Dissertationes Forestales 56

Impacts of natural disturbances on the development of European forest resources: application of model approaches from tree and stand levels to large-scale scenarios

Mart-Jan Schelhaas

Faculty of Forest Sciences
University of Joensuu

Academic dissertation

To be presented, with permission of the Faculty of Forestry of the University of Joensuu, for public criticism in the auditorium BOR 155 of the University of Joensuu, Yliopistokatu 4, Joensuu, on 28th March 2008, at 12 o'clock noon

Title: Impacts of natural disturbances on the development of European forest resources: application of model approaches from tree and stand levels to large-scale scenarios

Author: Mart-Jan Schelhaas

Dissertationes Forestales 56

Supervisors:
Prof Dr. Timo Pukkala, University of Joensuu, Finland
Dr. Gert-Jan Nabuurs, Centre for Ecosystem Studies, Alterra, Wageningen UR, the Netherlands

Pre-examiners:
Prof. Dr. Ola Sallnäs, Southern Swedish Forest Research Centre, Sweden
Dr. Cristopher P. Quine, Forest Research, UK

Opponent:
Prof. Dr. Barry Gardiner, Forest Research, UK

ISSN 1795-7389
ISBN 978-951-651-200-9 (PDF)

Year of publication: 2008

Publishers:
Finnish Society of Forest Science
Finnish Forest Research Institute
Faculty of Agriculture and Forestry of the University of Helsinki
Faculty of Forestry of the University of Joensuu

Editorial Office:
The Finnish Society of Forest Science
Unioninkatu 40A, FI-00170 Helsinki, Finland
http://www.metla.fi/dissertationes

Schelhaas, M.J. 2008. Impacts of natural disturbances on the development of European forest resources: application of model approaches from tree and stand levels to large-scale scenarios. Dissertationes Forestales 56. 28 p.
Available at http://www.metla.fi/dissertationes/df56.htm

ABSTRACT

Natural disturbances can significantly affect the sustainable production of forest services. Until now there has been no concise overview of the damage such disturbances have caused to European forests, and their role in projection models has often been ignored. This dissertation aims to contribute in filling those gaps. A literature review in Paper I revealed that from 1950 to 2000 the annual average timber volume damaged by disturbances was 35 million m^3: 53% by storms, 16% by fire, 8% by bark beetles and 8% by other biotic factors.

A natural disturbance module was added to a large-scale scenario model, which was then applied to Switzerland and Austria. For Switzerland, it was found that the inclusion of natural disturbances significantly affected the development of growing stock, both under current and changing climatic conditions (paper II). In Austria, climate change doubled the expected damage by bark beetles by the end of the century (paper III). Adaptation through replanting with different tree species after clear-felling had only a small mitigating effect, since older forests are the most vulnerable.

To study how silvicultural regimes affect the wind damage risk, a wind damage module was added to an individual-based forest simulator. The explicit inclusion of shelter and support from neighbouring trees enabled both individual tree and whole stand stability to be simulated in detail (papers IV-V). Silvicultural regimes leading to relatively low tree height to stem diameter (h/d) ratios experienced the least damage. Low h/d-ratios could be obtained by maintaining low stand densities in even-aged stands or by favouring trees with a low h/d ratio when thinning in uneven-aged stands. It is concluded that the inclusion of disturbances in projection models of different scales offers great possibilities for exploring alternative scenarios and associated risks, for example for adapting to expected future climate change.

Keywords: abiotic damage, biotic damage, wind damage, bark beetles, simulation model

ACKNOWLEDGEMENTS

Finally the moment is there to write one of the last pieces of this dissertation: the acknowledgements! Indeed a sign that the end of the journey is near. Sometimes I still can't believe it's really happening. Combining work, a family and a PhD called for creative working hours and places. Paper IV was finished during a parental leave. The last parts of paper V and the summary were finished in hotel rooms in Bulgaria, in between extensive lunches, dinners and breakfasts. I submitted it from the university in Sofia. I started putting everything in the right format at the airport of Vienna late noon, and finished it after midnight at the railway station of Utrecht, waiting for the train that would bring me home.

In the long list of people to thank, my "boss" Gert-Jan Nabuurs undoubtedly deserves the first place. You have given me many opportunities over all these years and it was you who first launched the idea of doing my PhD on natural disturbances. You introduced me to the world of science, modelling and travelling around the globe. Besides work I enjoyed your company in many other activities, like playing squash, running, mountain biking and snowball fights in- and outside the sauna. Yes, the sauna evenings are a thing to remember, like our attempt to attain 100% humidity in sauna. And no matter how busy work was, there was always time for a laugh!

My supervisor at the University of Joensuu was Timo Pukkala. Usually I would come to your office once a year, explaining that the progress I made was again less than I expected, and invariably I would come with a new optimistic estimate for the future. Thanks for your patience over the years and your guidance in writing the articles and the summary. Another person at the University that I owe great thanks is Heli Peltola. After our first contact you got involved more and more, and without you this dissertation would have been much harder to finish. You were always ready to answer my sometimes very detailed questions about HWIND, provide lengthy comments on manuscripts and doing practical things for me that are easy if you are in Finland, but impossible if you are somewhere else. And it was you that came up with the idea of introducing tree interactions in the fourth article. I'm still very happy about that!

The connection to Finland started in 1998 with a scholarship at the European Forest Institute (EFI), and many shorter and longer visits followed. EFI is a very nice place to be, with an interesting mix of people, nationalities and cultures. The working environment was always very good, mainly because of all the nice people. I will not try to list all of them, so just thanks to everybody! Just two exceptions: I had great times sharing the office with my "big brother" Ari Pussinen. We had big discussions on EFISCEN, and you were a master in drawing graphs and pictures, and explaining them. Although not directly involved in the dissertation work, you always had a clear view on where to go and what to do. They sure were helpful! A very special word of thanks goes to the Schuck family: Andreas, Annette, Lukas, Judith and Finn. Andreas introduced me to cross-country skiing, plop fights and music styles I didn't know they existed. Annette "forced" me to speak German, took me to concerts at the university, and we shared many board games and walks. The children adopted me as a kind of second daddy ("Papa Mart-Jan") and we had great fun together. Yes, I can surely say that you provided me with a second home in Finland.

Also at Alterra many colleagues were involved directly or indirectly in this work. During the literature review, the people at the library were very helpful in finding even the most obscure references. They even had to upgrade me to "special user" due to the large number of publications I was borrowing. Koen Kramer allowed me to use, modify and

expand the ForGEM model. Bert van der Werf assisted in programming, model design, bug hunting and statistical issues. The many discussions on forest management and windthrow with Sander “hee bedankt” Wijdeven were helpful in getting the model and manuscripts in shape. In ForGEM matters, also Isabel van der Wyngaert was a good sparring partner. Thanks to all of you! And of course thanks to all the other colleagues for relaxing and humorous coffee breaks, sometimes badly needed to get out of the work for a moment. With this respect I surely have to mention Sandra Clerkx, always ready for a chat, a joke, a gossip, chocolate, whatever as long as it is not work related. Thanks for sharing the office with me, respecting the “ear-plug” times and joining me on Fridays at 16:30 visiting the “magnet” downstairs.

Then there were many colleagues outside Alterra and EFI. Thanks to all those people who helped me with finding and translating local sources of information for the first paper. During the many travels, many people tried their best to let me feel at home and showed me around. I appreciate that a lot! Also many thanks to Rupert Seidl. Your scholarship proposal came as a welcome surprise to me. Besides the efficient cooperation, we had nice discussions on work and non-work related topics. I hope we can continue to collaborate in future! Although much of the work in this dissertation was done in the evening hours, some project time was spent on it as well. Particularly CAMELS, EFORWOOD and ADAM were projects that were closely related to the work in this dissertation. Furthermore, Alterra provided me the opportunity to follow courses for the study plan and resources to finish the work.

Of course there was life besides the PhD work as well. I spent lots of time with Detmer behind the computer, “working” together on “reports”, “articles” and other “useful” things. Those times I could really forget about anything else! Also having my weekly daddy-day helped in putting everything back into the right perspective. And whenever I needed to travel, my and Sandra’s parents were always ready to step in. I don’t know how we could have managed without you. My sincere thanks! And this brings me to the last person I really need to thank: my wife Sandra! Thank you for being my companion all this time and for your support, patience and love.

LIST OF ORIGINAL PUBLICATIONS

The thesis is a summary of following papers I-V:

I. Schelhaas, M-J., Nabuurs, G.J. and Schuck, A. 2003. Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biology 9:1620-1633.

