Feedbacks of windthrow for Norway spruce and Scots pine stands under changing climate

Panferov, O.; Döring, C.; Rauch, E.; Sogachev, Andrey; Ahrends, B.

Published in:
Environmental Research Letters

Link to article, DOI:
10.1088/1748-9326/4/4/045019

Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Panferov, O., Döring, C., Rauch, E., Sogachev, A., & Ahrends, B. (2009). Feedbacks of windthrow for Norway spruce and Scots pine stands under changing climate. Environmental Research Letters, 4(4), 045019. https://doi.org/10.1088/1748-9326/4/4/045019

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Feedbacks of windthrow for Norway spruce and Scots pine stands under changing climate

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2009 Environ. Res. Lett. 4 045019
(http://iopscience.iop.org/1748-9326/4/4/045019)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 192.38.90.17
The article was downloaded on 20/09/2012 at 12:38

Please note that terms and conditions apply.
Feedbacks of windthrow for Norway spruce and Scots pine stands under changing climate

O Panferov\textsuperscript{1}, C Doering\textsuperscript{2}, E Rauch\textsuperscript{1}, A Sogachev\textsuperscript{3} and B Ahrends\textsuperscript{2}

\textsuperscript{1} Department of Bioclimatology, Georg-August University of Göttingen, Buesgenweg 2, D-37077 Göttingen, Germany
\textsuperscript{2} Soil Science of Temperate and Boreal Ecosystems, Georg-August University of Göttingen, Buesgenweg 2, D-37077 Göttingen, Germany
\textsuperscript{3} Wind Energy Division, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, Roskilde, Denmark

E-mail: opanfyo@gwdg.de, anso@risoe.dtu.dk and bahrend@uni-goettingen.de

Received 15 May 2009
Accepted for publication 7 October 2009
Published 21 October 2009
Online at stacks.iop.org/ERL/4/045019

Abstract

Wind damage is one of the major natural disturbances that can occur worldwide in most types of forests. Enhanced management using adequate decision support systems (DSS) can considerably reduce the risk of windthrow. The decision support system ‘Forest and Climate Change’ (DSS-WuK) which is currently being developed at Göttingen University aims at providing a tool for the quantitative assessment of biotic and abiotic risks for forest ecosystems under the conditions of changing climate. In order to assess the future risks of wind damage the system employs a coupled modelling approach combining the turbulence model SCAlar DIStribution (SCADIS) with the soil–vegetation–atmosphere-transfer (SVAT) model BROOK 90. The present study investigates projections of wind damage in Solling, Germany under climate scenarios A1B and B1, taking into account the windthrow feedbacks—changes of microclimate as a result of tree fall and consequent stabilization or destabilization of a forest stand. The results of the study indicate that in Solling the risk of windthrow for spruce and pine forest stands is likely to increase considerably during the 21st century. The general tendencies indicate that under A1B the probability of damage would be higher than under B1 and that under the same climate and soil conditions the risk for spruce stands would be higher than for pine stands of equal age. The degree of damage and feedback contribution as well as a sign of feedback in each particular case will strongly depend on the particular local or regional combination of climatic and soil factors with tree species, age and structure. For Solling the positive feedback to local climatic forcing is found. The feedback contributes considerably (up to 6% under given conditions) to the projected forest damage and cannot be neglected. Therefore, the adequate projection of future damage probabilities can be performed only with a process-based coupled soil–atmosphere model with corresponding high spatial and temporal resolution.

Keywords: windthrow, climate change, feedback, boreal forest

1. Introduction

Wind damage is one of the major natural disturbances that can occur in most types of forests worldwide. Following Gardiner et al (2008) we will call henceforth any wind-induced damage leading to tree mortality—uprooting or stem breakage—a ‘windthrow’. Several studies pointed out that enhanced management using adequate decision support systems (DSS)
can considerably reduce the risk of windthrow (Gardiner et al. 2000). Such DSS, however, are few (Peltola et al. 2000, Schelhaas et al. 2007). The decision support system ‘Forest and Climate Change’ which is currently being developed at Göttingen University will provide a tool for the quantitative assessment of biotic and abiotic risks for forest ecosystems under the conditions of changing climate (Jansen et al. 2008).

