps.

The integration of the mechanistic wind damage model, airflow model and growth and yield model would have potential to predict the risk of wind damage due to any changes in the forest growth and dynamics and management (e.g. clear-cutting). In the above context, geographical information systems (GIS) could serve as a common data and analysis framework (Rao et al. 2000). It could be applied to couple these models and techniques, and to store, update, manipulate, analyze, and display the geographic information (ESRI 2004). In addition, the topology between polygons (e.g. forest stands) and/or polylines (e.g. forest edges) could be defined in the GIS so that spatial calculations can be done within the software.

The integration of different models for predicting the risk of wind damage over time could not alone output any optimal forest management solution (e.g. clear-cutting regimes) in regard to the risk management of wind damage as well as other targets in forest planning. However, there has not been presented any previous attempts so far to combine the wind damage models with optimization techniques for the risk management of wind damage in forest planning. On the other hand, in recent years, heuristic optimization techniques, have increasingly been used in forest planning (Borges et al. 2002), such as simulated annealing (SA, e.g. Dahlin and Sallnäs 1993, Lockwood and Moore 1993, Öhman 2000), tabu search (TS, e.g. Bettinger et al. 1997, Boston and Bettinger 1999), and genetic algorithm (GA, e.g. Lu and Eriksson 2000, Falcao and Borges 2001). Different variations and combinations of these techniques have also been applied in forestry (Bettinger et al. 1999, Boston and Bettinger 2002, Falcao and Borges 2002, Heinonen and Pukkala 2004).

Unlike traditional mathematical programming, heuristic techniques have the potential to solve optimization problems with complicated spatial constraints, which are non-linear 0-1 integer programming problems (Boston and Bettinger 2002). The use of mechanistic wind damage model and heuristic techniques together has potential to seek optimal forest management (e.g. the temporal schedules and spatial patterns of clear-cutting) regarding the acceptance of the level of risk of wind damage and timber harvesting objectives. Altogether, the integration of different models for forest growth and yield, wind damage and airflow along with the heuristic optimization methods and GIS software would make it possible to systematically analyse the short- and long-terms effects of forest management on the risk of wind damage at the regional level.

1.3 The aim of this study

This study aimed at investigating how forest management affects the wind flow over a forested region and the consequent risk of wind damage at forest edges. For this purpose, a GIS software ArcGIS was used to integrate the models that simulate airflow (WAsP), wind damage (HWIND) and forest growth (SIMA). The heuristics was also used to optimise the temporal schedules and spatial patterns of clear-cuttings regarding to the risk management of wind damage and timber harvesting objectives.

The integrated models were applied to analyse how clear-cuttings affect the speed and frequency of local winds and the short- and long-term risk of wind damage in a management unit located in central Finland. The risk of wind damage was analyzed in terms of the number of stands, their areas and length of vulnerable edges for different critical wind speeds and annual risk probabilities. The main research tasks of each Paper are listed below:

(1) Analyses of the influence of clear-cuttings on the local wind climate, based on simulations by the airflow model WAsP (Paper I);

(2) Analyses on the short-term influence of different clear-cutting regimes on the risk of wind damage compared with current forest conditions, based on integration of the wind damage model HWIND and airflow model WAsP with GIS software ArcGIS (Paper II);

(3) Analyses on the long-term influence of different clear-cutting regimes on the risk of wind damage compared with current forest conditions, based on integration of the wind damage model HWIND, airflow model WAsP and forest growth and yield model SIMA with GIS software ArcGIS (Paper III);

(4) Optimization of the temporal schedules and spatial patterns of clear-cuttings under the combined objectives for risk management of wind damage and timber harvesting, based on integration of the forest growth and yield model SIMA, wind damage model HWIND and heuristic techniques with GIS software ArcGIS (Paper IV).

2 MATERIAL AND METHODS

2.1 Description of the study areas

The study area of 64 km^2 used in this work was located in central Finland (63^{o}01'N; 27 ^{o}48'E). It was surveyed in 1990 and 2001, and it represented typical boreal forests. The dominated species were Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* Karst L.) stands, but some birch (*Betula spp*.) and other broad-leaved stands were also present. The 1990 survey covered an area of 1892 ha including 522 ha of Scots pine, 1225 ha of Norway spruce, 95 ha of birch and other broad-leaves, and 49 ha of open areas (including water area, open fields and clear-cut areas). The survey in 2001 included an area of 1528 ha consisting of Scots pine (424 ha), Norway spruce (930 ha), birch and other broad-leaves (101 ha), and open areas (73 ha). The area had an undulating terrain with some small hills, and elevations range between 85 and 190 metres (above sea level a.s.l.). This large study area (called later on as study area I) was used only to study the influence of clear-cuttings on the local wind climate (Paper I).

The centre part of this study area, about 7 km^2, was used equally in all separate studies (Papers I-IV). This study area surveyed in 2001 (called later on as study area II) included 395 ha of forests and 46 ha of open terrain. It consisted of 142 ha Scots pine (in 76 stands), 225 ha Norway spruce (158 stands), 26 ha of birch (27 stands) and 2.5 ha other broad-leaved species (5 stands). The altitudes of this smaller study area range between 90 and 170 meters (a.s.l.).

As a basis for the local wind climate of the whole study area, it was used the wind measurements made in 1990-2001 at the Ritoniemi meteorological station at Vehmersalmi (62°48′N, 27°55′E, 86 m a.s.l.), which is about 30 km north of the study area concerned. Most storms blew from the direction 270 (west), which was therefore selected to represent the whole body of wind climate for the study area. The orography of the study area (i.e. elevation contour lines) was represented by contour lines at 5 m interval, which were generated from a digital elevation model (DEM) with a pixel size of 25 m in ArcGIS (Booth 2000). Similarly, the roughness isolines for 1990 and 2001 were generated from digital aerial ortho-photos by visual interpretation in ArcGIS (ESRI 2002). Altogether, four roughness classes were recognized (Paper III, Table 1). In addition, forest stand data was used to improve the interpretation and digitization within the geographical extent of the aerial photos.

