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Challenges in Climate-Driven Decision Support Systems in Forestry

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1. Introduction

The history of Decision Support Systems in forestry is quite long as well as the list of created systems and reviews summarizing their merits and flaws. It is generally recognized that a modern decision support system (DSS) should address simultaneously as many economical and ecological issues as possible without becoming overly complex and still remain understandable for users (Reynolds et al., 2008). The ongoing global change including the climate change sets new boundary conditions for decision makers in the forestry sector. The changing growth conditions (Albert & Schmidt, 2010) and expected increasing number of weather extremes like storms force forest owners to make decisions on how to replace the damaged stands and/or how to mitigate the damages. This decision making process requires adequate information on the future climate as well as on complex climate-forest interactions which could be provided by an appropriate climate-driven decision support tool. Both the damage factors and the forest management (e.g. harvesting) result in changes of the structure of forest stands. The structural changes result in immediate changes of albedo and roughness of land surface as well as of microclimatological conditions within the stand and on the soil surface. The consequences are manifold. The changed stand density and leaf area index trigger energy and water balance changes which in turn increase or decrease the vulnerability of the remaining stand to abiotic and biotic damage factors like droughts or insect attacks. A change of the microclimatic conditions might strengthen the forest against drought, but at the same time reduce its resistance to windthrow. The sign and extent of vulnerability changes depend on complex interactions of the effective climatic agents, above- and belowground forest structure, and soil. There are many DSS that are capable of assessing one or several risk factors; however there are few that are able to assess the additional increase or decrease of risks triggered by modification of forest structure resulting from previous damage or forest management activities. Disregarding these effects will inevitably lead user to either under- or overestimation of the potential damages. The question arises whether these additional risks are significant enough to be considered in a DSS.

In this chapter we present a new DSS developed according to the above mentioned requirements and capable to provide decision support taking into account economical and ecological considerations under the conditions of changing climate - the Decision Support

System – Forest and Climate Change. We then use the modules of that system to investigate the contribution of additional forest damage risks caused by structure changes into the general vulnerability of forest stand under changing climate.

2. DSS WuK

The Decision Support System – Forest and Climate Change (DSS-WuK) was developed to assist forest managers in Germany selecting an appropriate tree species under changing climate, considering future risks (Jansen et al., 2008, Thiele et al., 2009). It operates with a daily time step and combines traditional statistical approaches with process-based models.

2.1 Input

The system is driven by SRES-climate scenarios and hindcast data modelled by coupled ocean - atmospheric general circulation model ECHAM5-MPIOM developed by the Max-Planck-Institute for Meteorology (Roeckner et al. 2006). Additional input data are a digital elevation model (Jarvis et al., 2008) and its derivatives: aspect and slope, soil data from the national forest soil map (Wald-BÜK, Richter et al., 2007) at a resolution of 1:1 Mio. and atmospheric nitrogen deposition estimated using a modified version of the extrapolation model MAKEDEP (Alveteg et al., 1998, Ahrends et al., 2010a) with data from Gauger et al. (2008). The user of the DSS provides additional input on stand characteristics (tree species, age, yield class) on the forest of interest.

2.2 Model structure

Besides the climate-dependent forest growth the system estimates also biotic (insect attacks) as well as abiotic risks (wind damage and drought mortality). At present the system is able to evaluate the site sensitive growth and risks for the five most important tree species in German forestry (*Norway spruce*, *Scots pine*, *European beech*, *Sessile oak*, *Douglas fir*) of any age and state growing on any of the 124 soils typical for Germany. Thus, the economic outcome estimated by the DSS-WuK is based on complex interactions of many factors, e.g. climate, soils, tree species, stand characteristics and relief. The results are averaged and summed up over climatological periods of 30 years as defined by the World Meteorological Organisation. The period of 1971-2000 was chosen as the "present state" and replaced the old standard reference period of 1961-1990. To characterize the future development of forests the system provides information aggregated for the three periods: 2011-2040, 2041-2070 and 2071-2100.

The system is web-based and freely accessible. To tackle the usual requirements of transparency, focus on target audience, and usability we involved the potential end users into the development process during all phases. As a result the system took a two-stage form:

- The first stage presents pre-processed data covering entire Germany. The report includes growth and yield data, the various risks, and an economic evaluation. The user can choose a tree species, soil conditions at the spatial resolution of the employed regional climate model (e.g. 0.2°x0.2° of CLM, Datastream 3). The report of the first stage is, therefore, based on rather coarse input data and enables the user to decide whether a more detailed analysis (second stage) is needed. The obvious advantage of a system based on pre-processed data is the very short response time. The disadvantages, however, are the coarse spatial resolution and the fixed stand characteristics for the

different tree species, since the first stage does not include stand growth. To avoid the underestimation of risks the stands are chosen roughly at their rotation age, as these stands have the highest vulnerability to wind and insect damage.

- If a user is interested in a detailed description of changes in growth and yield data or the various risks, she/he can obtain a more sophisticated analysis by starting the second stage of the system. In this part of the DSS-WuK the on-demand simulations for a user-defined stand with downscaled climate data (1 km resolution) are carried out. Because of the relatively long response time, the system sends a report as a pdf file via email. In the second stage, the stand does not have a static structure any more but grows climate-dependent using an individual-tree growth model. The stand characteristics are updated every 10 years and submitted to the risk modules which carry out their calculations with a new structure with a daily time step (Fig. 1). The effect of growing stands on the risks is evaluated, meaning the stand characteristics determine the effect of damage factors, i.e. extreme weather events. The risks in the system are defined as a percentage of area loss of a fully stocked stand.