II. Schelhaas, M-J., Nabuurs, G.J., Sonntag, M. and Pussinen, A. 2002. Adding natural disturbances to a large-scale forest scenario model and a case study for Switzerland. Forest Ecology and Management 167:13-26.

III. Seidl, R., Schelhaas, M-J., Lindner, M. and Lexer, M. 2007. Modelling bark beetle disturbances in a large-scale forest scenario model to assess climate change impacts and evaluate adaptive management strategies. Manuscript.

IV. Schelhaas, M-J., Kramer, K., Peltola, H., van der Werf, S.C. and Wijdeven, S.M.J. 2007. Introducing tree interactions in wind damage simulation. Ecological Modelling 207:197-209.

V. Schelhaas, M-J. 2007. The wind stability of different silvicultural systems for Douglas fir in The Netherlands: a modelling study. Manuscript.

Most of the work involved in papers I, II, IV and V was carried out by the present author, although comments made by others on the manuscripts were incorporated. The present author contributed very significantly to paper III by designing the model coupling, providing the EFISCEN model framework, assisting in the scenario development and writing the manuscript.

CONTENTS

1 INTRODUCTION

1.1 Development of forest resources and the role of natural disturbances

European forests are among the most intensively managed forests in the world. As a result, although only 5% of the global forest area is located in Europe (193 million hectares, excluding the Russian Federation), European forests account for 23% of the global round wood removals (FAO, 2007). Removals have increased: from just over 400 million m^3 in 1990 to nearly 500 million m^3 of timber in 2005 (FAO, 2007). In addition, removals of non-wood forest products are estimated to be over half a million tonnes per year (FAO, 2007). Meanwhile, other forest functions are also becoming more important: for example, the area designated primarily for nature conservation has tripled (from 6.6 million ha in 1990 to 20.3 million ha in 2005: FAO, 2007) and now accounts for 10.5% of the total forest area. A further 19.5 million ha (10.1%) has been assigned a primarily protective function (protection of soil, water, air and infrastructure, for example). Another important function of the forest, especially in more urbanised regions, is recreation. UN-ECE (2005) has estimated that the total number of person-visits to European forests was roughly 3.6 billion per year. Further, forests can play a significant role in combating climate change. Carbon stocks in European forests amounted to 19.5 Pg C in the 1990s, and have been increasing by 0.14 Pg per year (Nabuurs et al., 2003). Not surprisingly, forests can be an important source of bioenergy (EEA, 2006), and the higher oil prices and greater interest in bioenergy are likely to increase the demand for woody biomass from forests (IPCC 2007).

Despite their intensive use, the forest resources in Europe are growing. The forest area is currently increasing by about 760 thousand ha per year (0.4%; FAO, 2007) and the average growing stock volume increased from 124 m^3 ha^{-1} in 1990 to 141 m^3 ha^{-1} in 2005 (FAO, 2007). These trends are projected to continue for at least several decades to come (Schelhaas et al., 2006). Despite these positive trends, there are other developments that are cause for concern. One of these is natural disturbances (FAO, 2007). These disturbances can cause unforeseen loss of living forest biomass and reduce the value of the timber or forest stand. They play a significant role in forest development and also affect the projections of the development of forest resources. Consequently, disturbances are highly relevant factors in the sustainable management of forest ecosystems (FAO, 2007). However, information on the historical and current role of disturbances in European forests is very patchy and their role in forest projection models is usually ignored.

Risks, such as natural disturbances, can theoretically be described by the surface area of a triangle (Kron, 2002), where the sides represent hazard, exposure and vulnerability. Any change to one of the sides of the triangle will lead to a corresponding change in risk level. Hazard could be seen as a probability of occurrence, which in forestry is often related to the climate. For example, fire hazard depends for a large part on weather conditions, as it is increased by the factors high temperature, lack of precipitation and presence of wind. Another hazard factor is the presence of an ignition source. Most of the fires in Europe are caused by humans, either intentionally or through negligence. Only very few fires are ignited by lightning. Another hazard – that of wind – is entirely related to the climate. European countries with Atlantic coastlines generally experience higher wind speeds, with Ireland and the United Kingdom in particular having a rather severe wind climate. Also, mountainous regions generally experience a more severe wind climate due to the topographical influences.

Compared to fire and wind hazards, the biotic hazard is more difficult to characterise because of the great diversity of agents of biotic disturbance. Many insects are favoured by warm and dry conditions (Speight and Wainhouse, 1989), but fungi favour more moist conditions (Coakley et al., 1999). Low winter temperatures may reduce insect survival rates (Leather et al., 1993), but may on the other hand be favourable for the synchronisation of life cycles with host plant species (Buse and Good, 1996). In general, biotic hazard seems to be less in more extreme climatic conditions (Jactel et al., 2007). Further, biotic hazard depends on the dispersion capacity of the agent as well as on the presence of natural enemies. The latter might be related to many factors.

The exposure side of the triangle can be expressed in terms of the values that are at stake. In principle these values includes all forest functions (such as protection, timber production, biodiversity, landscape, amenity), but many of them are difficult to quantify. Therefore, in this thesis only the two variables that are easiest to quantify are taken into account as a proxy for exposure of forest to risk: forest area and wood volume. Vulnerability expresses how easily a forest is damaged by the agent under consideration. It can usually be linked to the actual state of the forest. For example, coniferous species generally burn more readily than broadleaved species (Meyer, 2005) and fire spreads more easily in young and dense stands (Vélez, 1985; Brown and Smith, 2000). A forest's vulnerability is also heightened by the presence of flammable material on the forest floor (litter and humus, for example).

Tree species composition is also important for vulnerability to wind. Coniferous species are considered more vulnerable to wind damage than broadleaved species, with Norway spruce (*Picea abies* (L.) Karst) being regarded as particularly vulnerable (Schütz et al., 2006). However, Norway spruce has often been used to afforest sites that have unfavourable soil conditions and are waterlogged (Böhm, 1981). Though rooting depth is an important factor in vulnerability to wind, many other factors play a role as well. Wind vulnerability is a very complex field of research, often resulting in conflicting findings. The tree and stand variables most important with regard to tree stability are tree height and the ratio of tree height to stem diameter at breast height (h/d ratio). Taller trees are more exposed to the wind than shorter ones, for example. Because stand or tree age is highly correlated with tree height, age is often used as a proxy for height.

Vulnerability to biotic agents is again difficult to characterise and largely depends on the specific agent under consideration. Some agents are specific to certain tree species or stages of stand development. Others are generalists, damaging trees regardless of whether they are young or old. Overall, broadleaved tree species seem to have more associated insect species than conifers (Southwood, 1961; Brandle and Brandl, 2001). However, tree species react differently to damaging agents. For example, broadleaves can react immediately to defoliation by forming new leaves and shoots, whereas defoliation in conifers can remain visible for several years. In general, trees will be more vulnerable to biotic agents if they are more exposed to stress (drought, extreme temperatures, pollution, damage from logging, wind or fire, etc.). Under such circumstances, many secondary agents are able to cause severe damage. In such cases, it often proves difficult to pinpoint one cause of tree mortality, which is why the term "complex" damage is often used.

1.2 Assessment of forest resource development and risks of natural disturbances

In order to sustain several different functions simultaneously, large areas of forests should be managed as multi-purpose forests. The increasing pressure from society on the forests to fulfil a diversity of functions calls for targeted policies and careful planning and management. However, it is not easy to oversee impacts and consequences of management and policy decisions on the whole range of forest functions. Thus, there is a clear need for numerical analysis tools; currently, however, only a few are available.

In general, mathematical models can be used to objectively quantify risks and can show the long-term implications of selected actions. Furthermore, such detailed tools are valuable for deriving vulnerability ratings over a large range of possible situations; such ratings are difficult or even impossible to obtain from field studies. One spin-off of the increased interest in multi-purpose forestry and nature-oriented management has been the advances made recently in modelling growth and yield (Hasenauer, 2006). Detailed tree-level simulation models are needed to cope with uneven-aged and mixed species forests. Some of these models have been extended to include specific disturbances.