2.2. Description of component models and heuristic techniques

The growth and yield model SIMA (Papers II-IV)

The non-spatial gap model SIMA (Kellomäki et at. 1992) was used in this study to simulate forest growth and yield in individual stands based on mean stand characteristics. In the model, the growth in mass (including foliage, branches, stem and roots) of each tree in a stand is calculated based on diameter growth, which is limited by light, temperature, soil moisture and nitrogen availability (Kellomäki et al. 1992). In the simulation, the mortality of the trees is controlled by stand age and minimum allowable growth rate of trees (Kellomäki et al. 1992). In this study, a newly planted stand was established after clear-cutting by giving initial seedling stand properties regarding tree species (the same as previously growing there), diameter of seedlings, and stand density (2000 seedlings per hectare for Scots pine and Norway spruce, and 1600 for birch). The simulation results (tree/stand variables) were used as both inputs for the HWIND simulations and for calculating the roughness values of the stands for the WAsP simulations.

The properties of the SIMA model, its parameters and inputs and the validity of its outputs, have been described earlier in detail by Kellomäki et al. (1992), Kolström (1998) and Talkkari et al. (1999). Based on these findings, the SIMA model is expected to facilitate the simulations on the dynamics of tree populations in managed Scots pine, Norway spruce and birch stands in agreement with the conventional growth and yield tables and with accuracy typical of conventional growth and yield models (see Kellomäki et al. 1992, Kolström 1998, Talkkari et al. 1999). However, its outputs (e.g. tree height, stem volume) are especially sensitive to any inaccuracy in the input of the diameter data (as tree height is calculated based on it).

The mechanistic wind damage model HWIND (Papers II-IV)

The mechanistic wind damage model HWIND (Peltola et al. 1999a) was used in this study to describe the mechanistic behaviour of Scots pine, Norway spruce and birch trees under wind loading and to predict the mean critical wind speeds lasting 10 minutes at 10 m above ground level at which trees will be uprooted and/or broken. In the model, a tree is assumed to be uprooted if the maximum bending moment (due to forces by wind and gravity) exceeds the resistance of the root-soil plate (Peltola et al. 1999a), and the stem is assumed to be broken if the breaking stress exceeds the critical value of the modulus of rupture (Petty and Worrell 1981, Petty and Swain 1985, Peltola et al. 1999a). The inputs of the model are tree species, average tree height, diameter at breast height (DBH) and stand density (which are the SIMA outputs), in addition to distance from the stand edge where the simulations are carried out and gap size. It should be noted that birch was simulated here without leaves, i.e. to correspond with the period of late autumn to early spring when most storms occur in Finland.

The properties of the HWIND model, its parameters, inputs and the validity of its outputs for podzol soil conditions in Finland, have been discussed in detail by Peltola et al. (1999a), Gardiner et al. (2000) and Talkkari et al. (2000). Based on these findings, the HWIND model is expected to facilitate simulations of bending moments and critical wind speeds needed to cause uprooting or stem breakage in managed Scots pine, Norway spruce and birch stands in agreement with the corresponding outputs of regression equations for Finnish tree pulling data (Peltola et al. 1999a) and with wind speeds known to cause damage to similar kinds of trees (e.g. Oliver and Mayhead 1974, Talkkari et al. 2000, Pellikka and Järvenpää 2003). Moreover, based on model comparisons, the HWIND model outputs have been found to be in reasonable agreement with the similar models such as GALES and FOREOLE (Gardiner et al. 2000, Ancelin et al. 2004). However, any inaccuracies in the input tree characteristics (e.g. DBH, height, crown depth and width) and parameters that control the magnitude of the wind loading (e.g. gust factor, drag coefficient, crown streamlining), can have a large influence on the predicted critical wind speed for uprooting and stem breakage (Peltola et al. 1999a, Gardiner et al. 2000).

The airflow model WAsP (Papers I-III)

The airflow model WAsP (Wind Atlas and Application Program, see Troen and Peterson 1989, Mortensen et al. 2002) provides a means of simulating airflow over a forested area based on the local wind climate, topography and surface roughness. Based on a polar grid terrain representation, orographic flow perturbations are evaluated in the model as the sum of spectral potential flow solutions using Fourier-Bessel expansion (Troen 1990). For vertical extrapolation in a flat terrain with homogeneous roughness, a logarithmic wind profile is assumed. To account for the influence of non-neutral stratification, the homogeneous-terrain wind speed is modified by the terrain perturbation. Resource grids are used to represent the output of the area concerned and each grid square has the values of coordinates, elevation, mean wind speed and Weibull parameters A and K at the height specified by user. Wind speeds and annual cumulative frequencies are simulated in WAsP by a Weibull distribution (Paper II, Eq. 1 & 3).

The input data for WAsP typically form a time series of wind measurements made at a single location, usually a meteorological station situated near or in the area of interest. The model also needs input data of surface roughness and orography of the measurement site and that of the area of interest. The properties of the WAsP model, its parameters, inputs, and the validity of its outputs as assessed against other models and field measurements of wind speed have been discussed in detail by Walmsley et al. (1990), Mortensen and Petersen (1997), Suárez et al. (1999), Achberger et al. (2002) and Mortensen et al. (2002).

Heuristic techniques (Paper IV)

The heuristics is a computational method that uses trial and error methods to approximate a solution for computationally difficult problems (ESRI 1995). Three different heuristics, i.e. 1) simulated annealing, 2) tabu search, and 3) genetic algorithm, were used in this study. The purpose was to find the optimal combination of treatment schedules of stands in regard to the risk management of wind damage with or without any timber harvest objectives. These techniques have been previously described in detail by Heinonen and Pukkala (2004) and Pukkala and Kurttila (2005) and the parameters of the heuristics used in this work were also based on experience of the application of those studies.