According to Leckebusch et al. (2007) ongoing climate change may result in the increased frequency of severe storms which in turn will produce wide-area damage events within forest ecosystems. The review of scientific literature by Albrecht et al. (2008) demonstrated, however, that the uncertainties of the projections for future storm strengths and frequencies are too large to develop a reliable adaptation strategy. On the other hand, Peltola et al. (1999) indicated that the projected warmer weather is expected to increase the windthrow risk as the tree anchorage in winter will be reduced due to a decrease in soil freezing. The increase of projected temperature is well supported by the results of climate modelling (IPCC 2007). Therefore, we can assume that, even if the strength and frequency of storms will remain at the same level as at present, the risk of wind damage can still increase due to the higher soil temperature and consequent reduction of tree anchorage. Thus, the risk of windthrow should be estimated as a result of the combined effect of biotic and abiotic factors (Gardiner et al. 2000, 2008). It is also very important to take feedback of each damage event on climatic forcing into account as demonstrated by Vygodskaya et al. (2007). The positive feedback of windthrow events on wind forcing in a forest gap was demonstrated by Panferov and Sogachev (2008) with the modified 3D atmospheric boundary layer (ABL) model SCADIS (Sogachev et al. 2002). Schelhaas et al. (2007) showed that the wind damage occurred not only on forest edges but also in the middle of stands. The feedback of windthrow is not limited to the increase of windload on the remaining trees around the gap (Panferov and Sogachev 2008). The feedback can be related to many other processes and can have both positive and negative effects—the changes of precipitation interception, water regime, radiation—to name a few. The present study focuses on investigation of such effects for two typical boreal tree species: Norway spruce and Scots pine and for six soil types under the projected climatic conditions of SRES A1B and B1.

2. Methods

2.1. Site description, tree species, soil conditions

The Solling highlands within the limits of 51.6°N to 52°N and 9.4°E to 9.8°E, i.e. about 1600 km², are chosen for the investigation. Two tree species: Norway spruce (Picea abies (L.) Karst) and Scots pine (Pinus Sylvestris, L.) with three age classes each are studied. The corresponding characteristics of all species’ classes are given in table 1.

In order to consider the effects of different soil types and soil textures on root–soil resistance, rooting depth and soil moisture, we have selected six different soils from the digital soil map of Germany (Richter et al. 2007), which are typical for the investigation area. All six soils are free draining soils, but with strongly contrasting physical characteristics, e.g. texture, stone content and thickness (table 2).

2.2. Climate projections

To represent possible future climatic conditions the calculations of two SRES climate scenarios A1B and B1 for the period of 2001–2100 as well as the 20th century scenario C20 for the period of 1960–2000 done by the coupled general circulation model—Max-Planck-Institute ocean model, ECHAM5-MPIOM, were used as defined in the German framework programme ‘klimazwei’. The modelled data were downscaled using the Climate Local Model, CLM (Rockel et al. 2008) to a spatial resolution of 0.2° × 0.2°. The daily mean values of climate variables for A1B, B1 and C20 with two runs per scenario were obtained from the CERA database (Lautenschlager et al. 2009). For all meteorological variables the time series of all available runs of A1B and B1 (1 and 2) were merged with corresponding runs of C20 so that continuous time series from 1960 to 2100 were built for both runs of A1B and B1. The following notation is assumed in further analysis: A1B–1, A1B–2 and B1–1 and B1–2 which are correspondingly the merged runs 1 and 2 of C20–A1B and C20–B1. The simple A1B and B1 denote respective merged scenarios averaged over the two runs.
Table 2. Soil hydraulic parameters by texture class from Clapp and Hornberger (1978) at saturation (subscript ‘s’) and at the upper limit of available water (subscript ‘w’). (Note that where BD is bulk density, \( \psi \) is matrix potential, \( K \) is hydraulic conductivity and \( \theta \) is volumetric water fraction. Soil types and horizon symbols are given according to FAO (1990).)