In recent years, substantial progress has also been made in the modelling of the mechanisms of wind damage to tree stands. Peltola et al. (1999) and Gardiner et al. (2000) have developed mechanistic models to estimate, for a given tree, the critical wind speed needed for stem breakage or uprooting. In these models, the stand under study is represented, however, by one “average” tree, assuming even-aged, mono-species stands with relatively little variation in height or diameter. In stands with higher variability among trees, such as in unmanaged or uneven-aged stands, a different approach is needed. Ancelin et al. (2004) recently extended this approach and evaluated the risk of wind damage for all trees in a particular stand. All these recent models evaluating the stability of individual trees largely ignore interactions with neighbouring trees. However, an important factor in stand stability is crown contact between trees. Not only can trees dissipate absorbed wind energy through crown contact (Milne, 1991), they can also physically support each other (Quine et al., 1995). One of the reasons for increased wind damage risk after thinning is that trees receive less support from their neighbours (Ruel, 1995). Thus, this modelling approach could still be further refined, making use of the improved shelter and support mechanisms between adjacent trees in a stand. At the same time, introducing such a mechanistic wind damage module into a stand simulator would make it possible to evaluate the risk of wind damage over time in relation to forest growth and dynamics as affected by silvicultural management.

In policy decisions, scenario projections can play an important role when forecasting the long-term impacts of alternatives in forest policy and management (Nabuurs and Päivinen 1996, Nabuurs 2001) and how they influence the fulfilment of forest functions. At the European scale the most widely used tool for such projections is the simulation model EFISCEN (European Forest Information SCENario model). It has, among other things, been used to study forest resource development under scenarios of demand for timber (Schelhaas et al., 2006; Nabuurs et al., 2007), climate change (Nabuurs et al., 2002; Schröter, 2004) and changing management regimes (Nabuurs, 2001; Schelhaas et al., 2007a). Furthermore, it has been used to assess the possible contribution of forests to biomass supply for bioenergy (EEA, 2006). Expected climate change impacts have already been incorporated in EFISCEN via the use of growth modifiers (Nabuurs et al., 2002), which can be derived, for example, from detailed process-based models. However, EFISCEN still needs to be refined to take into account the effect of natural disturbances, such as fire, storm, snow damage and biotic damage in projections made for current or changing climate conditions.

1.3 Aims of this thesis

The main aim of this thesis is to increase the understanding of the role of natural disturbances in the past and future development of European forest resources. Within this context, the special objectives of papers I-V were as follows:

- To present a comprehensive overview of past forest disturbances in Europe (Paper I).
- To extend the large-scale scenario model EFISCEN with a module that takes into account the influence of natural disturbances and that is able to handle hypothetical changes in disturbance regimes due to climate change. The extended model was parameterised for and applied to Switzerland, in order to study the behaviour and impact of the disturbance module (Paper II).
- To improve the EFISCEN disturbance module with respect to the simulation of bark beetle impacts under changing climate. This new module was applied to investigate the effects of adaptive management strategies on bark beetle damage in Austrian forests. A secondary aim of paper III was demonstrate the suitability of EFISCEN as a tool for upscaling the results of a more detailed model (Paper III).
- To develop a tool that can be used in quantifying the vulnerability of tree stands to wind damage under a range of stand conditions, in order to support forest management by predicting the consequences of different management actions at the stand level (Paper IV). The tool was used and demonstrated to evaluate the risk of wind damage for a variety of management regimes of Douglas fir at stand level (Papers IV and V).

2 NATURAL DISTURBANCES IN THE EUROPEAN FORESTS IN THE 19TH AND 20TH CENTURIES: A REVIEW (PAPER I)

Reports going back for more than 600 years show that natural disturbances are not a new phenomenon in Europe. However, early reports are scarce and no analysis can be done on these occurrences. Over time, the reports become more abundant, but not until after about 1950 are enough data available to allow missing data to be estimated. Over the period 1950-2000 an annual average of 35 million m^3 timber was damaged by disturbances; there was much variation between years. Storms were responsible for 53% of the total damage, fire for 16%, snow for 3% and other abiotic causes for 5%. Biotic factors caused 16% of the damage, with bark beetles being responsible for half of this. The bark beetle outbreaks were usually connected to severe windfall events, often in combination with adverse weather conditions in the following summers. For 7% of the damage no cause was given, or there was a combination of causes. The 35 million m^3 of damaged timber corresponds to about 8.1% of the total fellings in Europe and to about 0.15% of the total stem volume of growing stock.

Over the period 1961-2000, the average annual area affected by forest fires was 213,000 ha, which is 0.15% of the total forest area in Europe. Almost half (44.9%) of the total area affected by forest fire is in just two countries: Spain and Portugal. The total Mediterranean area (including France) accounted for 93.6% of the area burned.

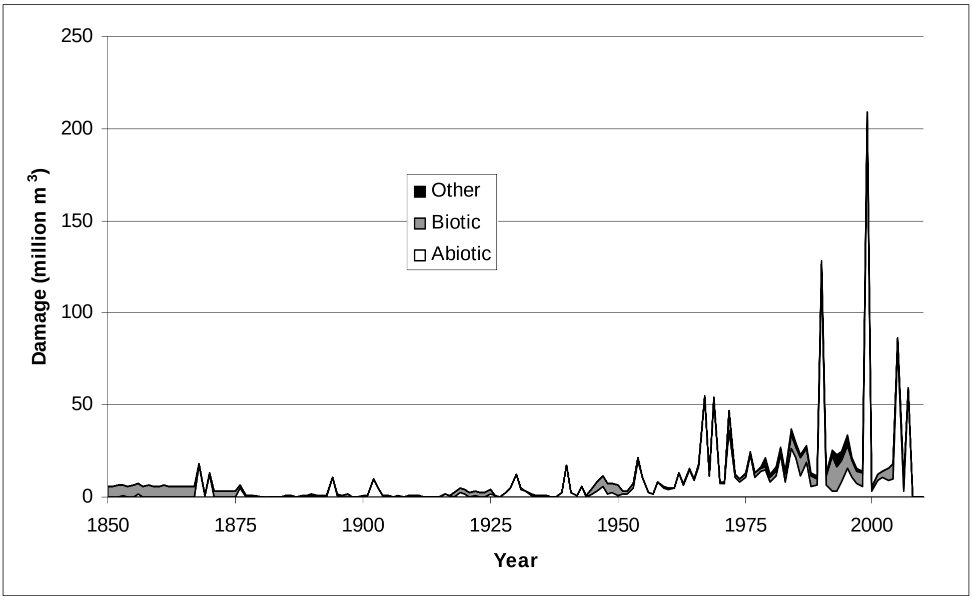

Figure 1. Reported volume of timber affected by natural disturbances in Europe, 1850-2007 (Paper I).

Though Figure 1 shows that most types of damage seem to be increasing, this is partly an artefact of the improved availability of information. However, more complete time series at national and regional levels confirm the rising trend, at least for storms (Holmsgaard, 1986; SFSO and FOEFL, 1996; Mosandl and Felbermeier, 1999) and fires (CREAF, 1999; Xanthopoulos, 2000; Konstantinov, 2003; Meta, 2003). At the same time, no study has found evidence of storms being more frequent or more intense (Schiesser, 1997; Dorland et al., 1999; Können, 1999; Lässig and Mocalov, 2000). The most likely explanations for an increase in damage from disturbances are changes in exposure, such as increases in forest area and average volume of growing stock, and changes in vulnerability, such as increased average stand age and a larger proportion of conifers.

3 MODEL APPROACHES AND APPLICATIONS (PAPERS II-V)

3.1 Large-scale scenario modelling including damage by various natural disturbances (paper II)

In paper II, a disturbance module is added to the large-scale scenario model EFISCEN (European Forest Information SCENario model) whose core dynamics are based on a model developed by Sallnäs (1990). EFISCEN is especially suitable for regional or country level applications, in which national forest inventory data are used as input. The state of the forest is depicted as an area distribution over age and stem volume classes in a matrix. A separate matrix is set up for each forest type, defined by region, owner class, site class and tree species. Processes such as growth, mortality, thinnings, final fellings and regeneration are simulated by transitions of the area to other volume classes. A detailed description of EFISCEN can be found in Schelhaas et al. (2007b).

In this research, the three most important disturbance agents in Europe were included in EFISCEN: fire, storm/snow and insects. All these agents are able to destroy a stand wholly (stand-replacing disturbances) or partially (non-stand-replacing disturbances). Both outcomes are simulated by movements of area through the matrix, in a way similar to that for final fellings (stand-replacing disturbances) and thinnings (non-stand-replacing disturbances). For each combination of forest type, disturbance agent and type of disturbance, a vulnerability matrix is set up. This matrix expresses the vulnerability of each cell in the matrix relative to all other cells in all matrices. The hazards for damage by storm/snow and fire are defined by lognormal distributions. The hazard for insect damage depends on the occurrence of storm damage and warm and dry years. Fire hazard is taken as a proxy for warm and dry years. Actual damage in a certain time step depends on the hazard (represented by random draws from the hazard distributions), vulnerability (as defined in the vulnerability matrices) and exposure (defined by the distribution of area over the matrix). Because of the stochastic character of the approach, Monte Carlo simulation is used.