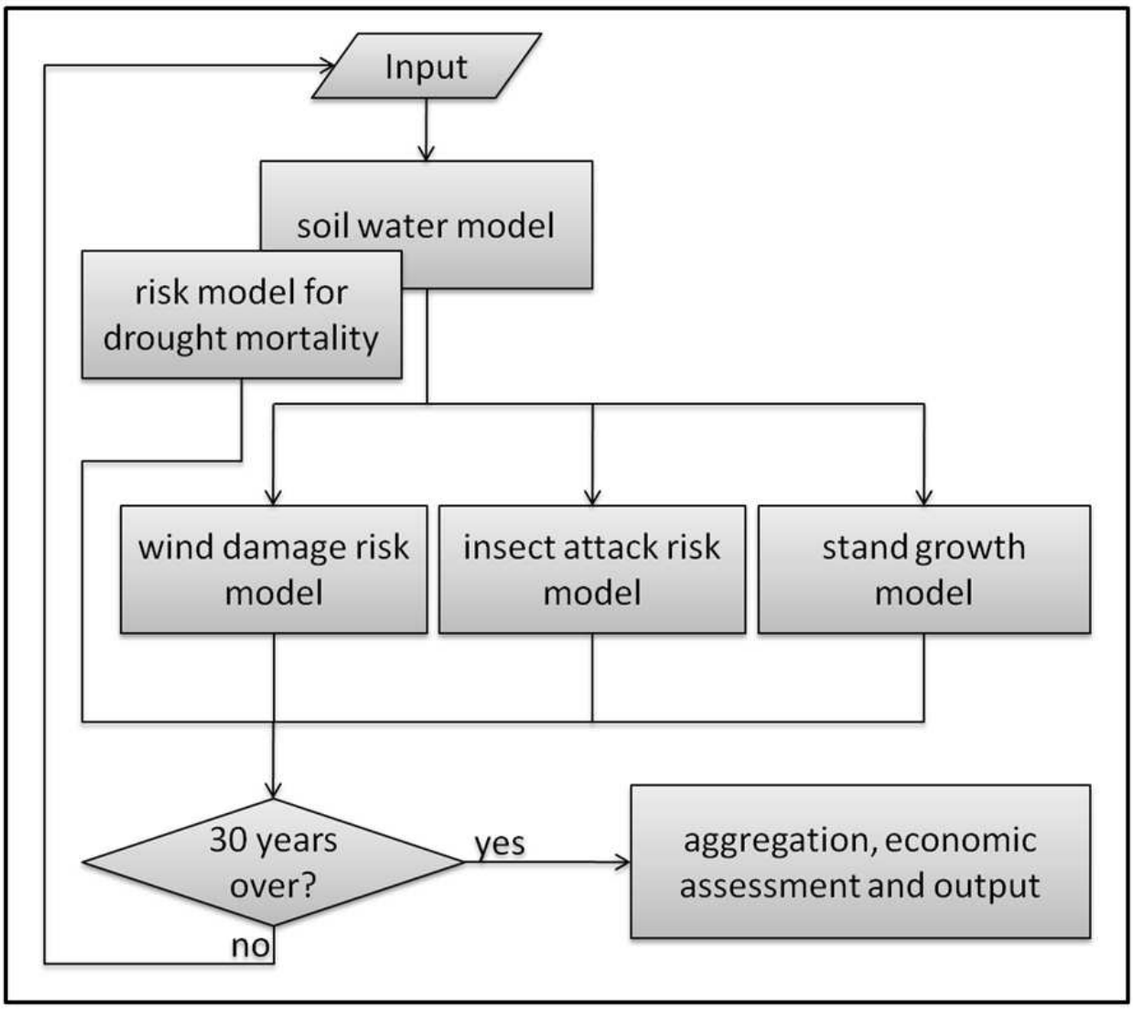


Fig. 1. A simplified flow chart of the core model process in DSS-WuK.

Both stages use the same core model (Fig. 1) and all calculations are carried out with daily resolution. All models get an update of their input data after each 10 year period. The risk model for drought mortality is coupled to the soil water model. The soil water itself, is influenced inter alia by the current stand characteristics. The soil water and climate conditions influence the output of the wind damage and insect attack risk models as well as the stand growth model. In the next iteration, the soil water model gets the stand characteristics actualized by the stand growth model. The results are finally aggregated to 30 year climatological periods mentioned above.
However, working at a level of forest stand the model is not able to consider the effect of the risks on stand growth, structure and microclimate, yet (Fig. 1). The estimated damage risks are not taken into account in calculations of stand growth and are executed (conceptually) in parallel. The system, thus, ignores the fact that a tree, which was, for example, thrown by wind, cannot be damaged by insects or drought later on. Overcoming this weakness is one of the challenges in forest decision support systems development. In the following, we will present the importance of this point by performing numerical experiments with a reduced-complexity, directly-interacting part of the simulation system DSS-WuK.

3. Setup of the experiment: risk assessment and damage factors interactions under current and future climate

The main purpose of the article is to demonstrate the interaction of factors influencing the forest vulnerability to abiotic risks and the feedback of forest damage to forest vulnerability under real and projected future climatic conditions. Results for a real forest stand under present climate are presented first, in order to show how the 30-years aggregated risk probabilities are formed. A detailed analysis of risk probabilities and interaction of different factors leading to or inhibiting the forest damage was performed on example of the real spruce stand research forest site "Otterbach", Solling, Central Germany. The meteorological data measured at the station of German Weather Service nearest to the forest stand with more than 30-years series of meteorological measurements were used as the basis for the investigation. The numerical experiments and analysis were carried out for generated idealized boreal forest stands under the conditions of climate scenarios C20 (reference) and SRES A1B.
To demonstrate the abilities of the DSS tool to evaluate the dynamics of abiotic risks and their variability for various climatic conditions the idealized forest stands growing in maritime and continental boreal zones of Finland and Russia, respectively, were generated. The hypothesis that similar forest damage can trigger different feedbacks in different climatic zones and under different development of climate conditions will be evaluated. The mechanism how the forest structure changes caused by forest damage or forest management activities are practically taken into account in coupled modules of DSS-WuK is described below.

3.1 Feedbacks of forest structure changes

Generally any changes in forest structure influence a forest ecosystem in many ways and perform a feedback to forest microclimate and stand vulnerability. In ecosystem and Soil-Vegetation-Atmosphere-Transfer process-based models the interaction of factors and the feedbacks can be summarized as shown in Fig. 2. The damage or thinning event reduces stand density and, thus, the Leaf Area Index (LAI) which is one of the most important

parameters in forest ecosystem models. The decrease of leaf area leads immediately to the decreasing of rain and light interception and, therefore, to the enhanced supply of light and water under the forest canopy. This in turn results in increased evaporation from soil surface under the canopy, but decrease of transpiration due to reduced LAI. Thus, the interplay of all these factors may lead to the increase or decrease of soil moisture depending on particular site conditions: latitude, meteorological conditions, soil type, tree species, initial LAI, extent of damage/management etc. These changed conditions may increase or decrease forest vulnerability and the probability of various consequent damages. If, for example, the resulting effect of windthrow would be an increase of soil moisture in a stand it would, on the one hand lead to the stand destabilisation against next storm, but at the same time – reduce the probability of drought stress (Ahrends et al., 2009).

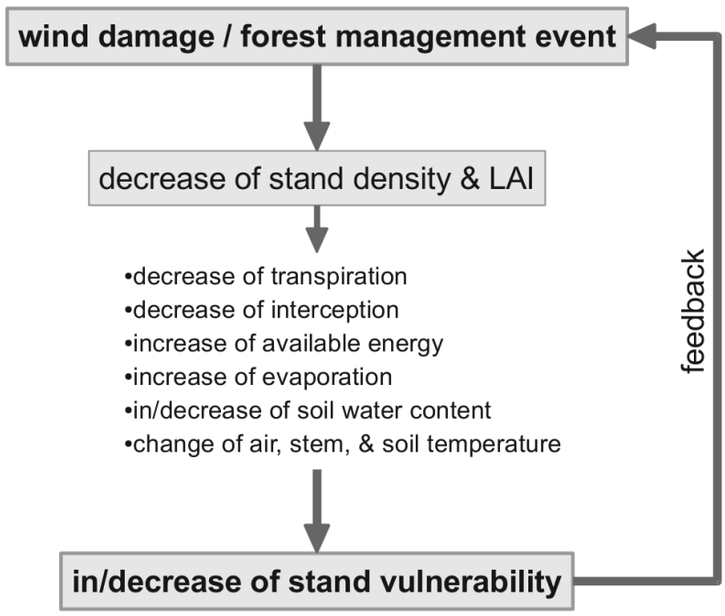


Fig. 2. Impacts of changing forest structure on stand vulnerability resulting from triggered interaction of ecosystem processes.

Therefore, to quantify the contribution of additional damage caused by forest structure changes the experiments with each of the chosen forest sites were carried out twice as shown in Fig. 3:

- with static structure, i.e. the climate caused structure damages were registered and summed up for the 30-years climatic periods, but the actual structure of modelled stands remained unchanged.
- with dynamic structure, i.e. the part of stand was removed according to the damage degree and the calculations proceed with the changed structure until the next damage event and so on for the rest of particular 30-years period.