| Soil type          | Depth (cm) | Horizon | Texture  | BD (g cm\(^{-3}\)) | \( \psi_w \) (kPa) | \( \theta_u \) | \( \theta_s \) | \( K_w \) (mm day\(^{-1}\)) |
|--------------------|------------|---------|----------|---------------------|---------------------|-------------|-------------|------------------|
| Cambisol (depth)   | 4–0        | L/F     | —        | 0                   | 0.2                 | -34.4       | 0.650       | 0.863            | 3.70             |
| Cambisol (shallow) | 4–0        | L/F     | —        | 0                   | 0.2                 | -34.4       | 0.650       | 0.863            | 3.70             |
| Cambisol (shallow) | 0–10       | Ah      | Clay loam| 27.5                | 1.15                | -25.0       | 0.365       | 0.485            | 13.13            |
| Cambisol (shallow) | 10–25      | Bw      | Clay loam| 50                  | 1.35                | -6.0        | 0.397       | 0.488            | 4.87             |
| Cambisol (shallow) | 30–50      | Bw/Bg   | Silt loam| 1.5                 | 1.75                | -25.0       | 0.365       | 0.485            | 13.13            |
| Cambisol (shallow) | 50–100     | Bg/Bt   | Silt loam| 9                   | 1.75                | -25.0       | 0.365       | 0.485            | 13.13            |
| Cambisol (shallow) | 100–130    | Bt/Bg   | Silt loam| 9                   | 1.75                | -25.0       | 0.365       | 0.485            | 13.13            |
| Cambisol (shallow) | 130–200    | Bw      | Silt loam| 27.5                | 1.75                | -25.0       | 0.365       | 0.485            | 13.13            |
| Stagnic luvisol    | 7–0        | L/F/H   | —        | 0                   | 0.2                 | -34.4       | 0.650       | 0.863            | 3.70             |
| Stagnic luvisol    | 0–30       | Ah      | Silt     | 1.5                 | 1.55                | -25.0       | 0.365       | 0.485            | 13.13            |
| Stagnic luvisol    | 30–50      | Bw      | Silt loam| 1.5                 | 1.75                | -25.0       | 0.365       | 0.485            | 13.13            |
| Stagnic luvisol    | 50–100     | Bg      | Silt loam| 9                   | 1.75                | -25.0       | 0.365       | 0.485            | 13.13            |
| Stagnic luvisol    | 100–130    | Bt      | Silt loam| 9                   | 1.75                | -25.0       | 0.365       | 0.485            | 13.13            |
| Stagnic luvisol    | 130–200    | Bw      | Silt loam| 27.5                | 1.75                | -25.0       | 0.365       | 0.485            | 13.13            |
| Cambic podzol      | 8–0        | L/F/H   | —        | 0                   | 0.2                 | -34.4       | 0.650       | 0.863            | 3.70             |
| Cambic podzol      | 0–5        | AEh     | Silt loam| 50                  | 1.35                | -25.0       | 0.365       | 0.485            | 13.13            |
| Cambic podzol      | 5–10       | Bw(AEH) | Silt loam| 50                  | 1.35                | -25.0       | 0.365       | 0.485            | 13.13            |
| Cambic podzol      | 10–30      | Bw      | Silt loam| 50                  | 1.35                | -25.0       | 0.365       | 0.485            | 13.13            |
| Cambic podzol      | 30–50      | Bw2     | Silt loam| 72.5                | 1.55                | -25.0       | 0.365       | 0.485            | 13.13            |
| Cambic podzol      | 60–200     | R       | Silt loam| 92.5                | 1.98                | -25.0       | 0.365       | 0.485            | 13.13            |
| Podzol             | 9–0        | L/F/H   | —        | 0                   | 0.2                 | -34.4       | 0.650       | 0.863            | 3.70             |
| Podzol             | 0–10       | AhE     | Sand     | 1.5                 | 1.15                | -7.0        | 0.188       | 0.509            | 3.96             |
| Podzol             | 10–25      | AE      | Sand     | 1.5                 | 1.35                | -7.0        | 0.188       | 0.450            | 3.96             |
| Podzol             | 25–30      | Bh      | Sand     | 1.5                 | 1.55                | -7.0        | 0.188       | 0.395            | 3.96             |
| Podzol             | 30–40      | B       | Sand     | 1.5                 | 1.55                | -7.0        | 0.188       | 0.395            | 3.96             |
| Podzol             | 40–80      | C       | Sand     | 1.5                 | 1.55                | -7.0        | 0.188       | 0.412            | 3.96             |
| Podzol             | 80–200     | C       | Sand     | 1.5                 | 1.55                | -7.0        | 0.188       | 0.412            | 3.96             |