In paper II, EFISCEN was applied to Switzerland to study the behaviour and impact of the newly developed disturbance module on projections of forest resources. For this purpose, a 60-year period was simulated, with and without the disturbances module. In both cases, the felling volume required (planned fellings) was kept the same. In the first case, the volume of unplanned fellings due to disturbances was kept constant, equal to the historical level. In the second case, the volume of unplanned fellings was determined by the disturbances module. Furthermore, a climate change scenario was applied, where the degree of disturbance and the size of the wood volume increment were increased simultaneously. The climate change assessment is based on the HadCM2 scenario (Mitchell et al. 1995), which assumes that in the period 1990 to 2100, the concentration of atmospheric CO2 doubles. On average, the climate scenario predicted that mean annual temperature would be 1.5 °C higher in 2050 compared with 1990, and that during the same period, average annual precipitation would increase by between 5% and 15%. Associated changes in the size of the wood volume increment were derived from earlier detailed simulations with the TREEDYN3 model (Bossel, 1996; Sonntag, 1998, Kramer and Mohren, 2001).

3.2 Large-scale scenario modelling including damage by bark beetles (paper III)

In paper III, EFISCEN was applied to all Norway spruce forests in Austria to study the development of damage due to the European spruce bark beetle (*Ips typographus* (Scol. Col.)). In this application, vulnerability and hazard were calculated outside the model and no Monte Carlo approach was applied. Two adaptive management scenarios were compared with a “business as usual” scenario. Adaptive management consisted of changing the tree species distribution to more closely resemble the potential natural vegetation (PNV). In the first adaptation scenario, tree species change was implemented immediately, whereas in the second, the species change was delayed by 20 years. All three management scenarios were evaluated under current and changing climate conditions. The climate change scenario was based on the B2 emission scenario of the IPCC (2000) as predicted with the climate model HadCM3 (Mitchell et al. 2004). The average temperature change for the last decade of the 21st century relative to the period 1990-2004 at was +2.4°C, averaged over whole Austria. Precipitation increased only slightly (+20mm), with limited decrease and increase in the individual provinces. The LPJ model (Schröter, 2004) was used to derive changes in wood volume increment under climate change, while the PICUS model (v 1.41, Lexer and Hönninger, 2001; Seidl et al., 2005; Seidl et al., 2007) was used to assess bark beetle hazard and vulnerability.

3.3 Stand-level modelling for assessment of risks from wind damage (papers IV-V)

In paper IV, a wind damage module is added to the ForGEM (Forest Genetics, Ecology and Management) model, henceforth referred to as ForGEM-W. ForGEM is a forest model that simulates the growth and development of individual trees on a scale of up to several hectares (Kramer, 2004; Kramer et al., 2007). Most of the key processes are modelled essentially similar to those of SORTIE (Pacala et al., 1993; Pacala et al. 1996), except for the gap-type approach for light interception (Bugmann, 2001). Individual tree growth is driven by light interception. Intercepted light is transformed into photosynthates, which are allocated to specific parts of the tree. Crown expansion is influenced by competition from other trees. Regeneration is explicitly simulated by the processes of seed production, dispersal and germination.

The wind damage module uses a static mechanistic approach. It determines for a given mean hourly wind speed which trees will be damaged. Tree height and crown and stem shape determine how much wind drag the tree experiences. The weight of the displaced stem and crown add to the total turning moment at stem base, which is also affected by the shelter and support received from surrounding trees. The sheltering effects depend on relative heights of trees and the presence of foliage. Trees can also experience additional loading if hit by fallen trees (the domino effect), which affects the total turning moment, too. However, trees with a height of less than 5m are not expected to be uprooted or broken by wind, though they can be destroyed by other falling trees. Gaps in the stand are also explicitly taken into account in determining wind load and shelter zones. Trees are assumed to break or be uprooted if the maximum stem resistance or the maximum anchorage resistance, respectively, is exceeded. Both stem resistance and anchorage are functions of diameter at breast height (DBH).

In a case study, the ForGEM-W model was parameterised for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) in the Netherlands. Damage patterns were explored in three simulated 60-year old stands with different management history at two different wind speeds (paper IV). These situations were also used to conduct a sensitivity analysis of the model. Furthermore, six different management regimes were evaluated over a full rotation period, to compare their effectiveness in reducing wind damage (paper V).

4 RESULTS

4.1 Large-scale scenario modelling application including damage by various natural disturbances (paper II)

Without the natural disturbances module, EFISCEN projected that the growing stock volume in Switzerland would increase from 366 m^3 ha^{-1} in 1984 to 592 m^3 ha^{-1} in 2048. When the natural disturbances module was included, the growing stock increased to only 460 m^3 ha^{-1} in 2048 (Figure 2). The difference is attributable to changes in the vulnerability of the forest, which cause the impact of natural disturbances to increase over time: from 2.8 m^3 ha^{-1} in 2003 to 3.9 m^3 ha^{-1} in 2048. Under a simulated climate change scenario, the frequency of disturbances was assumed to increase, which resulted in 25% more damage. However, the increment increased more than the damage done by disturbances, which resulted in a simulated growing stock volume of 530 m^3 ha^{-1} in 2048. The increase in damage must mainly be attributed to an increasing average volume of standing timber.

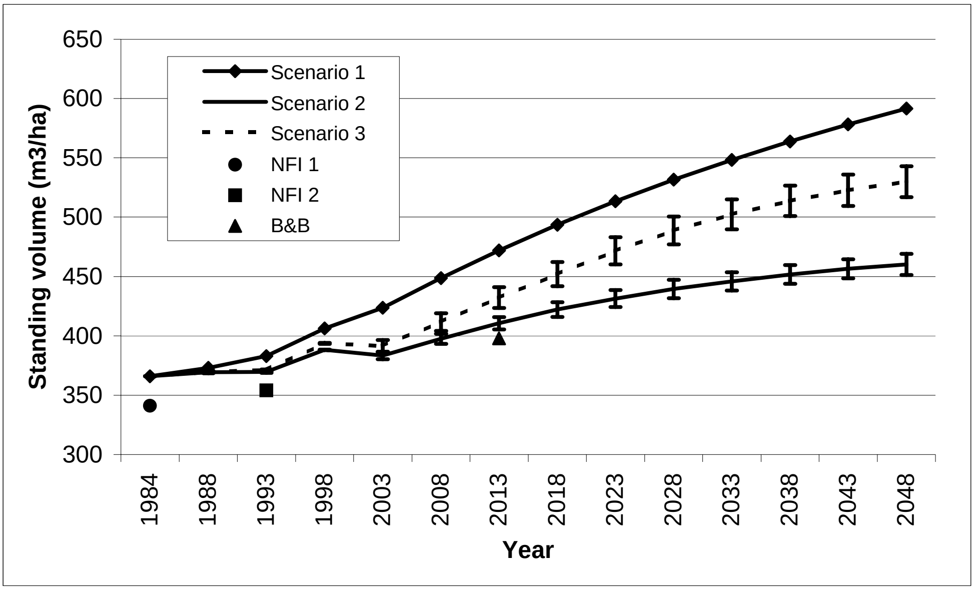

Figure 2. Development of standing stem volume in Switzerland under 1) current climate and without disturbances (Scenario 1), 2) current climate with disturbances (Scenario 2) and 3) climate change and disturbances (Scenario 3), with standard deviation. Also shown are the standing volume as given in National Forest Inventory 1 (NFI 1) (Mahrer 1988), NFI 2 (Brassel and Brändli 1999) and corresponding stem volume (B&B) according to the projection by Brassel and Brändli (1999). The initial difference in standing volume is due to the fact that temporarily unstocked areas were not included in the EFISCEN dataset.