Simulated annealing and tabu search are local improvement methods, which mean that the initial solution is gradually developed through local improvements. A change of the solution is called a move. In this work, a move was equal to making two simultaneous changes in the current solution (clear–cuts regimes), i.e. the treatment schedule was changed simultaneously in two stands. All solutions that can be obtained with one move form the neighbourhood of the current solution.

Simulated annealing uses the best of a set of random combinations of stands' treatment schedules as the initial solution. A candidate move consists of first selecting two random stands and then a random schedule per stand. The selected schedules replace the schedules that are currently in the solution. A move that improve the objective function value is maintained. However, non-improving move with a certain probability may also be maintained. The probability of accepting inferior move decreases gradually during the optimisation process and at the end of the search it is close to zero.

Compared to simulated annealing, tabu search searches the neighbouring solution space before accepting one change in the solution. The production of a set of candidate moves and accepting one of them is repeated for many iterations. Typical of tabu search are also tabu lists. Schedules that participate in the move are kept in the tabu list for a certain number of iterations. This number is the initial tabu tenure of the schedule. A schedule could again participate in a move once its tabu tenure is decreased to zero. The best non-tabu move of the inspected candidates is accepted, or alternatively the one with the shortest tabu tenure, if all candidates are in the tabu list. If a candidate move yields a solution better than the best one obtained so far, it is accepted even if the move is tabu. Tabu search is stopped when a certain number of iterations are completed.

Unlike simulated annealing and tabu search, the search process of genetic algorithms is not based on neighbourhood search. Instead, genetic algorithms are based on an initial population of solution alternatives, their evaluation and their breeding. Each iteration (named as a generation) has a set of alternative solutions called parent chromosomes. When generating a new chromosome, a chromosome is selected with the probability proportional to its ranking; another is chosen randomly with an equal probability for all the remaining chromosomes. The two selected parent chromosomes are processed by crossing over (combining parts of two chromosomes) and mutation (random change in one or several genes, or stands) giving a birth of a new chromosome (offspring). In the incremental genetic algorithm technique used in this study, the new chromosome replaced one chromosome of the current population. The removed chromosome is selected based on its objective function value, the probability of removal being highest for chromosomes that has a low objective function value.

2.3 Studies on the effects of clear-cuttings on the local wind climate and the risk of wind damage

Study on the effects of clear-cuttings on the local wind climate (Paper I)

Some clear-cuttings occurred in the study area I between 1990 and 2001 inventories. Therefore it was analyzed if the changes observed in the forest structure over time affect the wind speeds at 10 m above ground. For this purpose, the mean wind speed was simulated for the study area I by calculating the average speeds of the grid square values using 100×100 m grids in WAsP simulations.

In the study area II, two different clear-cutting regimes were also applied by adopting the Finnish forest management regulations (Yrjölä 2002), i.e. clear-cuts were done: i) whenever stands reached the minimum acceptable species-specific mean diameter (DBH) and/or stand age (Case II, MINDBH in Paper I) and ii) whenever the stand age exceeded 100 years (Case III, 100Y in Paper I). In Case II the DBH criterion was 28 cm for all species and the age criteria were 100, 90 and 80 years for Scots pine, Norway spruce and birch, respectively. Within each clear-cutting regime, the cuttings were assumed to be carried out simultaneously in all stands fulfilling the criteria at the beginning of the simulations. The wind speeds of these two clear-cutting regimes were compared with the current situations (Case I, CURR in Paper I). Mean wind speed was simulated by calculating the average of grid square values using 50×50 m grids.

Regarding the airflow simulations for both study areas I and II; it was analyzed whether the cumulative probability of wind speeds higher than 11, 18, or 25 m s^{-1} would change in response to any changes in surface roughness (1990 versus 2001, and Case I versus Case II and III). The probabilities of wind speeds above the selected limits were calculated based on the Weibull distribution used in WAsP (Paper I, Eqs. 2 & 3) and separate probabilities obtained for each grid square.

In addition, a case-study airflow simulation by WAsP was conducted in which a west wind at a mean speed of 18 m s^{-1} was assumed to be prevailing at a height above ground of 10 m in the middle of the study area (Paper I, Fig. 1A). The aim of this simulation exercise was to find out whether any influence of the changes of surface roughness (mostly induced by clear-cutting) on wind speed could be found in the case of high wind speeds.

Studies on the effects of different clear-cutting regimes on the short- and long-term risk of wind damage (Papers II-III)

Because under Finnish conditions, wind damage is most likely to occur in stands located at the newly created forest edges, the risk of wind damage was calculated in this study only for the stands adjoining gaps (edge stands) with a stand height ≥ 10 m. This was done in regard to the number of stands at risk, their areas and length of vulnerable edges (the edges between those stands and gaps). The risk to stands with these edge conditions depends on their own stand characteristics (i.e. height, DBH and stand density), the size of upwind gaps, surrounding stands and topography.

In these studies (Paper II-III), only the study area II was used. The two clear-cutting regimes applied were the same as when studying the influence of clear-cuttings on local wind climate (Paper I). The critical wind speeds and annual risk probabilities after clear-cuttings were compared to the current situation (i.e. no new clear-cutting was carried out, Case I) to study the short-term influence of clear-cuttings on the risk of wind damage

(Paper II). Regarding the long-term influence of clear-cuttings on the risk of wind damage (Paper III), the clear-cut stands were first planted artificially before the simulations forest growth. The development of each stand was simulated over 20 years by the SIMA model and the results (tree/stand characteristics) of 1st, 5th, 10th, 15th and 20th years of each case study were used to calculate the risk of wind damage. The first year of the simulation represents conditions immediately after clear-cutting and planting of the seedlings. No other forest management practices took place during the simulation period after clear-cutting.

In each case study, the open gaps (including water area, clear-cut areas, open fields and small seedling stands with height < 2 m) were fixed in ArcGIS. If adjacent polygons represented gaps, they were merged into one polygon to form one gap. Most of the gaps were found to be irregular in shape, i.e. the gap sizes (the length of gap in direction of wind) differed in different directions and even different locations of the same edge at the same direction. They were therefore simplified for the HWIND calculations, i.e. treated as circular, with diameters determined by their areas representing the average gap size. The edge stands and the edges between the edge stands and gaps were extracted in ArcGIS in the form of polygon maps and polyline maps, respectively. The attributes of the stands were appended to the corresponding attribute tables of the polylines to ensure that the edges had the same stand characteristics as the related forest stands.