3.2 Site description, tree species, and soil conditions

3.2.1 Otterbach, Solling

A 85-year-old pure spruce stand in Otterbach, located in the central part of Germany about 60 km North-West of Göttingen in the Solling highland, at 51.77° N and 09.45° E and about

300 m above sea level, was selected to study the possible effects of windthrow events on forest vulnerability to following windthrow damage risk – windthrow feedback. The characteristics of the investigated spruce stand are given in Table 1.

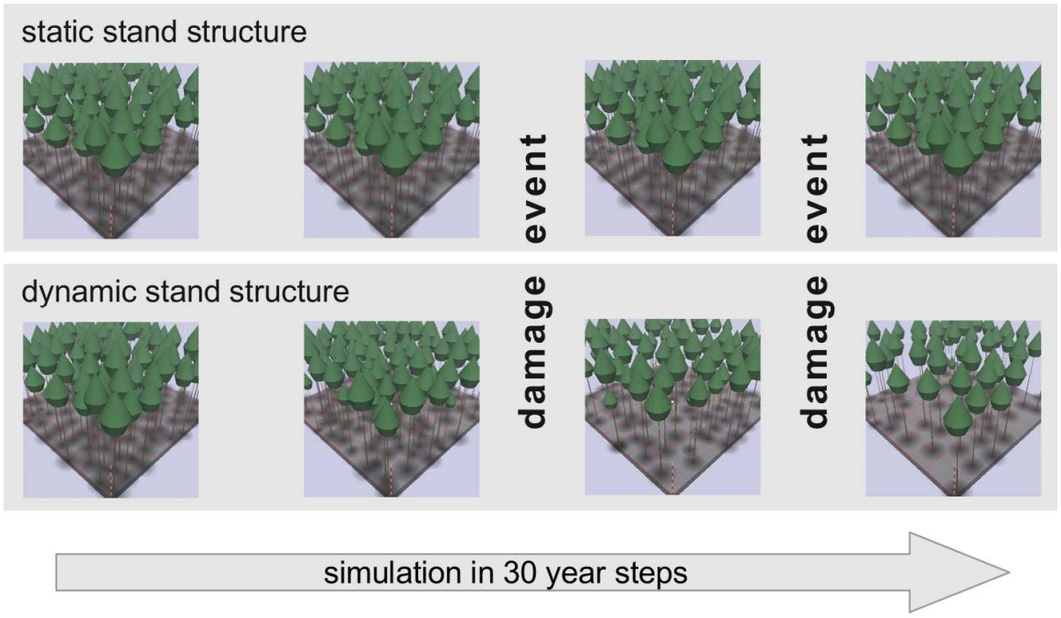


Fig. 3. The scheme of calculations with damage-independent structure (upper panel) and with forest structure updated (LAI and stand density reduced) after each damage event during 30-years period (lower panel).

Parameter	Unit	Value	Source
age	years	85	Olchev et al., 2009
tree density	trees ha^{-1}	350	Olchev et al., 2009
average tree height	m	34.0	Olchev et al., 2009
diameter at breast height, dbh	cm	36.0	Olchev et al., 2009
max. leaf conductance	cm s^{-1}	0.53	Federer et al., 2003
max. leaf area index	m^2 m^{-2}	4.6	Olchev et al., 2009
relative winter LAI	-	0.8	Hammel & Kennel, 2001
Fine root length	m m^{-2}	3100	Federer et al., 2003
Critical leaf water potential	MPa	-2.0	Czajkowski et al., 2009
Albedo	-	0.14	Federer et al., 2003
Albedo with snow	-	0.14	Federer et al., 2003

Table 1. Structural characteristics and model parameters of the forest in Otterbach (central Germany).

To describe the soil water budget a characteristic soil profile for this stand was selected (Fröhlich, 2009). According to FAO (1990) the soil type is a Dystric Cambisol derived from Triassic sandstone covered by loess. The soil hydraulic parameters are given in Tab. 2. According to Fröhlich (2009) free drainage is accepted at the lower boundary condition at 2 m depth.

Depth	Stone	Ψ_u	θ_u	θ_s	b	K_u	f_i
	[%]	kPa	-	-	-	mm day^{-1}	-
+5-0 (FF)	0	-6.3	0.384	0.848	5.23	2.3	0.92
0-5	2	-6.3	0.615	0.621	6.4	4.98	0.92
5-15	3	-6.3	0.615	0.621	6.4	4.98	0.92
15-20	3	-6.3	0.508	0.517	6.12	4.98	0.92
20-40	3	-6.3	0.508	0.517	6.12	4.4	0.92
40-60	30	-6.3	0.472	0.482	8.7	4.4	0.92
60-70	30	-6.3	0.472	0.482	8.7	1.76	0.92
70-95	30	-6.3	0.371	0.377	26.5	1.76	0.97
95-200	30	-6.3	0.371	0.377	26.5	1.28	0.97

Table 2. Soil hydraulic at saturation (subscript 's') and at the upper limit of available water (subscript 'u'). Note that ψ is matrix potential, K is hydraulic conductivity, θ is volumetric water fraction, b is the pore-size distribution parameter, f_i is the Clapp-Hornberger inflection point, K_u is the hydraulic conductivity at the upper limit of available water and FF is the forest floor. The stone content was taken from Feisthauer (2010).

The climate conditions at the research site "Otterbach" in Solling was characterized by means of long-term measurements at the meteorological station "Silberborn" (51.76°N, 9.56°E, 440 m a.s.l.) of German weather Service located near "Otterbach" site. The measurements time series cover the period from 1976 to 2008. To account for 140 m altitude difference between "Otterbach" site and "Silberborn" station the station's temperature was corrected using constant gradient of 0.0065°C m^{-1}.

3.2.2 Finland and Russia

The changes of forest risks in 21st century in dependence on changing climate were projected for two idealized forest stands located in two variations of boreal climate zone: a maritime one (Finland) and a continental one (Central Russia). The location for Finnish site was approximated at the centre of ECHAM5 grid cell (62.48°N, 28.125°E) and the location of Russian site – at 53.16°N, 91.875°E. To separate the effects of climate and damage feedbacks from the effects of other factors – soils, topography, vegetation composition etc. both Finnish and Russian stands were modelled identically: monocultural, mean tree height of 16 m, mean diameter at breast height (dbh) of 20 cm, and a stand density of 860 trees ha^{-1}. The Podzol soil type was assumed as typical for boreal zone according to FAO (2003): Map of World Soil Resources. The soil characteristics are given in FAO (2003) and therefore do not need to be repeated.

3.3 Modelling methods

The climate, wind and drought damage modules of DSS-WuK were used to investigate the contribution of additional structure-caused risks to the vulnerability of forest stands. The forest structure dynamics leads to both short- (days, months) and long-term (years, climatic periods) changes. To investigate the dependence of forest risk factors and of additional damage on short- and long-term climate variations we used the SRES climate scenario A1B (IPCC, 2000) modelled by a coupled ECHAM5-MPIOM general circulation model for AR4 of IPCC as climatological input.

3.3.1 Leaf area index

For modelling the leaf area index dynamics the LAI model by Ahrends et al. (2010b), applied previously at the Solling site (Sogachev et al., 2010, Panferov et al., 2009, 2010, Ahrends et al., 2009) is used. The model was calibrated to the maximum LAI value given by Olchev et al. (2009). After a windthrow event the damaged trees are 'removed' from the stand; accordingly the stand density and leaf area index, decrease. The calculations with other modules continued from the time point of damage with the new values of structural characteristics. The changes in structure result in a modified stand's water balance, which might enhance or inhibit the next windthrow event, thus creating positive or negative feedback.