4.2 Large-scale scenario modelling application including damage by bark beetles (paper III)

EFISCEN projects that damage due to bark beetles in Austria will increase dramatically under the climate change scenario: from 1.33 million m³ yr^{-1} in the period 1990-2004 to 4.46 million m³ yr^{-1} in the period 2095-2099, with a peak of 6.09 million m³ yr^{-1} (Figure 3). Under the current climate with business as usual management scenario, damage in the period 2095-2099 amounted to 2.38 million m³ yr^{-1}. Average damage per hectare was found to be highest in pre-alpine Norway spruce stands, but simulated increases in accumulated damage under climate change were greatest in the inner Alps (+166%). The two adaptive management strategies (i.e. species change) revealed a considerable time-lag between the start of adaptation measures and a decrease in simulated damage by bark beetles. When EFISCEN simulations including the new bark beetle disturbance module were compared with 15 years of observed bark beetle damage for Austria there was also good agreement between the observed and predicted data at province level.

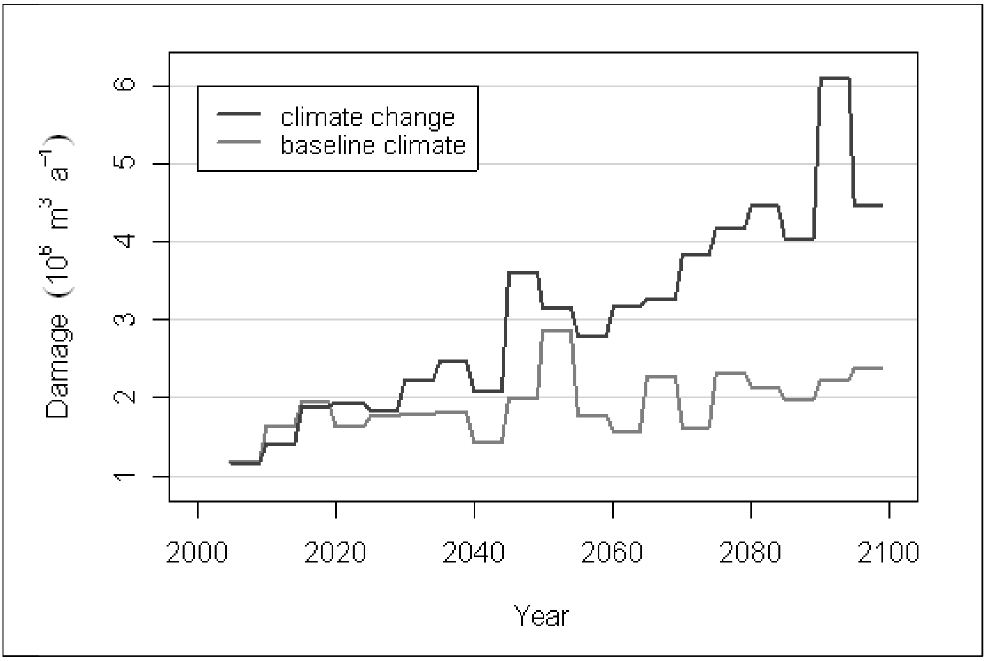

Figure 3. Development of total damage in Austria from bark beetles under current and changing climate conditions.

4.3 Stand-level modelling application for wind risk (papers IV-V)

First, the wind damage patterns in three forest stands with different management histories were studied using the ForGEM-W model (paper IV). At the same wind speed, stands freshly exposed to wind showed considerably more damage than sheltered stands (Figure 4). In exposed stands, the damaged trees were located significantly closer to the upwind edge than undamaged trees. In sheltered stands, trees with a higher height to diameter ratio (h/d ratio) than average were most sensitive to wind damage, but lower individual tree stability in dense stands was clearly compensated for by the support of other trees. The wind speeds needed to cause damage approximated those of known windthrow events.

The wind damage module proved to be especially sensitive to the parameters determining resistance to uprooting and to the drag coefficient. Two of the tree characteristics to which the wind damage module proved to be very sensitive were tree height and diameter at breast height (paper IV). This was also found in paper V, in which it was reported that the management regimes that were most successful in avoiding wind damage were those that led to relatively low h/d ratios (Figure 5): for example, low h/d ratios could be obtained in even-aged situations by having a relatively low stand density throughout the rotation; in uneven-aged systems they could be obtained by favouring trees with relatively low h/d ratio in thinning. Admixture of a stable species (beech *Fagus sylvatica* L.) resulted in less damage only when the beech replaced Douglas fir. Admixture of beech in a Douglas fir stand with wide spacing increased the damage in Douglas fir, because the h/d ratios of the Douglas fir increased in response to the increased competition from the beech.

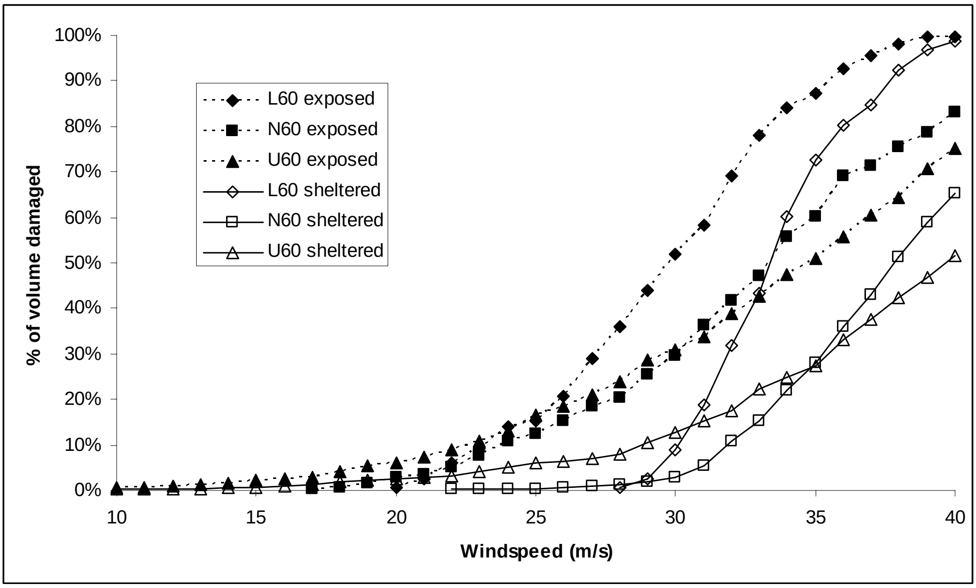

Figure 4. Percentage of standing volume damaged at different wind speeds for exposed and sheltered stands of different tree densities at age 60 (L=low density, N= normal density, U=unmanaged)

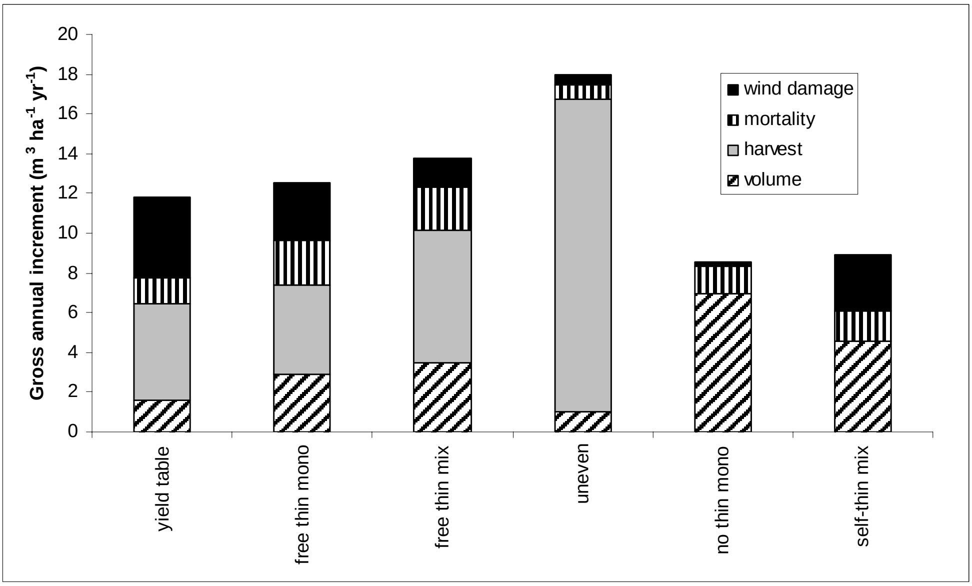

Figure 5. Average gross annual stem wood increment and its components, averaged over the period needed to obtain an average diameter of 60 cm or over a period of 100 years, in different management scenarios. Normal: thinning from below, following yield table density; high mono: free thinning from above, monoculture Douglas fir; high mix: free thinning from above, equal mixture of Douglas fir and beech; uneven: uneven-aged management; 200 mono: monoculture of 200 Douglas fir trees, no thinning; 200 mix: 200 Douglas fir trees with admixture of 3800 beech trees, no thinning.