The resource grid squares of size 50×50 m in WAsP were used to represent the distribution of wind speed and frequency at a height of 10 m above ground level (corresponding to the HWIND calculations of critical wind speeds). As the grids did not match the forest stands in spatial shape, the maximum values of the grids located in the same stand were selected to represent the stand values, or the nearest grid represented the stand which had too small area to contain a grid. For each edge stand and separately for each case study, the cumulative probabilities were calculated for wind speeds higher than critical wind speeds using the critical wind speeds (calculated from the HWIND model) and the local distribution of wind speeds (based on the Weibull distribution). Thus, the output was the time frequency of possible wind damage events in a year, i.e. the annual duration of the occurrence of these damaging winds could be calculated by multiplying the annual cumulative frequency value by 365 days.

Study on the optimization of the clear-cuttings for the risk management of wind damage (Paper IV)

In this study (Paper IV), the dynamics of forest stands were simulated over a 30 year period using again the SIMA model. A no-cutting and a maximum of three alternative clear-cutting schedules were simulated for the stands at 5th, 15th and 25th year during the simulation. The criteria, which specified whether a clear-cutting was allowed or not, were mean DBH and age. The clear-cutting was simulated if the stand's DBH exceeded the DBH criterion or its age exceeded the age criterion. The clear-cut criteria used in this study differed from those used the Papers I – III. The clear-cutting criterion of DBH was set as 30 cm for Scots pine, and 28 cm for Norway spruce and birch; whilst the age criterion for Scots pine and Norway spruce was 80 years and for birch 70 years. After clear-cutting, an artificial regeneration was applied. No other management practices took place during the simulation period. Therefore, each stand had a maximum of 4 alternative treatment schedules. But this was not necessarily the case for those stands which didn't exceed clear-cut criteria at the 5th, 15th, or 25th year.

The critical wind speed was calculated, for each schedule and each stand with a height ≥ 10 m in HWIND at the 5th, 15th and 25th year. These critical wind speeds were used to represent the risk of wind damage at those edges from which its neighbouring stand was clear-cut (and became a gap). The critical wind speed of 20 m s^{-1} was used as the baseline criterion for defining stands that were at risk. Moreover, the gap sizes were simplified in this study, i.e. fixed gaps size of 10 times the average tree height at stand edge was used in computations (which outputs the maximum risk in regard to gap size, see Peltola et al. 1999a).

Altogether three different heuristic techniques were compared to optimize the temporal schedules and spatial patterns of clear-cutting regarding timber harvesting objectives and risk management of wind damage. For this purpose, four very different sets of management objectives were assumed, ignoring the possible irrelevance of some problem formulations in forestry practice: (1) The risk of wind damage was maximised as the only objective (Problem 1); (2) The risk of wind damage was minimised as the only objective (Problem 2); (3) The risk of wind damage was maximised with an even-flow target of harvested timber (Problem 3); (4) The risk of wind damage was minimised with an even-flow target of harvested timber (Problem 4).

The objective function was an additive utility function formulated as follows:

$$U = w_1u_1(E_1) + w_2u_2(E_2) + w_3u_3(E_3) + w_4u_4(H_1) + w_5u_5(H_2) + w_6u_6(H_3) \quad (1)$$

where U is total utility; w_i is the importance of objective i; u_i is a sub-utility function for objective i; E_j is the percentage of vulnerable edges of the total length of all the stand boundaries in the middle of management period j (i.e. when a stand adjoined gaps with certain critical wind speed (< 20 m s^{-1} in this work), part of its boundary adjoining the gaps was considered as having risk of damage); H_j is the total timber harvested during period j. In problems 1 and 2, objective weights w_4, w_5, and w_6 were zero and weights w_1, w_2, and w_3 were all 0.333 (1/3). All the weights were equal to 0.167 (1/6) in problems 3 and 4.

In problems 1 and 3, the sub-utility increased as a function of the length of vulnerable edges (Paper IV, Fig. 1 A), and decreased in problems 2 and 4 (Paper IV, Fig. 1 B). The sub-utility functions for harvest had an ascending-descending shape with the sub-utility increasing until the target cut of 12 000 m^3 was reached, after which the sub-utility started to decrease (Paper IV, Fig. 1 C). Therefore, maximizing the risk of wind damage means trying to lengthen forest edges with critical wind speeds < 20 m s^{-1}; whilst minimizing was trying to shorten forest edges with critical wind speeds < 20 m s^{-1}.

Sensitivity analysis on the predictions of the integrated models (Papers II-IV)

Previously, Blennow and Sallnäs (2004) have analysed the sensitivity of the integrated models of HWIND and WAsP under Swedish conditions. Since there is no propagation of data between HWIND and WAsP, the integration of these two models outputs similar sensitivity results as HWIND when used independently, which has been previously been analysed in detail by Peltola et al. (1999a). Therefore, in this context only the wind climate data (wind speeds) was changed by ±20% to study the sensitivity of the integrated model in regard to its input wind data (Paper II).

When SIMA is added to the integrated model system, the errors of input forest data may propagate from SIMA to HWIND and WAsP. To analyse the propagation of these errors in the integrated model system, the forest stand data was modified for input height, diameter and stand density by ±20%. With these varying inputs, the forest stands were simulated over a 20 year period. The simulation results for the 20th year were used to demonstrate the sensitivity of the outputs in respect to differing risk probabilities between modified and original input data (Paper III).