2.3. Critical wind speed

The critical wind speed (CWS) for windbreak, CWS\(_{\text{break}}\), and for overturning, CWS\(_{\text{ot}}\), defined as the speed at the tree tops are shown:

\[
CWS_{\text{break}} = \frac{1}{k} D \left[ \frac{\pi \text{MOR} \times \text{DBH}^3 \cdot f_{\text{knot}}}{32 \rho G (d - 1.3)} \right] \ln \left( \frac{h - d}{z_0} \right) \quad (1)
\]

\[
CWS_{\text{ot}} = \frac{1}{k} D \left[ \frac{C_{\text{reg}} \times \text{SW} \cdot f_{\text{knot}}}{32 \rho G d} \right] \ln \left( \frac{h - d}{z_0} \right) \quad (2)
\]

where \( k = 0.41 \) is von Karman’s constant, \( d \) (m) is the zero-plane displacement, \( z_0 \) (m) is the aerodynamic roughness, \( D \) (m) is the average spacing between trees (table 1), DBH (m) is diameter at breast height (1.3 m above ground), \( h \) (m) is mean tree height (table 1) and \( \rho \) (1.226 kg m\(^{-3}\)) is the dry air density. \( C_{\text{reg}} \) (N m kg\(^{-1}\)) is a regression constant that is dependent on soil and rooting depth and SW (kg) is the stem weight of the tree. The factors \( f_{\text{knot},w} \) (=0.85) and \( f_{\text{CW}} (=1.17) \) account for the reduction in wood strength due to knots and the additional load due to the overhanging weight of the tree displaced from the vertical position by the wind stress. \( f_{\text{edge}} \), taking into account the position of the tree relative to the forest edge, is ignored because of the assumption of horizontal homogeneity. \( G \) is a dimensionless gust factor (Gardiner et al. 1997, Achim et al. 2005):

\[
G = 18.585 - 28.35 \frac{D}{h} + 1.59165 \ln \left( \frac{D}{h} \right). \quad (3)
\]

The influence of rooting depth was taken into account. We assume that the tree anchorage and consequently the CWS estimated by means of functions based on tree pulling experiments are valid for ‘average’ species-specific rooting depths: 1.04 m for spruce and 1.3 m for pine. Then the deviations of rooting depths from these mean values caused by a combination of tree species and soil type (Lehnhardt and Brechtel 1980, Raissi et al. 2009) produce a corresponding linear positive or negative deviation from mean tree anchorage (Blackwell et al. 1990, Peltola et al. 1999, Nicoll et al. 2006) and, thus, deviations of CWS from the initial ‘average’ value.
In general, the risk of windthrow increases with increasing soil moisture content because of the weakening of tree anchorage and consequent reduction of CWS (Stathers et al. 1994). As a dynamic indicator of the soil moisture status, we use the time-dependent relative extractable soil water, \( \text{REW}(t) \), which is calculated with the daily timestep as the ratio of actual to maximum extractable water according to García-Santos et al. (2009)

\[
\text{REW}(t) = \frac{\theta_r(t) - \theta_k}{\theta_{fc} - \theta_k} \tag{4}
\]

where \( \theta_r \) (m\(^3\) m\(^{-3}\)) is the actual (correspondingly—daily) volumetric (\( \theta_v \)) soil water fraction; \( \theta_{fc} \) (m\(^3\) m\(^{-3}\)) is the maximum soil water content extractable by plants (\( \theta_{fc} \) means field capacity) and \( \theta_k \) (m\(^3\) m\(^{-3}\)) is the residual soil water content. We distinguish between dry and wet soil conditions where the wet conditions mean that the soil moisture has exceeded a certain threshold and the tree anchorage starts to decrease. As there are no published data on the critical level of soil moisture, the threshold of \( \text{REW}(t) \geq 0.6 \) is chosen in this study because at this level the optimum water content has been exceeded (Howard and Howard 1993, Walse et al. 1998, Wildung et al. 1975).