5 DISCUSSION AND CONCLUSIONS

5.1 Evaluation of the large-scale scenario model including the overall disturbance module (paper II)

The EFISCEN model is designed to work on a large scale and should be able to be applied throughout Europe. Because of its general applicability, however, the model cannot take account of local circumstances, such as the complicated relief in Switzerland, in great detail. Another point worthy of note is the assumed distribution of the damage due to disturbances. In the Swiss case, these distributions were derived from historical records. However, a better method would be to couple the observed climate directly to disturbance damage, thus also enabling a better assessment system for future climate conditions. There is also great scope for improving the quantification of volume increment changes due to climate change. The approach used here must be seen as a what–if scenario to demonstrate the model’s ability and the consequences of such a scenario.

The projections for Switzerland showed large differences in forest resource development depending on whether or not natural disturbances were included. This shows that ignoring natural disturbances in resource projections can lead to biased and over-optimistic views. Despite the sometimes rather crude assumptions in the natural disturbance module, the model projections correlated well with other projections (Brassel and Brändli, 1999). However, the model approach has various limitations and still has scope for improvement, as discussed above.

5.2 Evaluation of the large-scale scenario model including the bark beetle damage module (paper III)

The simulations in Austria showed good agreement between the model and observations of stem wood increment levels, increases in the volume of standing growing stock and bark beetle damage. The model results were the outcome of combining the use of simulated forest structures in EFISCEN with an upscaling of PICUS model logic on bark beetle damage. The current implementation of bark beetle damage in PICUS was found to be very suitable to the requirements of such upscaling. Whereas the absence of year-to-year fluctuations in bark beetle populations damage has to be seen as a major limitation of the current approach in PICUS (cf. Seidl et al. 2007), the annually independent calculation fitted well for an upscaled application in the EFISCEN environment.

A major limitation of the approach presented for Austria is the implicit assumption of an average amount of material for bark beetles to breed in, not dependent on wind or snow damage events. In view of this limitation, the projections have to be seen as indicative investigations of the climate dependencies of the herbivore–host relationship. Since several studies point at the possibility of increases in extreme weather events such as storms under climate change (e.g., Leckebusch and Ulbrich, 2004), the results presented in the scenario analysis have to be seen as conservative estimates.

The investigated adaptation scenarios of changing the tree species composition after clear felling proved to be ineffective over the time horizon considered. Even if the tree species change were implemented immediately, the first effects would not become visible until the second half of this century. Additional strategies are to be tested, for example involving increasing the harvest volumes in highly vulnerable areas, reducing rotation lengths, or introducing other tree species in existing stands.

5.3 Evaluation of the stand-level application for assessment of risks from wind damage (papers IV –V)

As demonstrated in papers IV-V, the inclusion of a shelter and support mechanism in the wind damage module of ForGEM is an important improvement in the modelling of wind damage within a large range of different stand types. The approach enables the balance between individual tree stability and stand stability to be studied in much more detail. However, much work is still needed, not only to improve and calibrate the model, but also on other aspects of the wind damage module. Two particularly important issues which should be considered in greater detail in the future are the acclimatisation of trees to windy conditions, and the anchorage component. Within the tree growth model, special attention should be paid to competition processes, both above and below ground, and to the process of declining diameter growth with age. There are currently no data sets available that allow a validation of the wind damage module.

The applications of ForGEM-W clearly show how management can influence a stand’s vulnerability and exposure and thus the risk of wind damage. At the landscape scale, vulnerability can be influenced by planning clear fellings in such a way that damage could be minimised at the newly created edges (Zeng 2006, Zeng et al. 2007). At an even larger spatial scale, an evenly distributed area over all age classes might be an effective way of limiting risks (Savill, 1983). At such large scales, EFISCEN can be a valuable tool to evaluate the development of damage patterns under different scenarios. Model results at a smaller scale, such as those obtained using ForGEM-W or PICUS, can also be useful in parameterising the disturbance module of EFISCEN.

5.4 Conclusions

The historical evaluation showed a tendency for damage from most disturbance agents to increase. This tendency can be explained in terms of changes in hazard, vulnerability and exposure. The future risk of disturbance is just as dependent on the same factors. Although it is impossible to accurately predict such stochastic events as disturbances, it is possible to evaluate the likely trends of each of the sides of the risk triangle and give an outlook on future disturbance risk.

An obvious change in hazard is posed by changes in climate. Although climate change will have different effects in different regions in Europe, there is a general tendency for higher temperatures and more variability in precipitation (Meehl et al., 2007). Although precipitation is expected to increase in some cases, it might be more than offset by expected temperature increases. This will probably lead to an increase in future fire hazard (Kurz et al., 1995; Gerstengarbe et al., 1999; Schelhaas and Moriondo, 2007). The same factors will be influential for biotic hazards. An increase in temperature is expected to increase the reproductive capacity and number of completed life cycles per year of important biotic disturbance agents such as bark beetles (Harrington et al., 2001; Bale et al., 2002). Moreover, climate change is likely to cause shifts in the outbreak ranges of insect species (e.g., Parmesan et al., 1999; Williams and Liebhold, 2002). Additionally, an increase in environmental stress factors for the host species, such as drought, may reduce host resilience to insect infestation (e.g., Wermelinger, 2004; Rouault et al., 2006).

It is still unclear how climate change will affect the European wind climate. Some studies project an increase in storminess (Zwiers and Kharin, 1998; Lunkeit et al., 1996, Meehl et al., 2007), while others expect a decrease (Lässig and Schönenberger, 2000). Apart from climate change, other developments can influence the hazard of specific agents. For example, the increased use of forests for recreation increases the fire hazard due to an increase of ignition sources, but at the same time the chances of early detection increase as well. Another example is globalisation: increased trade increases the probability of accidentally introducing exotic pest species.

In this research, exposure was defined in terms of forest area and wood volume. Both variables have increased considerably in Europe since at least 1950 (Kuusela, 1994). Due to the high proportion of relatively recent afforestations, the European forest can be considered as rather young. The observed trend of increasing growing stock is largely attributable to an increase in the average age of the European forest. In the coming decades, both the forest area and the growing stock are projected to continue to increase (Schelhaas et al., 2006). However, increased demand for biofuels could lead to more harvesting in existing forests and less land becoming available for afforestation due to the establishment of dedicated bioenergy crops.

Vulnerability to various disturbance agents is mainly dependent on the state of the forest, expressed in terms such as species composition, age class composition, density/thinning status and distribution over diameter and height classes. In Europe, the state of the forest is largely determined by historical management actions. The current age class structure with a relatively large proportion of young forests is the result of heavy exploitation decades to centuries ago and more recent mass afforestation. Currently, increment figures largely exceed the volume harvested, so it is expected that in the future the age class structure will become more uniform. This will be facilitated by the Europe-wide shift towards more nature-oriented management (Nabuurs, 2001). One aspect of nature-oriented management is the favouring of broadleaves rather than conifers. Increased use of broadleaves and a tendency for older forest would reduce the vulnerability of forests to fires. However, much agricultural land is being abandoned, especially in the Mediterranean region, leading to larger contiguous forest areas where fire can spread more easily. Furthermore, the pioneer species that colonise this land might be conifers that burn easily.

A shift towards more broadleaved species will also decrease wind vulnerability. However, such changes will only take place very gradually. On the other hand, the current trend towards older forests is happening relatively fast and will continue for some time still. This change will probably be more influential in the shorter term and will negatively affect the overall wind vulnerability. It is difficult to predict how vulnerability to biotic disturbances will develop. Each tree species and each stand development phase has its own associated portfolio of biotic disturbance agents. A shift in tree species or stand structure will be favourable for avoiding certain pests, but might lead to increased occurrence of other agents.

We can conclude that hazard and exposure are likely to increase for most disturbance agents in the near future. The development of vulnerability is less easy to predict, but drastic decreases in vulnerability are not very likely in the short term. Therefore, it seems very likely that in the coming decades we will have to reckon with an increased role of disturbances. Changing disturbance regimes may impose adverse feedbacks on the sustainable provision of important forest services and functions (e.g, Ayres and Lombardero 2000, Dale et al. 2000). Adaptive strategies may help to reduce the expected impact of future disturbances. Such strategies will have to focus on reducing exposure and vulnerability. A reduction in exposure could be achieved by earlier harvesting, less growing stock and limiting forest expansion in risky areas. Vulnerability could be reduced by modifying species composition, changing the age-class distribution and adopting specific forms of management aimed at reducing vulnerability to prevailing disturbance agents.