Furthermore, in the optimisation of clear-cutting regimes (Paper IV); the critical wind speed criterion was changed by ±25% (15 and 25 m s^{-1}). This was because a broad range of wind speeds (e.g. 14-30 m s^{-1} for 10 minutes) have been found to cause damage under Finnish conditions (Laiho 1987, Talkkari et al. 2000, Pellikka and Järvenpää 2003, FMI 2003). Since only minimizing vulnerable edges (Problems 2 & 4) was a realistic task in forest management, the sensitivity analyses were carried out with Problems 2 and 4. Similarly, the timber harvesting objective was also changed by ±25% (using 9000 and 15000 m^3/10yr) in Problem 4 to find out how the change in the harvesting objective affected the optimisation results.

3 RESULTS

3.1 Effects of clear-cuttings on the local wind climate (Paper I)

The coverage of older forests (trees over 15 m height) in the study area I decreased from 45% in 1990 to 28% in 2001, whereas the area of younger forests (tree height less than 15 m) increased roughly by 16% (Paper I, Figs. 1 & 2). This change in forest structure over time was due to regeneration cuttings and consequent establishment of new seedling stands. In the study area (II), the total clear-cut area was in Case II 109 ha (corresponding 24070 m^3 of harvested timber) and 32 ha in Case III (4479 m^3 of harvested timber). Especially in Case II, clear-cuttings significantly changed the forest structure and landscape configuration (Paper I, Fig. 3; Paper III, Fig. 4). As a result of intensive clear-cuttings, the total area of gaps in Case II was more than twice as large as in Case I, while that in Case III was about 40% higher than in Case I.

Over the whole study area I, no noticeable difference was observed in the mean wind speeds between the two stand inventories of 1990 and 2001, i.e. the mean wind speeds simulated by WAsP were 2.33 and 2.35 m s^{-1} at 10 m height above ground (medians 2.23 and 2.24 m s^{-1}). When the probabilities of wind speeds higher than 11 m s^{-1} were examined, it was also found that there were not any significant differences between the two surveyed years, even though the surface roughness changed during the 10 year period. The mean probability (average of all grid squares) of very high wind speeds (> 25 m s^{-1}) differed in some degree in 1990 and 2001, i.e. they were 3.8 and 4.0%, respectively.

When a storm from the west with a high speed of 18 m s^{-1} at 10 m above ground was assumed to blow, it was observed that there were locations where the wind speed was up to 2-3 m s^{-1} higher in 2001 than in 1990 (Paper I, Fig. 4). The mean wind speeds over the whole area in this hypothetical weather situation were 15.5 and 15.7 m s^{-1} in 1990 and 2001, respectively. The changes in wind speeds were associated with roughness changes induced by clear-cuttings. As far as the area coverage of a change in high wind speed (> 18 m s^{-1}) was concerned, it was found that the probability of the occurrence of such speeds had increased between the 1990 and 2001 in 73% of the 6562 grid squares, whilst it decreased in about 23% and remained unchanged in 4% of the squares (Paper I, Fig.5). Comparison of the decrease in roughness length from 1990 to 2001 (17% over the whole area, see Paper I, Fig. 2) indicated that the area where the probability of a high wind speed increased was larger than might have been expected. Thus, the decrease in the area of older forests by clear-cutting seemed to increase, locally, the risk of occurrence of high wind speeds.

Over the study area II, no noticeable difference was observed in the simulated mean wind speed, when current situation in 2001 (Case I) was compared with situations in which new forest edges were created through two different clear-cutting options (Case II & III). The mean wind speeds were 2.30, 2.32 and 2.31 m s^{-1} for Case I-III (and medians 2.24, 2.32 and 2.24 m s^{-1}). When the probability of high wind speeds was analyzed with 11 m s^{-1} as the limit, it was similarly found that there was not any significant difference between these cases. When a storm of 18 m s^{-1} at 10 m above ground was assumed to blow from the west, the mean wind speeds were 14.9, 15.0 and 14.9 m s^{-1} in Case I-III, respectively. It was observed also that the probability of an occasional occurrence of a wind speed higher than 18 m s^{-1} increased in 50% of the total of 2924 grid squares for Case II compared to Case III, and decreased in approximately 1% and remained the same in about 49% of the grid squares (Paper I, Fig. 6). The main difference between Case II and III was the larger total clear-cut area in Case II (9% more) and smaller amount of old forests (7% less). This relatively small change was able to create an increase in wind speed in approximately 50% of all the grid squares.

3.2 Effects of different clear-cutting regimes on the risk of wind damage (Papers II-III)

In principle, forest stands with critical wind speeds less than 20 m s^{-1} could be expected to be quite vulnerable to wind damage in Finland. In this study, the critical wind speeds of single stands in the risk probability class < 0.1%, for example, ranged from 15.1 to 40.7 m s^{-1}. The small probability of even quite low critical wind speeds in some stands (< 0.1%) was due to the influence of the topography and/or roughness, i.e. those stands were located on the lee side of a hill or surrounded by stands with high surface roughness, which reduced the actual wind speed locally. By comparison, the ranges of critical wind speeds in the risk probability classes 0.1-1% and ≥ 1% were 13.3-24.9 m s^{-1} and 8.3-16.6 m s^{-1}, respectively. In this study, the edge stands with critical wind speed of < 20 m s^{-1} or risk probability ≥ 0.1% were taken as representing the highest risk and the analysis of the risk of wind damage was therefore concentrated on these stands.

When analyzing the short-term influence of clear-cutting regimes on the risk of wind damage (Paper II), it was found that the number of stands at risk (the edge stands with height ≥ 10 m), their area, and length of vulnerable edges generally decreased for critical wind speeds of less than 20 m s^{-1} in Case II relative to the current risk (Case I) and Case III, while they increased for critical wind speeds greater than 20 m s^{-1} (Paper II, Fig. 3). Although the risk increased locally for some stands in Case II because of the higher wind speeds at the edges of clear-cut areas, the overall risk regarding the number and area of stands at risk and the length of vulnerable edges (with risk probabilities ≥ 0.1%) decreased regionally in Case II relative to Case I and III (Paper II, Fig. 3 & Table 2). Only 19 stands had a risk probability ≥ 0.1% in Case II, the corresponding figures in Case I and III were 30 and 36, respectively (Paper II, Table 3). The related areas at risk and vulnerable edges also decreased in Case II compared with Case I and III (Paper II, Table 3). This could be explained by the fact that the average tree size of the stands decreased at the regional level (when old stands were cut down) and therefore critical wind speeds increased an average in

Case II relative to Case I and III (Paper II, Table 1 & Fig. 3). On the other hand, the risk increased at the regional level in Case III relative to Case I and II, because additional vulnerable forest edges were created and a lot of vulnerable old stands still existed at these edges.