The rate of mineralization, used as a proxy, slows down which indicates the prevailing anaerobic conditions and consequently filling most soil pores with water. The moistening of the soil beneath a soil–root plate reduces the tree’s resistance to wind (Kanimura et al. 2009). Therefore, we assumed for free draining soils that when a \( \text{REW}(t) \) exceeds 0.6 the CWS decreases linearly:

\[
\text{CWS}(t) = \begin{cases} 
\text{CWS}_{\text{act}} \times 0.6 & \text{REW}(t) \geq 0.6 \\
\text{CWS}_{\text{break}} & \text{REW}(t) < 0.6
\end{cases} \tag{5}
\]

### 2.4. Soil water

To simulate the water balance of a given combination of tree species and ages with certain soil types the 1D-SVAT model BROOK90 (version 4.4c) is used (Federer 1995, Federer et al. 2003). It is a detailed, process-oriented model that can be used as a reliable tool to investigate the potential effects of changes in tree species, soil types and climate scenarios. For all tree species—soil type combinations—free drainage is accepted as the lower boundary condition at 2 m depth. For each soil horizon the parameters of the water retention curve and the hydraulic conductivity function are deduced from soil texture with the pedotransfer function of Clapp and Hornberger (1978). The porosity values are corrected according to Federer et al. (1992). For the soil textural classification the program TRIANGLE of Gerakis and Bear (1999) is implemented.

The architecture of root systems is mainly influenced by the parent material, soil type, bulk density, chemical soil conditions, 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 Raissi et al. (2009) are applied. The relative root density is modelled as a function of soil depth (Jackson et al. 1996).

The BROOK90 calculations for all climate scenarios and runs were started at the timepoint 01.01.1960 and carried out with daily timesteps continuously for 140 yr up to 2100. The evaluations of results were accomplished for the following four periods: P0: 1981–2010—assumed as the ‘present conditions’ or reference period, P1: 2011–2040, P2: 2041–2070 and P3: 2071–2100.

### 2.5. Risk assessment and feedbacks

In the numerical experiments the following assumptions are made: (1) all forest stands are unmanaged; (2) no large gaps result from windthrow events—the windthrow damage is distributed evenly within the forest stand and (3) the surviving trees are quantified as a share of total stand (\( 0 \leq \text{ST} < 1 \)) which is a function of windload. The minimal wind speed causing a windthrow is \( V_{\text{min}} = 8 \text{ m s}^{-1} \) (the corresponding load is denoted as \( F_{V_{\text{min}}} \)) and the wind speed of \( V_{\text{abs,max}} = 40 \text{ m s}^{-1} \) is set as the load of full damage (Schelhaas et al. 2007) (the corresponding load is denoted as \( F_{V_{\text{abs,max}}} \)). The relative load provided by the actual wind is then

\[
F_{\text{act}} = 1 - \frac{F_{V_{\text{abs,max}}} - F_{V_{\text{act}}}}{F_{V_{\text{abs,max}}} - F_{V_{\text{min}}}} \tag{6}
\]

and

\[
\text{ST} = 1 - F_{\text{act}}^b,
\]

where \( b = 3.73 \) is the best approximation of damage curves for unmanaged stands presented by Schelhaas et al. (2007).

To assess the effects of forest structure changes resulting from windthrow events on the probability of the next damage event the calculations are carried out in two ways. First, the damage is summed up during the 30 yr period, but the forest structure is not changed. Second, the damage is summed up and the damaged trees are ‘removed’ from the stand; accordingly the stand density and leaf area index, LAI, decrease. The calculations with BROOK90 continued from the timepoint of damage with the new values of structural characteristics. The changes in structure result in a stand’s microclimate changes, which might enhance or inhibit the next windthrow event, thus creating positive or negative feedback.