3.3.2 Soil water

To simulate the water balance the 1D-SVAT model BROOK90 (version 4.4e) is used (Federer, 1995; Federer et al., 2003). It is a detailed, process-oriented model which can be used to investigate the potential effects of changes in leaf area index. For each soil horizon the parameters of the water retention curve and the hydraulic conductivity Brooks & Corey (1966) function were fitted through the van Genuchten parameter (van Genuchten, 1980) given by Fröhlich (2009) for Otterbach site and by Hammel & Kennel (2001) for the forest floor. The parameter of the water retention curve for Finland and Russia were deduced from soil texture classes (Clapp & Hornberger, 1978). The architecture of root systems is mainly influenced by the parent material, soil type, bulk density, chemical soil conditions, and depth of ground water, tree species and age. However, in each particular situation the information on rooting depth and the root distribution within the soil profile is a main source of uncertainty. For estimation of the effective rooting depth the rules from Czajkowski et al. (2009) are applied. The relative root density is modelled as a function of soil depth (Ahrends et al., 2010b).

3.3.3 Wind load

The model of atmospheric boundary-layer SCADIS (SCAlar, DIStribution, Sogachev et al., 2002) was used to calculate the wind load on trees. The model implements a two-equation closure approach. The model constants were modified by Sogachev and Panferov (2006) to enhance the applicability of approach for description of air flow over heterogeneous landscape coved by forest vegetation. The modification was shown to perform well for different vegetation canopies. In present study the model was driven by measured meteorological parameters as well as by climate model data. Other input parameters are forest structure: height, stand density, Leaf Area Density and aerodynamic drag coefficient Cd. Model equations and details about numerical schemes and boundary conditions can be found in Sogachev et al. (2002). It should be noted however, that the model is capable to describes separately the mean and gust loads on trees which allows more exact evaluation of possible wind damage cause and of high risk areas within the stand (Panferov and Sogachev, 2008).

The estimation of critical loads leading to overturning or breakage of trees is described in details in Panferov et al. (2009, 2010). Here we would like to show the modification of critical loads caused by changes soil moisture, LAI and rooting depth, which in turn were triggered by changes in forest structure.

It was assumed that the critical values of wind load derived from tree pulling experiments were obtained under some "normal" conditions characterising certain soil moisture and

temperature, rooting depth and applied on a standard leaf area typical for a given tree species. The variations of these characteristics increase or decrease critical wind load threshold.

Influence of rooting depth (RD) is taken into account as the linear factor describing the ratio of actual tree anchorage (RD_{act}) to "reference" value (RD_{ref}) for given tree species, age and state $f_{RD}= RD_{act}/(RD_{ref})$. As an indicator of soil moisture provided by soil water module the Relative Extractable Water (REW) (Granier et al., 2007) was adapted. The effect of soil moisture on windthrow is expressed as a linear function of REW deviations relatively to its reference value: REW_{ref} = 0.6 REWt,s, for the certain combination of tree species (subscript "t") and soil type (subscript "s"). The critical wind load (CWL) for actual soil moisture and forest structure is, therefore, derived from its reference value: $CWL_{act}= CWL_{ref}/REW_{act}* f_{RD}$. The system distinguishes between wet, dry (REW_{ref} < 0.6 REWt,s) and frozen (Tsoil < 0°C) conditions. Under dry and frozen conditions the probability of overturning is assumed zero and only a damage caused by stem breakage is possible.

Thus, when the actual wind load calculated from climate and wind modules exceeds the CWL (either for overturning or for stem breakage) modified by outcome of soil and LAI modules, the next wind damage event occurs. The stand density and LAI are reduced, which in turn leads to changes in stand microclimate, soil water regime and tree anchorage as described above, and consequently to further modification of CWL. The new CWL can be either higher or lower then the one before the damage event, so the stand vulnerability is either increased or decreased. Simultaneously the risk of drought stress is changed as well.

4. Results

4.1 Reference period, Otterbach

4.1.1 Climate and water budget components

As mentioned above the system was run at first for the real spruce stand at research site "Otterbach" under real climate measured during the period from 1976 to 2008.

Fig. 4 demonstrates the time courses of air temperature and maximal wind speed at the research site. A slight trend towards higher temperatures can be observed in the 32-year series. The warming trend generally results in a destabilization of forest stands in terms of wind damage as the number of days with frozen soil decreases in winter - e.g. the anchorage is reduced during the period of winter storms (Peltola et al., 1999). The wind curve shows several years with very strong storm events: 1983, 1990, 1993, and 1994. The Fig. 5 shows the course of precipitation sums and of the major water balance components calculated by the soil water module of the system. Except for 1994 the storm years were not accompanied by unusually high annual precipitation sums.

4.1.2 Windthrow

The calculations of wind damage with unchanged structure, i.e. without feedback clearly shows that despite the importance of soil, relief and vegetation factors the driving force defining the temporal pattern of damage is the wind (Fig. 6). The extensive windthrow events coincide with the strong windstorm years listed above, with the largest event in 1993 – the year with the strongest storm. The effect of other factors, however, is clearly visible in the non-linear relationship between storm strength and damage amount. For instance the damage in 1990 is lower than in 1994 and 1995, although the storm was stronger. The

possible reason could be deduced from Fig. 5 where it is shown that 1990 was also drier than both 1994 and 1995. The drier soil provided better anchorage for trees.

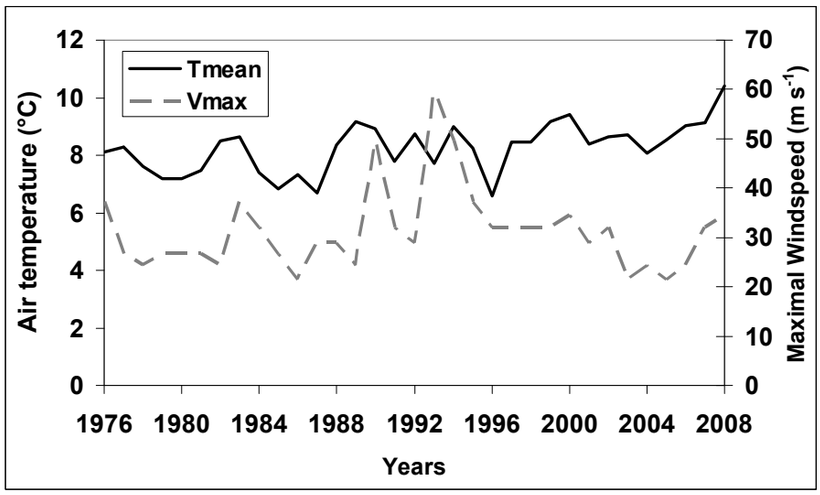


Fig. 4. Mean annual air temperature and maximal windspeed measured at the meteorological station of German Weather Service near research station "Otterbach" for the simulation period from 1976 to 2008.