Correspondingly, in the analyses of the long-term influence of clear-cutting regimes on the risk of wind damage (Paper III), it was found that as the clear-cuts closed due to the growth of the seedling stands in these gaps, the total number of edge stands generally decreased in all case studies, as did the number of open areas and total area of gaps (Paper III, Fig. 5). However, during the first 10 years after clear-cuttings, the number of gaps even increased in Case II and III compared to Case I. This was because some large gaps joined together as a result of clear-cutting at the beginning of the simulation. But, over time they were partly divided again into smaller gaps, i.e. when seedling stands passed 2 m in height and were no longer treated as gaps. In Case II the number of edge stands and length of edges also remained significantly high during the first 15 years, compared with Case I and III as could be expected based on intensive cuttings (Paper III, Fig. 5 and 6). However, at the end of the 20 year simulation period no significant differences existed between the case studies regarding the number of open areas and gaps, total gap area, number of edge stands or the length of total edges. At that stage, most of the existing gaps left were permanent gaps.

Despite the large differences in area that had been clear-cut, there was, throughout the simulation period, an average of only 15% less vulnerable edges in Case I (7294 m) and 7% less in Case III (7951 m) compared to Case II (8539 m) with risk probability ≥ 0.1% (Paper III, Fig. 6). Moreover, the average number of stands located at these vulnerable edges (35 stands) and their area (61 ha) with a risk probability ≥ 0.1% decreased over the 20 year simulation period in Case II compared to Case I (40 stands at risk, total area of these stands 81ha) and III (41 stands and 82ha) (Paper III, Fig. 7). Thus, the average number and area of stands at risk in Case II were about 14% and 29% less compared with Case I and III, respectively. The effects of different clear-cutting options used on the amount of vulnerable edges as well as number of edge stands at risk (with a risk probability ≥ 0.1%) and their area gradually disappeared towards the end of the 20 year simulation period, except in Case III, where the risk increased again in the last five year cycle.

3.3 Optimization of the clear-cuttings for the risk management of wind damage (Paper IV)

All the three heuristic optimisation methods compared outputted reasonably similar results in the preliminary analyses (Paper IV, Fig. 2). Moreover, the objectives of timber harvesting (Problems 3 and 4) were almost fulfilled for each 10 year period. The difference observed between the actual harvest volume and target level (i.e. 12 000 m^3/10yr) was very small for each period, i.e. it ranged in Problems 3 and 4 from -7 to 13 m^3/10 yr in simulated annealing, from -18 to 7 and from -3 to 11 m^3/10 yr in tabu search and genetic algorithm, respectively. However, the simulated annealing performed best in all the 4 problems on average, i.e. it outputted higher values for maximizing vulnerable edges and lower values for minimizing vulnerable edges. Therefore, the more detailed analysis of optimisation results concentrated only on the output by simulated annealing.

When minimizing the occurrence of vulnerable edges was the only objective (Problem 2), there were still some new clear-cuts created (Paper IV, Table 1 and Fig. 3). Those clear-cut stands were, however, clustered together to avoid the increment of total edges (Paper IV,

Fig. 4). Minimizing the length of vulnerable edges created a smooth landscape in which young stands were located at edges (Paper IV, Fig. 5). Thus, a few optimised clear-cuttings could shorten the vulnerable edges even if there were no timber production objectives given. If the minimization of vulnerable edges was combined with the sustainable even flow of timber harvesting (Problem 4), there were more vulnerable edges created (Paper IV, Fig. 3), and the clear-cut stands were not as well clustered as in Problem 2 (Paper IV, Fig. 4). The total length of vulnerable edges was on average nearly 4 times higher in Problem 4 compared to Problem 2 over the 30 year planning period. The total timber harvest over the 30 year period was about 160% higher in Problem 4 compared to Problem 2. Therefore, the sustainable even flow timber harvest will limit the minimization of the length of vulnerable edges to a certain extent.

On the other hand, if maximising the occurrence of vulnerable edges was the only objective (Problem 1), the clear-cuts were distributed uniformly and often next to an old stand (Paper IV, Fig. 4). As a result, the landscape developed towards a fragmented landscape regarding the tree height. Furthermore, fewer clear-cuts occurred compared to the optimisation with the even-flow target for timber harvesting (Problems 3 and 4; see Paper IV, Table 1). There were also less vulnerable edges (26%) in Problem 3 than in Problem 1, although the length of vulnerable edges was also maximized in Problem 3. Thus, the even-flow target for timber harvesting limited the possibility of maximizing the length of vulnerable edges because it was affected by heavy cutting.

When there were no timber harvesting objectives given (Problems 1 and 2), large differences were observed in the occurrence of not only vulnerable edges but also in the total length of edges between Problems 1 and 2 (Paper IV, Fig. 3). If the timber harvesting objective was included (Problems 3 and 4), there was little difference in the total amount of edges between the maximizing and minimizing vulnerable edges due to the constraints of timber harvest objectives. The difference of the vulnerable edges, however, was significant in Problems 3 and 4 (Paper IV, Fig. 3).

3.4 Sensitivity of predictions by the integrated models approach (Papers II - IV)

When the component models were integrated together, the changes of the input diameters had a significant and uniform effect on the annual cumulative risk probabilities (Paper III, Table 2). Whereas the input height and stand density had, in general, either insignificant or no uniform effect on the final risk probabilities. In addition, the integrated models were also sensitive to the changes of wind speeds (Paper II, Table 4). Norway spruce was found to be more sensitive than Scots pine to any changes in the stand characteristics (Paper II, Table 2). It was also more sensitive in more windy conditions (+20%) than Scots pine, while less sensitive in less windy conditions (-20%).