### 3. Results and discussion

To characterize the projected climate conditions in the 21st century in the Solling area the CLM data were post-processed according to the recommendations of Keuler et al. (2007). The data of A1B1, A1B2, B1L1 and B1L2 are aggregated to annual means (sums in the case of precipitation). Spatial averaging over the 9 CLM grid points representing the study area is carried out for all mentioned climate characteristics. The spatial variations within the chosen area are very low (coefficient of variation \( < 10^{-2} \)) so that the spatial means are assumed to be representative. To describe the tendencies of climate development the spatial mean values are averaged over the 30 yr periods: P0–P3 and relative differences are calculated: \( \Delta \psi_i = (\psi_i - \psi_i)/\psi_i \times 100\% \), where \( \psi_i \) is the 30yr mean value of the spatially averaged climate variable listed above for the climatic period \( i = 1, 2 \) and 3 and \( \psi_0 \) is the mean value of the same variable for P0: 1981–2010.
Towards P3, soil temperatures increase monotonically and rather strongly so that the shallow cambisols and the lowest by stagnic all scenarios, tree species and ages the highest risk probability (up to 6%) for both A1B and B1. Considering the influence of higher risks (up to 8%) than 65 yr old spruce on stagnic luvisol investigated soil type. The 85 yr old pine on deep cambisol has higher risks than spruces of all ages on almost any other scenarios, and even that young pines on shallow cambisols than spruces of the same age on stagnic luvisol under both pines on shallow cambisols have higher risk probabilities be taken into consideration. For instance, one can see that case this general rule cannot be applied and all factors should be taken into consideration. The magnitudes of risks generally increase, performing a positive feedback. The feedbacks contribute up to 5% in B1 and up to 6% in A1B to the initial wind damage. This effect is caused by the joint influence of several factors: the windthrow leads to a reduction of stem density in a stand and to a reduction of LAI. The total observed effect under the particular climatic and soil conditions is the increase of the soil water interception. The moderate values for deeper cambisol, vertic cambisol and cambic podzol lie between these extremes and are very close to each other. Interestingly, for the youngest (45 yr old) trees the influence of soil type is higher for pine, where the difference in damage between lowest and highest risks reaches 8%, than for spruce (difference within 1%). For the 65 and 85 yr old trees the tendency is opposite—the soil-dependent variability of windthrow risks is generally higher for spruce than for pine. The right panels for both species in figure 2 show the contributions of feedbacks to the wind damage. When stand structure is adjusted according to the damage the projected risks generally increase, performing a positive feedback. The feedbacks contribute up to 5% in B1 and up to 6% in A1B to the initial wind damage. This effect is caused by the joint influence of several factors: the windthrow leads to a reduction of stem density in a stand and to a reduction of LAI. The lower LAI in its turn causes the increase of radiation input and evaporation, but a decrease of transpiration and precipitation interception. The total observed effect under the particular climatic and soil conditions is the increase of the soil water content which leads to the reduction of CWS and, thus, to an increase of the probability of following windthrow.

The magnitudes of risks generally increase, performing a positive feedback. The feedbacks contribute up to 5% in B1 and up to 6% in A1B to the initial wind damage. This effect is caused by the joint influence of several factors: the windthrow leads to a reduction of stem density in a stand and to a reduction of LAI. The lower LAI in its turn causes the increase of radiation input and evaporation, but a decrease of transpiration and precipitation interception. The total observed effect under the particular climatic and soil conditions is the increase of the soil water content which leads to the reduction of CWS and, thus, to an increase of the probability of following windthrow.

The height which increases exponentially with age. The observed differences between tree species are rather remarkable: the contribution of feedback is stronger for the youngest pines than for the youngest spruces, but weaker for middle and older pines compared to spruce stands of the same ages. The influence of the soil type on the feedback contribution is quite strong.
Figure 2. Scenarios of absolute windthrow damage (%) as a share of total stand for different tree species, tree ages and soil types. — △—: cambisol (shallow), — ●—: podzol, — O—: stagnic luvisol, — □—: cambisol (deep), — ○—: vertic cambisol, — ×—: cambic podzol.
Figure 3. Scenarios of relative windthrow damage (%) as a share of total stand for different tree species, tree ages and soil types. —△—: cambisol (shallow), ——●—: podzol, —●—: stagnic luvisol, —⋄—: cambisol (depth), —○—: vertic cambisol, —×—: cambic podzol.
but varies significantly between different combinations of tree species with stand ages. Some general rules could, however, be deduced: in 65 and 85 yr old spruce and pine stands the feedback provides the strongest contribution on the ‘highest risk’ soils like shallow cambisols, and the lowest contribution on the lowest risk soils like stagnic luvisols. The pattern for the youngest stands is somewhat more complicated: with spruces the order is reversed—lowest risk soils like podzols get the highest and stagnic luvisols the lowest contribution; with pines the stagnic luvisols also gets the smallest contribution: the highest contribution, however, is observed for vertic cambisols. In terms of climatic conditions the risks for all species, stand ages and soil types are generally lower under B1 than under A1B for which the higher wind speeds are projected.