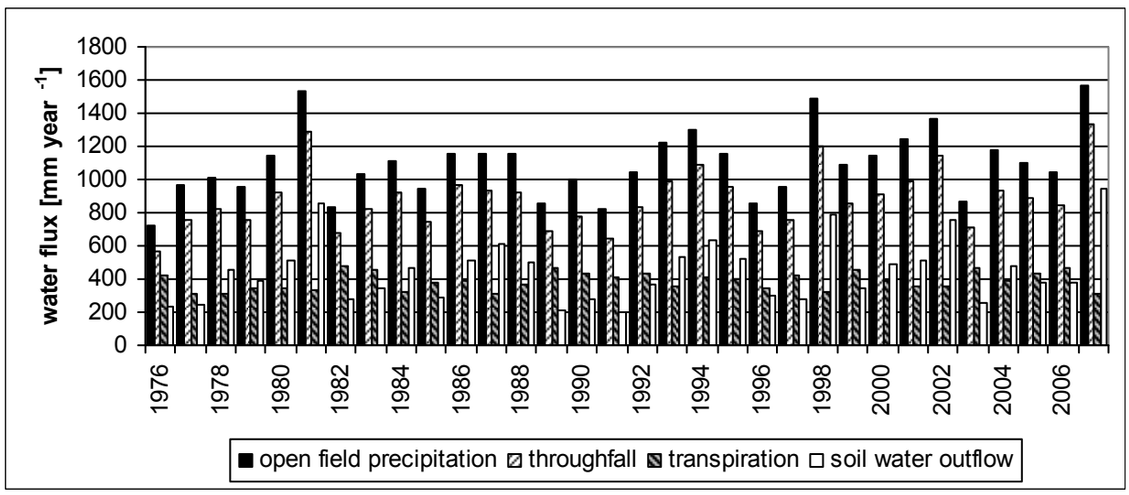


Fig. 5. The main water budget components for the simulation period from 1976 to 2007.

This effect could be observed even better when the feedbacks of the windthrow damage are taken into account (Fig. 6, lower panel). The reduction of stand density and LAI resulting from first strong storm in 1990 leads to considerable destabilization of stand and increase of its vulnerability, so that the strongest storm in 1993 produced even higher damage. This, in its turn results in more than 5% damage increase during following storms in 1994-1995. Thus, the decreasing resilience of stands and decreasing of CWL produce a cascade of wind damage events at the end of the period. Though each event in itself is not very extensive, the constantly decreasing CWL sum up the small damages to the significant annual sums. The constant small windthrows are also observed in reality at the Otterbach research site. This

cascade is not observed in modeling results when the feedbacks are not considered (Fig. 6, upper panel).

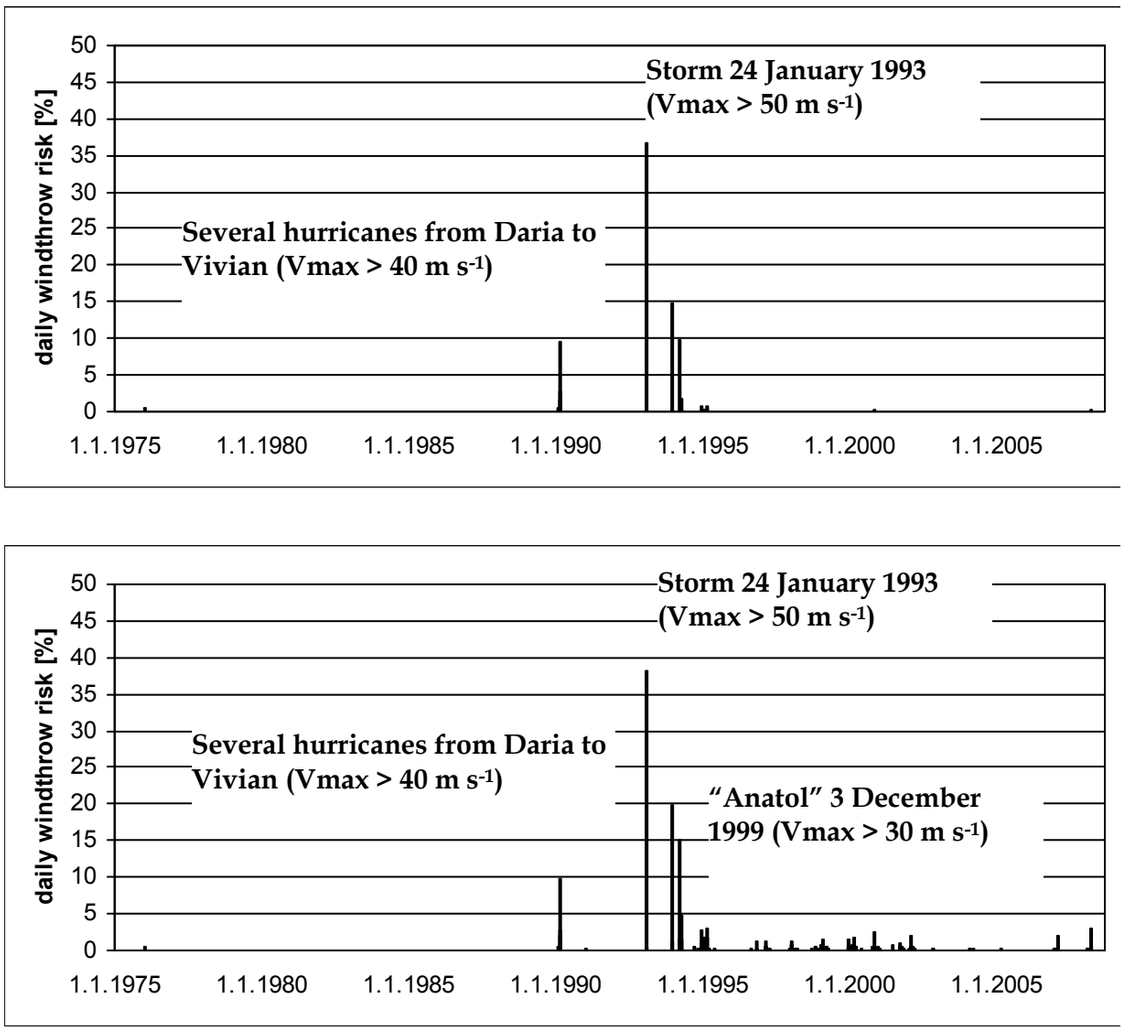


Fig. 6. Daily windthrow risk without (upper panel) and with feedback (lower panel) for the simulation period.

4.1.3 Interaction of risk factors

To analyse the causes and consequences of these additional risks caused by damaged forest structure, the strong storm and forest damage event of 25.01.1993 is considered here in details (Fig. 7).

The upper panel shows the stand LAI reduced after storm from 3.7 to 2.4 m^2 m^{-2}. The reduced LAI resulted in slightly decreased transpiration during following summer comparing to the simulation without feedback (Fig. 7, middle panel). Another effect of decreased LAI is the higher soil water content in "feedback simulation" which is the combined result of lower transpiration and higher throughfall (lower interception due to fewer trees).