When the SIMA and HWIND were integrated with heuristic techniques and the critical wind speed criterion was decreased by 25 % (to 15 m s^{-1}), less stands were expected to have a significant risk compared to the baseline wind speed of 20 m s^{-1} . Therefore, the total length of vulnerable edges was significantly decreased in Problems 2 and 4, while the timber harvests were increased over the 30 year period in Problem 2 (Paper IV, Table 2). On the other hand, when the critical wind speed criterion was increased by 25 % (to 25 m s^{-1}), more stands were expected to have significant risk compared to the baseline wind speed of 20 m s^{-1} and therefore, the total length of vulnerable edges was increased in both Problems 2 and 4; whilst the timber harvest decreased in Problem 2 (Paper IV, Table 2).

Furthermore, the harvested stands over the 30 year simulation were kept almost the same for all the three critical wind speed criteria cases when the Problems had the same timber harvesting target (Paper IV, Table 2 & Fig. 6). But most of the clear-cut stands differed in the timing of cutting within the 30 year simulation, however (Paper IV, Fig. 6).

When the timber production objective was decreased to 9 000 or increased up to 15 000 m^3/10yr compared to the baseline harvest of 12 000 m^3/10yr, there were only small changes in the total length of vulnerable edges on average over the whole optimisation period (Paper IV, Table 3). It should be noted, however, that the harvest objective of 15 000 m^3/10yr could not be fully fulfilled since there were not enough old stands satisfying the clear-cut criteria.

4 DISCUSSION AND CONCLUSIONS

4.1 Validity of integrated models approach (Papers I-IV)

Based on earlier validation work carried out individually in each of the component models (SIMA, HWIND and WAsP), it could be expected that their predictions should provide results with an accuracy typical for these kinds of models. Previously, Talkkari et al. (2000) have also integrated the mechanistic wind damage model HWIND with the airflow model MS-Micro/3 (Walmsley et al. 1993) under Finnish conditions and Blennow and Sallnäs (2004) have integrated HWIND with the WAsP airflow model under Swedish conditions. The studies by Talkkari et al. (2000) and Blennow and Sallnäs (2004) found that these integrated models were reasonably successful when their predictions were applied to real damaged stands.

No significant wind damage has been inventoried in the study area used in this study, however, to test the integrated model system. This was even though relatively low wind speeds have recently been found to cause actual damage under Finnish conditions (Laiho 1987, Talkkari et al. 2000, Pellikka and Järvenpää 2003, FMI 2003). The wind speeds needed for actual damage are nevertheless quite rare under Finnish conditions also according to the meteorological statistics, and as confirmed by this study, i.e. a critical wind speed range of 8.3-24.9 ms^{-1} corresponded to a wind risk probability $\geq$ 0.1%.

When only wind damage model HWIND and airflow model WAsP were integrated together to study the current risk of wind damage, the output results were found to be most sensitive to tree height and DBH (Blennow and Sallnäs 2004). Furthermore, the errors of output risk probabilities could also be induced by the lack of proper input data for wind climate (Paper II). Similarly, it was found that when the forest growth and yield model SIMA was added to the integrated model system in order to simulate the long-term risk of wind damage, the errors of any input data were expected to propagate between models and affect the accuracy of the risk assessment (Paper III). For example, the errors in input DBH affect the development of the stand (simulated by SIMA). This includes effects on the predicted height which in turn affects the classification of young seedling stands into open gaps (height < 2m) and stands with a possible risk of damage (height $\geq$ 10m) at these edges and their predicted critical wind speeds (HWIND). Moreover, this also affects WAsP predictions (e.g. errors in roughness values for stands affect the simulation of wind distribution) and as a result, the predicted risk probabilities of damage. In addition, the integrated models of HWIND and WAsP were sensitive to input height. While the integration of SIMA, HWIND and WAsP were not, because in the SIMA model, DBH development is used to calculate height during the tree growth simulation.

It may be noted that the integrated models simplified the input data, i.e. by using the mean tree/stand attributes of each stand as inputs to SIMA model. The gap sizes were also calculated by assuming their shapes were circular; and only one direction of the wind was used to simulate the local wind climate. In addition, using the whole polygon area of stands at risk to represent the areas at risk might overestimate the loss of timber, and vice versa. Those simplifications could be improved by more precise calculation in the future work.

All the three heuristic techniques, which were coupled with SIMA and HWIND, outputted reasonable clear-cutting patterns when aiming at minimizing or maximizing the risk of wind damage with or without even flow of harvested timber (Paper IV). The simulated annealing was found on average to perform better than tabu search and genetic algorithm in all the four planning problems. This was also in line with the previous findings by Bettinger et al. (2002), for example. As a comparison, Palahi et al. (2004) and Pukkala and Kurttila (2005) suggested that genetic algorithm is the most suitable method for solving the most difficult spatial problems. However, the optimisation problems differed between these studies; and this kind of performance rank is also quite variable since the problem formulations, implementation of the technique and parameter settings can greatly affect the performance of different algorithms (Crowe and Nelson 2002).

The optimal solution was, however, quite sensitive to the criterion of critical wind speed. Therefore, it is useful to know how a change in this criterion affects the optimisation solution. This information will help to predict the impacts of different wind speed events on the stands in a region. At the forest unit level, the optimised clear-cut regimes depend also on the age structure and spatial distributions of permanent gaps and old stands. When different critical wind speed criteria were set in Problem 4, the even-flow harvesting target constrained the flexibility to select clear-cutting stands in the whole 30 year period. However, the optimisation process could select proper stands to cut for each period. But, the results were sensitive to the weights of different criteria.