3.1. Projected relative changes of windthrow

When estimating the trends of windthrow risks in the 21st century compared to present conditions, i.e. relating the projected damage for periods 1, 2 and 3 to the reference P0 (figure 3), it is obvious that the values generally increase towards 2100. The increment reaches values as high as 90% for 45 yr old pines under A1B. As the relative changes of $V_{\text{max}}$ towards P3 are rather weak—within 2%—the considerable increment of damage could be explained by the reduction of CWS caused by a combined effect of soil moisture increase due to the increase of precipitation (figure 1) with an increase of air and soil temperature. On the one hand, the increase in temperature increases the evaporation which has a drying effect leading to stabilizing of stands and increasing of CWS. However, on the other hand the rise of temperature leads to the destabilization of stands via the increasing share of liquid precipitation and the decreasing number of days with ground frost, thus decreasing the CWS. The resulting effect for the studied conditions is destabilizing, i.e. leads to the decreasing of CWS and increasing of wind damage risks. The changes, i.e. relative increases of risks, are generally stronger under A1B conditions (e.g. >50% for P3) than under B1 (<50% for P3). However, the temporal course of changes and the relative contribution of feedback are of a more complicated character depending on a combination of scenarios, tree species and soil types (figure 3). For all 65 and 85 yr old stands under B1 and for 65 and 85 yr old pine stands under A1B the curves show a period between P1 and P2 where both the increase of relative risks and feedback contributions slow down (e.g. 65 yr old pine), remain at the same level or even decrease. The effect is caused by the combined effect of precipitation and windspeed changes: an increase of the annual values of both causes the strong increase of damage risks during P1 relative to P0 under both A1B and B1. However, the weaker increment of annual precipitation during P2 slows down the relative increase of damage under A1B and the simultaneous weak reduction of precipitation with strong reduction of windspeeds (figure 1) causes with some soils (e.g. podzols) even a negative trend for P2 compared to P1. The strong increase of the windspeed during P3 combined with a stabilization of annual precipitation causes the second strong increase from P2 to P3 of projected damage relative to present conditions (P0). The pattern of relative damage with feedback contributions (figure 3, right columns by both species) is similar to the pattern of relative damage itself, but shows higher values for all species and soils. For all the spruce stands and youngest pine stands under A1B the risks and feedback contributions increase monotonically toward P3. The youngest spruces under B1 show the same monotonic increase despite the irregular changes of wind speed described above. It is caused by the increase of air and soil temperatures and by seasonal distribution of precipitation and CWS during the 21st century. It means: the mentioned reduction of annual precipitation and wind speed increments are caused by the reductions of summer half-year values while both the winter precipitation and the number of days with CWS increase toward 2100, causing monotonic damage increase by shallow-rooted spruce and youngest pine compensating for the reduction during the summer months.

Comparing the risk increments of both species one can notice that risk increments with (up to 95%) and without feedbacks (up to 90%) are higher for pine than for spruce (up to 70% and 80%, respectively) under A1B and—for youngest pine—under B1. For older stands under B1 the risks are slightly lower than for spruce. The reason is that the shallower-rooted spruce has considerably higher probability of damage already during P0 than pine (figure 2). That results in lower than pine values of relative (relative to P0) damage under the strong increase of $V_{\text{max}}$ during A1B and from P0 to P1 under B1. The relative values also show the role of soils. By considering figures 2 and 3 one can see that, in general, the forests on soils with high absolute values of risk damage (e.g. shallow cambisol) experience a lower relative increment both with and without feedback than the forests on ‘low damage soils’ like stagnic luvisol. This general tendency can be explained in a similar way—shallower soils are already close to ‘risk saturation’ during P0 and the high risk values of P0 results in a lower relative increment than for low risk soils. The dependence, however, is not that straightforward: under B1 the highest risk changes, with a well-expressed difference for older trees, is observed for podzols—the second lowest damage risk.