However, as the results of paper III show, it can take a long time before the effects of adaptation measures become visible. Before then, forest managers can anticipate the occurrence of disturbances and, for example, increase the flexibility of their management plans and take measures that limit the consequences of disturbances. Regional and national authorities should also be prepared for the occurrence of damage and have contingency plans in place. One adaptation strategy has already been incorporated as an aspect of nature-oriented management: natural disturbances are increasingly seen as part of the system and their occurrence has increasingly been accepted and seen as an opportunity rather than a loss.

To conclude, natural disturbances can significantly affect the sustainable provision of services that forests provide. Although unpredictable, they occur regularly and forest management should be prepared for them. All decisions taken concerning the management of the forest can affect the risk of disturbances. It is therefore important to understand the processes behind disturbances and to be able to indicate the effects of decisions on the risk of disturbance. At the stand scale, the coupling of tree growth simulators with disturbance models offers great possibilities for exploring alternative management regimes and their associated risks. Similarly, at the regional and national scales, forest resource scenario models are being used to support policy makers. Inclusion of disturbances in such models has a significant effect on the projections and thus possibly on decisions to be derived from them. The inclusion of disturbances also offers the possibility of exploring scenarios for adapting to expected future climate change.

REFERENCES

Ancelin, P., Courbaud, B. and Fourcaud, T. 2004. Development of an individual tree-based mechanical model to predict wind damage within forest stands. Forest Ecology and Management 203:101-121.

Ayres, M.P. and Lombardero, M.J. 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. The Science of the Total Environment 262:263-286.

Bale, J.S., Masters, G.J., Hodkinson, I.D. Awmack, C., Bezemer, T.M., Brown, V.K., Butterfield, J., Buse, A., Coulson, J.C., Farrar, J., Good, J.E.G., Harrington, R., Hartley, S., Hefin Jones, T., Lindroth, R.L., Press, M.C., Symrnioudis, I., Watt, A.D., Whittaker, J.B. 2002. Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. Global Change Biology 8:1-16.

Böhm, P. 1981. Sturmschäden in Schwaben von 1950 bis 1980. Allgemeine Forstzeitschrift 36, 1380.

Bossel, H., 1996. TREEDYN3 forest simulation model. Ecological Modeling 90:187-227.

Brandle, M. and Brandl, R. 2001. Species richness of insects and mites on trees: expanding Southwood. Journal of Animal Ecology 70:491-504.

Brassel, P. and Brändli, U.-B.(Eds.). 1999. Schweizerisches Landesforstinventar. Ergebnisse der Zweitaufnahme 1993-1995. Birmensdorf, Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft. Bern, Bundesamt für Umwelt, Wald und Landschaft. Bern, Stuttgart, Wien, Haupt.

Brown, J. K. and Smith, J. K. 2000. Wildland fire in ecosystems: effects of fire on flora. Gen. tech. rep. rmrs-gtr-42-vol. 2, U.S. Department of Agriculture, Forest Service. Available: http://www.fs.fed.us/rm/pubs/rmrs_gtr42_2.html.

Bugmann, H. 2001. A review of forest gap models. Climatic Change 51:259-305.

Buse, A. and Good, J.E.G. 1996. Synchronisation of larval emergence in winter moth (*Operoptera brumata* L.) and budburst in pedunculate oak (*Quercus robur* L.) under simulated climate change. Ecological Entomology 21:335-343.

Coakley, S.M., Scherm, H., and Chakraborty, S. 1999. Climate change and plant disease management. Annual Review of Phytopathology 37:399-426.

CREAF. 1999. CREAF 1988-1998, Center for Ecological Research and Forestry Applications - CREAF, Barcelona.

Dale, V.H., Joyce, L.A., McNulty, S. and Neilson, R.P. 2000. The interplay between climate change, forests, and disturbances. The Science of the Total Environment 262: 201-204.

Dorland, C., Tol, R.S.J. and Palutikof, JP. 1999. Vulnerability of the Netherlands and Northwest Europe to storm damage under climate change: A model approach based on storm damage in the Netherlands. Climatic Change 43:513-535.

EEA. 2006. How much bioenergy can Europe produce without harming the environment? European Environment Agency. EEA report 07/2006, Copenhagen. ISSN 1725-9177. 67 pp.

FAO. 2007. State of the World’s Forests 2007. Food and Agricultural Organization of the United Nations, Rome. 144 p.

Gardiner, B., Peltola, H. and Kellomäki, S. 2000. Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. Ecological Modelling 129:1-23.

Gerstengarbe, F.-W., Werner, P.C., Lindner, M. and Bruschek, G. 1999. Estimation of Future Forest Fire Development in the State of Brandenburg. International Forest Fire News, No. 21, 91-93.

Harrington, R., Fleming, RA. and Woiwood, I.P. 2001. Climate change impacts on insect management and conservation in temperate regions: can they be predicted? Agricultural and Forest Entomology 3:233-240.

Hasenauer, H. 2006. Sustainable forest management: growth models for Europe. Springer, Berlin, 398 p.

Holmsgaard, E. 1986. Historical development of wind damage in conifers in Denmark In: Minimizing wind damage to coniferous stands, Proceedings of the workshop organized jointly by the Danish forest experiment station and the commission of the European Communities at Løvenholm Castle, Denmark, March 3-7, 1986:2-4.

IPCC. 2000. Emissions Scenarios 2000. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. 570 pp.

- 2007. Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge UK

Jactel, H., Vodde, F., Branco, M., Carnus, J.M., Gonzalez, J.R., Grodzki, W., Langström, B., Moreira, F., Netherer, S., Nicoll, B., Orazio, C., Piou, D., Santos, H., Schelhaas, M.J. and Tojic, K. 2007. Prevalence of sanitary hazards in European forests. EFORWOOD Deliverable 2.4.2.

Können, G.P.R. 1999. De toestand van het klimaat in Nederland 1999, Koninklijk Nederlands Meteorologisch Instituut, De Bilt. 64 pp.

Konstantinov, V. 2003. “Bulgaria - Analysis of the Problems Connected to Forest Fires in Bulgaria.” International Forest Fire News, 28.

Kramer, K. (Ed.). 2004. Effects of Silvicultural Regimes on Dynamics of Genetic and Ecological Diversity of European Beech Forests; Impact Assessment and Recommendations for Sustainable Forestry. Alterra, Wageningen.

- , Mohren, G.M.J. (eds). 2001. Long term effects of climate change on carbon budgets of forests in Europe. Alterra Report 194. Alterra, Wageningen, the Netherlands. 209 p.

- , Buiteveld, J., Forstreuter, M., Geburek, T., Leonardi, S., Menozzi, P., Povillon, F., Schelhaas, M.J., Teissier du Cros, E., Vendramin, G.G. and van der Werf, D.C. 2007. Bridging ecophysiological and genetic knowledge to assess the adaptive potential of European beech. Ecological Modelling, submitted manuscript.

Kron W. 2002. “Flood risk = hazard x exposure x vulnerability”. In: Wu M. et al., (ed.), Flood Defence, Science Press, New York, 82-97.

Kurz, W.A., Apps, M.J., Stocks, B.J. and Volney, W.J.A. 1995. Global Climate Change: Disturbance Regimes and Biospheric Feedbacks of Temperate and Boreal Forests. In: Woodwell, G.M., Mackenzie, F.T. (Eds), Biotic Feedbacks in the Global Climatic System, pp. 119-133.

Kuusela, K. 1994. Forest resources in Europe, 1950-1990. Cambridge University Press, Cambridge, 154 p.

Lässig, R and Mocalov, SA. 2000. Frequency and characteristics of severe storms in the Urals and their influence on the development, structure and management of the boreal forests. Forest Ecology and Management 135:179-194.

Lässig, R. and Schönenberger, W. 1997. Was passiert, wenn man die Natur sich selber überlässt? Ergebnisse der Sukzessionsforschung auf Windwurfflächen. Laufener Seminarbeiträge 1/1997, pp. 67-74.

Leather, S.R., Walters, K.F.A. and Bale, J.S. 1993. The Ecology of Insect Overwintering. Cambridge University Press, Cambridge, 255 p.

Leckebusch, G.C. and Ulbrich, U. 2004. On the relationship between cyclones and extreme windstorm events over Europe under climate change. Global and Planetary Change 44:181-193.