4.2 Effects of clear-cuttings on the local wind climate and the risk of wind damage (Paper I-III)

The results indicated that clear-cuttings on the scale typically carried out in Finnish forestry does not have a substantial influence on regional mean wind speeds. This is because the clear-cutting areas involved are relatively small and new trees are planted immediately after harvesting. However, large gaps can produce a markedly increment of local wind speeds, especially in terms of high speed winds (Paper I). This may increase the risk of wind damage especially in recently thinned stands and mature stands adjacent to newly clear-felled areas. On the other hand, the short-term risk of wind damage at a regional level may not necessarily increase after clear-cuttings as was demonstrated in Paper II. This is the case, especially if the old and most vulnerable stands are cut intensively. But if there were still left some old stands in the forest (as was done in Case III in Paper II), new clear-cuttings will increase the short-term risk of damage in these stands.

In this study, it was observed two opposite long-term tendencies regarding the risk of wind damage at a regional level. Critical wind speeds of individual tree stands decreased over time when tree stands aged (and stand height increased), which increased the risk of wind damage. On the other hand, when gaps closed due to growth of the seedling stands, fewer stands adjoined gaps and wind speed was slowed down locally, which reduced the probability of damage. In the study area II used in this work, the decrease in total gap area seemed to have more effect at a regional scale than the increment in tree size so that the probability of wind damage gradually decreased over time (when new clear-cuts were not created).

Altogether, the clear-cutting scenarios applied in this study (Case II and III), represented very different types of harvesting interests by forest owners. In Case II there was over 4 times more timber harvested than in Case III, whereas in Case I there were not done any new clear cuttings. Despite this, the clear-cuttings in Case III induced only an average of 7% less risk of wind damage over the 20 year simulation in regard to the length of vulnerable edges than that in Case II. Moreover, in Case III, there existed many stands having a high risk over the 20 year period, because only stands over 100 years of age were harvested at the beginning of the simulation study. Thus, forest managers must consider the variations of the risk of wind damage when harvesting timber.

It should be kept in mind, however, that the current spatial configuration of stands (with its age class distribution and development stages), as well as topography and local wind climate, affected the level of risk the forest suffered. Thus, the effects of the harvest regimes observed in this study may not be directly applicable to other forest areas and regions. Moreover, any of these cases I-III analysed (in Papers II-III) did not represent any optimal solution for temporal schedules and/or spatial patterns of clear-cuttings in regard to the risk management of wind damage and the amount of harvested timber (and incomes) expected at the regional level.

4.3 Optimisation of clear-cuttings for the risk management of wind damage (Paper IV)

In this study, the planning problems that solely aimed at minimizing the length of edges at risk (Problem 2) or as combined with an even flow of harvested timber (Problem 4) were realistic planning problems, unlike those in which the length of vulnerable edges was maximised (Problems 1 and 3). The latter ones offered, however, means for the sensitivity analyses of the spatial pattern of clear-cutting in regard to the spatial objectives used in this study. The harvest target used in this study could be kept as realistic because the total harvested volume of timber (36 003 m^3) in Problem 4 was less than the volume growth over the planning period considered (44 661 m^3), i.e. the final volume of timber in the forest unit even increased during the planning period.

The even flow of harvested timber may limit this possibility (measured as the total length of vulnerable edges) as was demonstrated in this work (see Problem 4 compared to Problem 2). With a proper intensity, interval and locations of cuttings, however, it is possible to reduce the risk of wind damage in a forest, i.e. the total length of vulnerable edges could be reduced by: i) aggregating clear-cuttings (i.e. decrease the total amount of edges); ii) locating clear-cuttings at the edges of young stands (i.e. tree height < 10 m) or stands with critical wind speeds high enough to indicate lower level of risk of damage (i.e. to decrease the percentage of the vulnerable edges of the total edges); and iii) smooth the landscape by decreasing the spatial fragmentation of stand height. In addition, any creation of clustered clear-cutting stands during the same period may decrease the costs of logging operations (Pukkala and Kurttila 2005).

4.4 Conclusions

Only very few attempts have been made so far to study the effect of alternative forest management options on the risk of wind damage over time at a regional scale. In fact, Dunham et al. (2000) are among the first to couple the mechanistic wind damage model ForestGALES with the wind climate model DAMS and the Yield Class Model to estimate annual damage of stands at different time steps. As a comparison, this work represented an attempt to integrate a forest growth and yield model SIMA with the mechanistic wind damage model HWIND and airflow model WAsP in order to assess the short- and long-term risk of wind damage for alternative forest management options (i.e. clear-cutting options) at a regional scale.

The short- and longer-term risk of wind damage was evaluated in a forest management unit in respect to the number of stands at risk, their areas and the length of vulnerable edges. As the effects of clear-cut schedules and patterns vary, it is in practice difficult to find out optimal clear-cut regime over a forested area. This is the case especially if simultaneous timber harvesting and risk management objectives are given. For that purpose, this study presented a first attempt to employ heuristic optimisation techniques together with a forest growth and yield model, a mechanistic wind damage model and GIS software to solve the multi-objective planning problem. GIS software such as ArcGIS, which was also used in this study, can offer tools to define the neighbourhood between forest stands (polygons) and link the forest boundary (arc) to its left and right forest stands based on topology. The vector data of the forest could, therefore, directly be processed in the integrated approach. The output results are, thus, more approximate to actual situations.

As a conclusion, it could be expected that the integrated models approach can be used to help forest managers to make more efficient decisions regarding the risk management of wind damage. This is because it could assist to understand how forest management affects the local wind conditions (also considering factors such as topography, surface roughness and forest structure), and consequently the short- and long-term risk of wind damage. In the above context, the use of heuristics could help in proper management planning under the risk management of wind damage and timber harvesting objectives. Moreover, GIS software could be used to visualize landscape configuration of forest structure and management regimes (e.g. clear-cutting patterns) and the locations of the most vulnerable stands and edges. However, how any clear-cuttings in a forested area affect in practice on the risk of wind damage at their margins, depend on the tree and stand characteristics of these edge stands, but also on the landscape configurations of the specific forest (i.e. age structure, development stage and topography) and the temporal schedules and spatial patterns of clear-cuttings in addition to the occurrence of high wind speeds.

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