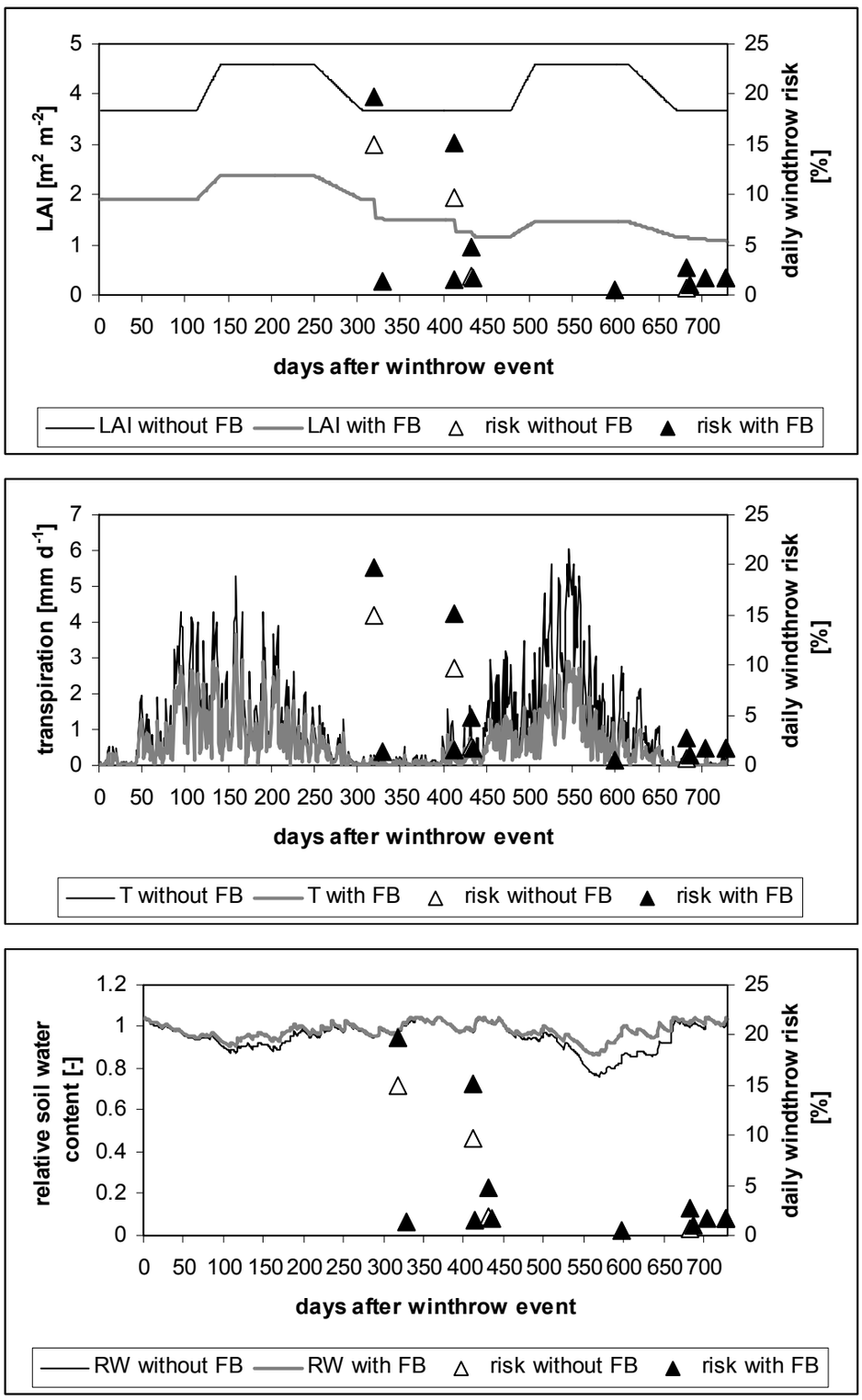


Fig. 7. Effect of static and dynamic (with feedback) forest structure on water budget components after strong wind storm at 25.01.1993.

However, towards the next winter (1994) the temperature limited transpiration and increased precipitation result in highest soil water content both for feedback (reduced LAI) and without feedback (normal LAI) calculations. Therefore, the 5% higher damage produced by the next storm (1994) in calculation with feedback is caused only to very small degree by reduced anchorage in soil, but mainly due to destabilisation of forest resulted from reduced stand density. Another consequence of this destabilisation is the occurrence of several small windthrows in the feedback calculations, which are definitely the product of reduced CWL and therefore not observed in calculation without feedback. The latter one registers only the damage of two main storms in 1994.
The strong events in 1994 caused further decrease of LAI in the feedback version which lead to even stronger difference in transpiration in summer 1995 (Fig. 7, middle panel, days 450-650) and, therefore, significantly higher soil moisture (Fig. 7, lower panel, days 450-650). Combined with reduced stand density the total effect was such a strong reduction of CWL that it led to the untypical windthrow event in late summer around the day 600 from initial windthrow event in 1993. The damage risks from feedback are twice higher then without feed under the presented soil and climate conditions.

4.2 Climate projection SRES A1B and damage risks in Finland and Russia

4.2.1 Projected climate

The experiment was limited to the two variations of boreal climate: the more continental one in Russia and the maritime one in southern Finland. The Norway spruce and Scots pine stands were chosen as typical for boreal zone. According to the same criteria a podzol was taken as soil type for the experiment. The calculations were carried out for a period of 120 years (1981 – 2100) with daily time step.
The analysis of the projected climate data shows a considerable increase of both summer and winter temperatures for boreal climate zone (Fig. 8). The precipitation in Finland increases noticeably during the 21st century, while the increase is due to higher summer and winter precipitation. In Russia the projected increase of precipitation is very weak, whereas only the winter precipitation shows the consistent rise (Fig. 9).
Both in Finland and in Russia the maximal windspeed shows similar pattern during 21st century: strong increase from present conditions to the period 2011-2040 and almost constant values (or even slight decrease) towards 2100 (Fig. 10). For both sites the winter winds are stronger then in summer, while in Finland the difference is more pronounced. The period 2041-2070 has the highest number of strong storms (not shown here) and period 2071-2100 with second highest number.

4.2.2 Wind damage and feedbacks

All trends of climate variables projected by ECHAM5-MPIOM as SRES A1B scenario indicate an increase of vulnerability of maritime and continental boreal forests. The increased temperature leads to reduced number of days with frozen soil, decreasing the anchorage of trees during autumn and spring storms. Higher precipitation result in higher soil moisture also leading to reduced tree anchorage. Stronger winds and higher number of storms on the other hand increase the wind load on forest. However, it is expected that pine trees will be less vulnerable to the wind damage than spruce.
If simulations are performed with the given setup the system indeed projects higher windthrow risks for boreal forests during 21st century. Figure 11 shows the windthrow risks in 21st century for Finland and Russia aggregated over 30-year periods. The upper panel

demonstrates the nonlinearity of damage dependence on combination of influencing climatic factors. The projected damage risks are generally higher for Finland due to higher windspeed and precipitation. The differences in temporal patterns of Russian and Finnish