Lexer M.J. and Hönninger, K. 2001. A modified 3D-patch model for spatially explicit simulation of vegetation composition in heterogeneous landscapes. Forest Ecology and Management 144:43–65.

Lunkeit F., Ponater M., Sausen R., Sogalla M., Ulbrich U. and Windelband M. 1996. Cyclonic Activity in a Warmer Climate. Contributions to Atmospheric Physics / Beiträge zur Physik der Atmosphäre 69, 393-407.

Mahrer, F. (ed.). 1988. Schweizerische Landesforstinventar. Ergebnisse der Erstaufnahme 1982-1986. Swiss forest land inventory. Results of the first period 1982-1986. Eidgenössische Anstalt für das Forstliche Versuchswesen, Birmensdorf, Switzerland. Berichte no. 305.

Meehl, G.A., Stocker, T.F., Collins, W., Friedlingstein, P., Gaye, A., Gregory, J., Kitoh, A., Knutti, R. and Co-authors, 2007: Global climate projections. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M.Manning, Z. Chen, M.Marquis, K.B.Averyt, M. Tignor and H.L.Miller, Eds., Cambridge University Press, Cambridge, 747-846.

Meta, M. 2003. “Albania - Update on the Forest Fire Situation.” International Forest Fire News 28.

Meyer, J. 2005. Fire effects on forest resource development in the French Mediterranean region – projections with a large-scale forest scenario model. Technical Report 16. European Forest Institute. 86 p.

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

Mitchell, T.D., Carter, T.R., Jones, P.D., Hulme, M. and New, M. 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Tyndall Centre Working Paper 55, 25 pp.

Mitchell, J.F.B., Johns, T.C., Gregory, J.M. and Tett, S.F.B. 1995. Climate response to increasing levels of greenhouse gases and sulphate aerosols. Nature 376:501-504.

Mosandl, R. and Felbermeier, B. 1999. Auf dem Weg zum naturnahen Wald. AFZ/Der Wald 910-914.

Nabuurs, G.J. 2001. European forests in the 21st century: impacts of nature-oriented forest management assessed with a large-scale scenario model. Alterra Scientific Contributions 2, Alterra, Wageningen.

- and Päivinen, R. 1996. Large scale forestry scenario models: a compilation and review. European Forest Institute, Working Paper 10, Joensuu, Finland.

- , Pussinen, A., Karjalainen, T., Erhard, M. and Kramer, K. 2002. Stemwood volume increment changes in European forests due to climate change –a simulation study with the EFISCEN model. Global Change Biology 8:304-316.

- , Schelhaas, M.J., Mohren, G.M.J., and Field, C.B. 2003. Temporal evolution of the European Forest carbon sink from 1950 to 1999. Global Change Biology 9(2):152-160.

- , Pussinen, A., van Brusselen, J. and Schelhaas, M.J. 2007. Future harvesting pressure on European forests. European Journal of Forest Research 126, 391-400.

Pacala, S.W., Canham, C.D. and Silander, J.A. Jr. 1993. Forest models defined by field measurements: 1. The design of a northeastern forest simulator. Canadian Journal of Forest Research 23: 1980-1988.

- , Canham, C.D., Saponara, J., Silander, J.A. Jr., Kobe, R.K. and Ribbens, E. 1996. Forest models defined by field measurements: II. Estimation, error analysis and dynamics. Ecological Monographs 66:1-43.

Parmesan, C., Ryrholm, N., Stefanescu, C. et al., 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming. Nature, 399:579-583.

Peltola, H., Kellomäki, S., Väisanen, H. And Ikonen, V.-P. 1999. A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce, and birch. Canadian Journal for Forest Research 29:647-661.

Quine C., Coutts, M., Gardiner, B. and Pyatt, G. 1995. Forests and wind: Management to minimize damage, Forestry Commission Bulletin 114. HMSO, London.

Rouault, G., Candau, J.N., Lieutier, F., Nageleisen, L.M., Martin, J.C. and Warzée, N. 2006. Effects of drought and heat on forest insect populations in relation to the 2003 drought in Western Europe. Annals of Forest Science 63:613-624.

Ruel, J-C. 1995. Understanding windthrow: silvicultural implications. Forestry Chronicles 71:435-445.

Sallnäs, O. 1990. A matrix growth model of the Swedish forest. Studia Forestalia Suecica No 183. Swedish University of Agricultural Sciences, Faculty of Forestry, Uppsala.

Savill, P.S. 1983. Silviculture in windy climates. Forestry Abstracts 44:473-488.

Schelhaas, M.J. and Moriondo, M. 2007. Bosbrand en klimaatverandering. Vakblad Natuur Bos Landschap 4(8):13.

- , van Brusselen, J., Pussinen, A., Pesonen, E., Schuck, A., Nabuurs, G.J. and Sasse, V. 2006. Outlook for the Development of European Forest Resources. A study prepared for the European Forest Sector Outlook Study (EFSOS). Geneva Timber and Forest Discussion Paper, ECE/TIM/DP/41. UN-ECE, Geneva. 118 p.

- , Cienciala, E., Lindner, M., Nabuurs, G.J. and Zianchi, G. 2007a. Selection and quantification of forestry measures targeted at the Kyoto Protocol and the Convention on Biodiversity. Alterra report 1508. 95 p.

- , Eggers, J., Lindner, M., Nabuurs, G.J.,Pussinen, A., Päivinen, R., Schuck, A., Verkerk, P.J., van der Werf, D.C., and Zudin, S. 2007b. Model documentation for the European Forest Information Scenario model (EFISCEN 3.1). Wageningen, Alterra, Alterra report 1559, EFI Technical Report 26, Joensuu, Finland. 118 p.

Schiesser, H.-H, Pfister, C. and Bader, J., 1997. Winter storms in Switzerland north of the Alps 1864/65-1993/94. Theoretical and applied climatology 58: 1-19.

Schröter, D. (Ed). 2004. ATEAM final report 2004. Advanced Terrestrial Ecosystem Analysis and Modelling. Potsdam Institute for Climate Impact Research (PIK). 139 pp.

Schütz, J.P., Götz, M., Schmid, W., Mandallaz, D. 2006. Vulnerability of spruce (*Picea abies*) and beech (*Fagus sylvatica*) forest stands to storms and consequences for silviculture. European Journal of Forest Research 125:291-302.

Seidl, R., Lexer, M.J., Jäger, D. and Hönninger, K. 2005. Evaluating the accuracy and generality of a hybrid forest patch model. Tree Physiology 25:939-951.

- , Rammer. W., Baier, P., Schopf, A. and Lexer, M.J. 2007. Modelling tree mortality from bark beetle infestation in Norway spruce forests. Ecological Modelling 206:383-399.

SFSO and FOEFL. 1996. Forestry and Timber Industry in Switzerland, Yearbook. Swiss Federal Statistical Office, Bern.

Sonntag, M. 1998. Klimaveränderungen und Waldwachstum: TREEDYN3-Simulationen mit einer Analyse modellstruktureller Unsicherheiten. Verlag Mainz, Aachen. Dissertation, University of Kassel, Germany.

Southwood, T.R.E. 1961. The numbers of species of insect associated with various trees. Journal of Animal Ecology 30: 1-8

Speight M. R., Wainhouse, D. 1989. Ecology and Management of Forest Insects. Clarendon Press, Oxford, 374 pp.

UN-ECE, 2005. European Forest Sector Outlook Study, Main report. ECE/TIM/SP/20. United Nations, Geneva.

Vélez, R. 1985. Fire prevention in Aleppo pine forests. In: Le pin d'Alep et le pin brutia dans la sylviculture méditerranéenne, volume 1986 of Options Mediterraneennes. CIHEAM, 167–178. Available: http://ressources.ciheam.org/om/pdf/s10/CI010861.pdf.

Wermelinger, B. 2004. Ecology and management of the spruce bark beetle Ips typographus – a review of recent research. Forest Ecology and Management 202:67-82.

Williams, D.W. and Liebhold, A.M. 2002. Climate change and the outbreak ranges of two North American bark beetles. Agricultural and Forest Entomology 4:87-99.

Xanthopoulos, G. 2000. “The 1999 Forest Fire Season.” International Forest Fire News 22:76-84.

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

- , Pukkala, T., Peltola, H. 2007. The use of heuristic optimization in risk management of wind damage in forest planning. Forest Ecology and Management 241:189-199.

Zwiers, F.W. and Kharin, V.V. 1998. Changes in the extremes of the climate by CCC GCM2 under CO2 doubling. J. Climate 11:2200-2222.