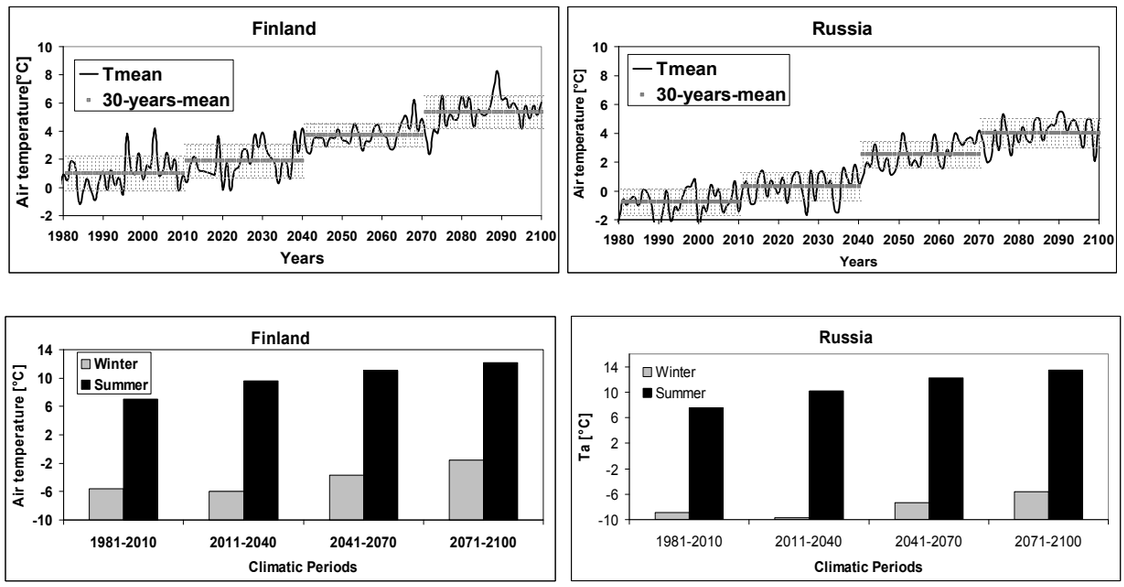


Fig. 8. Changes of mean annual air temperature (upper panels) and mean seasonal temperatures for 30-years climatic periods (lower panel) in 21st century in Russia and Finland according to SRES A1B (ECHAM5-MPIOM).

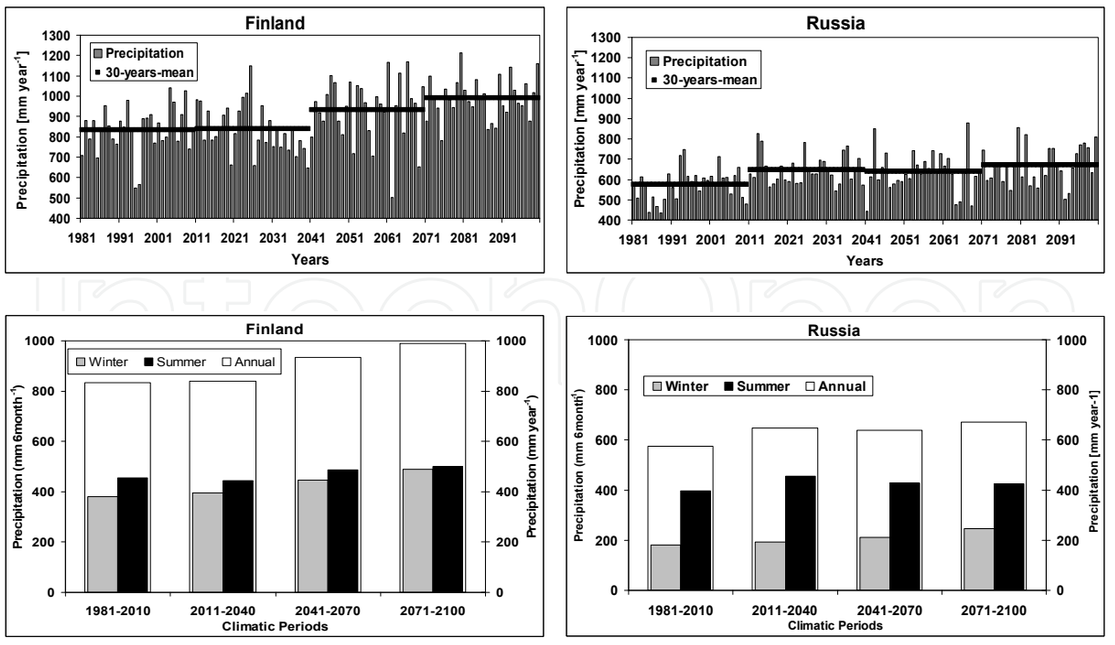


Fig. 9. Changes of annual precipitation sum (upper panels) and mean seasonal precipitation sums for 30-years climatic periods (lower panel) in 21st century in Russia and Finland according to SRES A1B (ECHAM5-MPIOM).

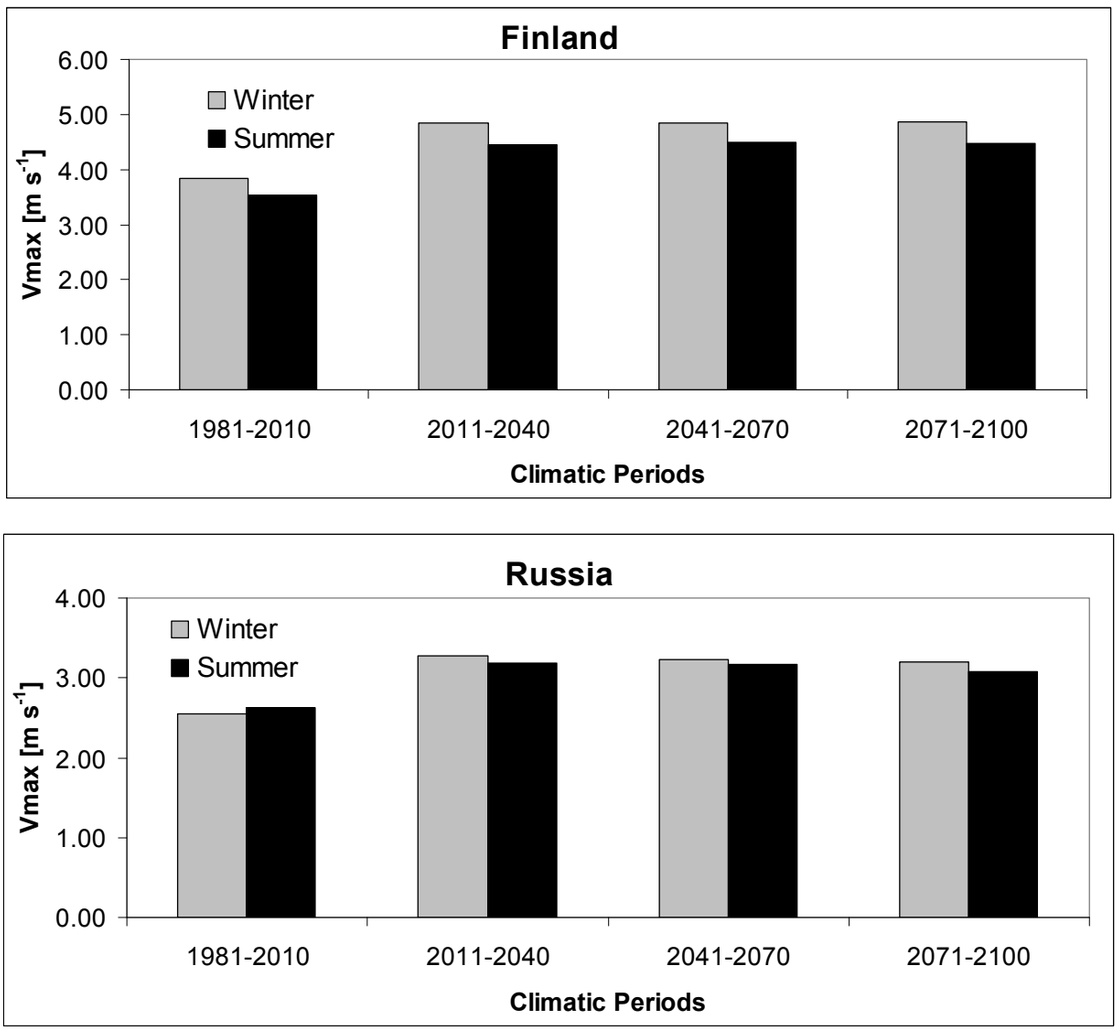


Fig. 10. Changes of seasonal-averaged daily maximal windspeed (Vmax) for 30-years climatic periods (lower panel) in 21st century in Russia and Finland according to SRES A1B.

sites are not easily explained. In Russia the maximum of windthrow falls on the period of 2011-2040 where the maximal increase of mean windspeed is observed. The maximal increase of windspeed in Finland is also observed in 2011-2040, however the maximal damage risk is projected for 2041-2070. The main reason is the higher number of extreme storms events during 2041-2070 though the mean Vmax is almost as high as in 2011-2040. Additionally the joint effect of increased precipitation and temperature which are considerably higher than in 2011-2040 contributes to the difference. The following decrease of wind damage toward 2100 in Finland is caused by reduction of windstorms comparing to previous period. Although the storms number during the period 2071-2100 is similar to the reference period the slightly higher mean Vmax and considerably higher temperature and precipitation result in twice higher damage during 2071-2100 comparing to P0. The analysed dynamics of wind damage demonstrates that to capture such joint effects of several climatic parameters the system has to use coupled process-based approach.

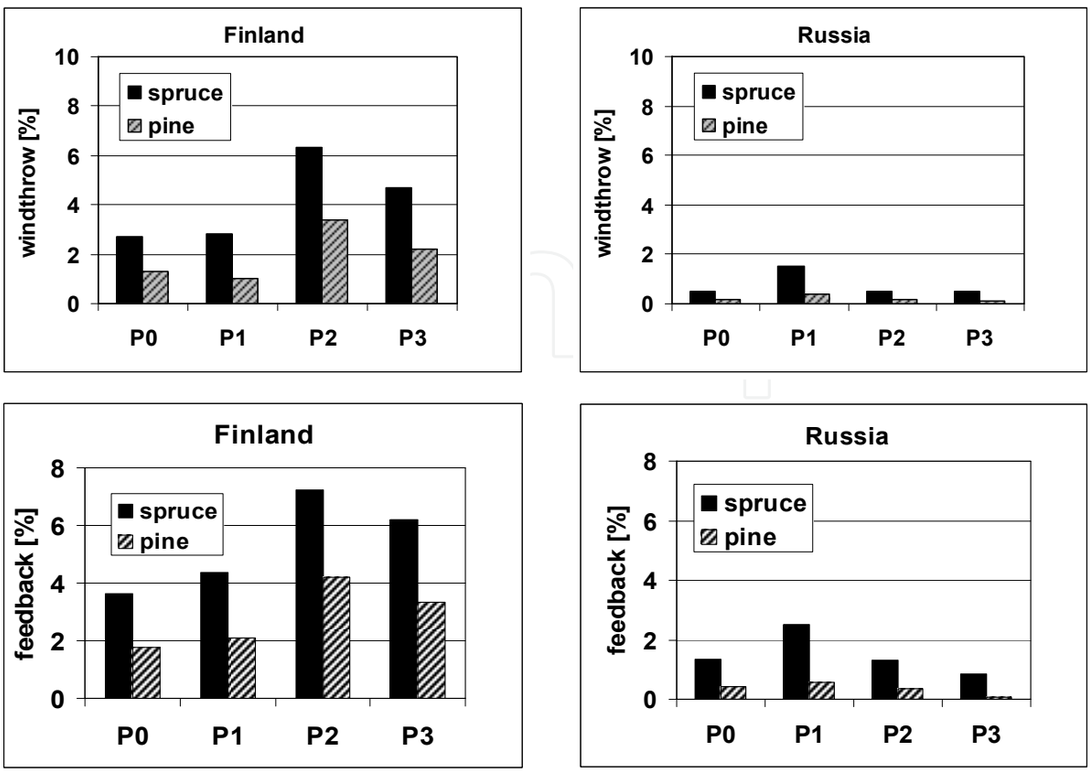


Fig. 11. Changes of windthrow risks and feedback contribution to wind damage aggregated for 30-years climatic periods (upper panel) in 21st century in Russia and Finland according to SRES A1B. Periods P0: 1981-2010, P1: 2011-2040, P2: 2041-2070, P3: 2071-2100.

The lower panel of figure 10 shows the contribution of feedbacks to initial damage, i.e. the additional damage produced in model when the vegetation damaged by initial windthrow event is "removed" from the modelled stand as described in previous sections. Comparing the upper and lower panels as well as Finnish site to the Russian one, one can see again the non-linear dependences of damage risks on combinations of effecting factors. Generally the magnitude of feedbacks is proportional to the magnitude of initial damage. Therefore the feedback contribution in Finland is higher than in Russia. However, the complexity of influencing agents might produce a complex response which would be higher or lower than considering only one factor. For instance the damages in P0: 1981-2010, P1: 2011-2040 (Finland) are almost of the same magnitude – for pine even lower in 2011-2040 - however due to the higher windspeed in 2011-2040 the same or lower initial damage produces more extensive consequences. The same is true for Russian site when compare the periods P2: 2041-2070 and P3: 2071-2100. Generally the contribution of feedbacks to initial damage in modelled stands is almost negligible comparing to real conditions presented in section 4.1. The main reason is the coarse resolution of Global Circulation Model (ECHAM5-MPIOM) which is not really suitable for evaluation of wind damage event at stand level. Due to wide area averaging it underestimates considerably the small-scale variations of windspeed caused by local surface heterogeneities and therefore – wind gustiness and Vmax. In present study it was implemented for purely demonstration purposes. For any practical use of DSS with climate projections, the downscaled scenarios should be implemented.

5. Conclusions

The additional damage caused by forest structural changes resulting from previous damage or forest management activities might contribute considerably to the projected forest risks and it is advisable to take it into account in a decision support process. It is emphasized that the degree of contribution as well as a sign of feedback in each particular case will strongly depend on the local or regional combination of climatic and soil conditions with tree species, age and structure. The DSS-user should be aware that one kind of damage might strengthen (windthrow -> windthrow) or weaken (windthrow -> drought) the contribution of other damage factors. Although, the projected total amount of damaged forest might even remain the same the losses would be redistributed between damage factors, which are the extremely important information for the forest owner looking for a decision support. Therefore, the adequate evaluation of projected risks in forestry requires the coupled modelling capable to consider the combined effect of risk factors.
The DSS-user should be also aware that although the system is quite advanced it has certain limitations. We would like to list the main limitations here. In present form is applicable in Germany only as the empirical functions are derived there. The systems works with monospecies stands only. The user should also take into account that the climate projections are not forecasts and the skill of estimation of future risks is limited by uncertainties of climate scenarios.

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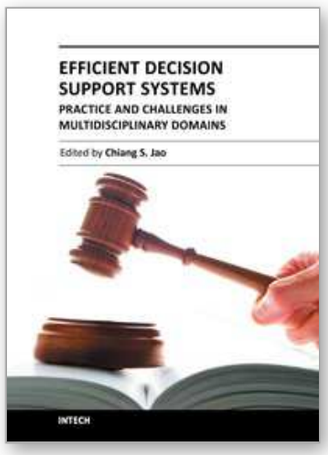
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