The time course of feedback contribution also depends on the combination of climatic, soil and stand factors (figures 2 and 3). For ‘risk saturated’ shallow-rooted youngest pine and spruce stands on all soils the contribution of feedback remains below 2% during all periods. The 65 and 85 yr old stands experience an increase of feedback contribution towards 2100 for all soils except for podzol and stagnic luvisol, where the contributions stabilize around P2 and show no or very weak increase towards P3. It should be noted that the feedback contribution for spruces increases with stand age from up to 5% for 65 yr to 6% for 85 yr old stands and from up to 4% to 5% under B1. Also the feedback contribution for both older pine stands on podzol and stagnic luvisol reach maximum risks in P1 and remain at this level till P3. The feedback contribution to risks in pine stands generally remains very low, exceeding 2% for 85 yr old stands only on highest risk shallow cambisols. The higher resistance of pine could be explained by the stronger role of deep rooting which compensates for the destabilizing effect of feedback, namely the increase of REW caused by LAI reduction through the windthrow.
4. Conclusions

The results of the study indicate that in Solling, Germany the risk of windthrow for spruce and pine forest stands is likely to increase considerably during the 21st century, although the projected increases of windspeed and annual precipitation sums are rather weak (up to 1.6% and 6.5%, respectively). The general tendencies indicate that under A1B the probability of damage would be higher than under B1 and that under the same climate and soil conditions the risk for the spruce would be higher than for the pine stands of equal age. However, it is shown that the degree of damage in each particular case will strongly depend on the particular local or regional combinations of tree species, age and structure with climatic and soil factors. It is also demonstrated that windthrow-caused changes of forest structure produce a positive feedback to local climatic forcing in Solling. The feedback contributes considerably (up to 6% under given conditions) to the projected forest damage and should not be neglected. However, the resulting sign of the feedback in other landscapes will depend on the interaction of separately mentioned climatic, soil and vegetation factors. Therefore, the adequate projection of future damage probabilities could be performed with a process-based coupled soil–atmosphere model with corresponding high spatial and temporal resolution, although the more accurate estimation of the REW contribution to stabilization/destabilization of trees on different soils still remains a great challenge and requires more experimental studies.

Acknowledgments

This study was supported by the German Ministry for Education and Research within the frameworks of klimazweig—programme (Project DSS-WuK) and by the Ministry of Science and Culture of Lower Saxony (Programme KLIFFF). We gratefully acknowledge this support.

References

Achim A, Ruel J C and Gardiner B A 2005 Evaluating the effect of precommercial thinning on the resistance of balsam fir to windthrow through experimentation, modeling, and development of simple indices Can. J. Forest Res. 35 1844–53
Ahrends B, Panferov O, Czajkowski T, Döring C, Jansen M and Bolte A 2009 Bundesweiter standortsbezogener Modellierungsansatz zur Abschätzung von Trockenstress ausgewählter Baumarten unter den Klimaszenarien A1B und B1 im DSS Wald und Klima Ber. Freib. Forstl. Forsch. 82 161–79
Albrecht A, Schindler D, Grebhan K, Kohlne U and Mayer H 2008 Klimawandel und Stürme über Europa—eine Literaturübersicht FVA Einblick 01/08 20-23
Blackwell P G, Rennolls K and Coutts M P 1990 A root anchorage model for shallowly rooted Sitka spruce Forestry 63 73–91
Clapp R B and Hornberger G M 1978 Empirical equations for some soil hydraulic properties Water Resources Res. 14/4 601–3
Czajkowski T, Ahrends B and Bolte A 2009 Critical limits of soil water availability (CL-SWA) in forest trees—an approach based on plant water status vTI Agric. Forest Res. 59 87–93
FAO 1990 Soil Map of the World (Legend. World Soil Resources Report 60) vol 1, p 119
Federer C A 1995 BROOK90: a simulation model for evaporation, soil water and stream flow Version 3.1. Computer Freeware and Documentation. USDA Forest Service PO Box 640, Durham NH 03825, USA
Federer C A, Turcotte D E and Smith C T 1992 The organic fraction—bulk density relationship and the expression of nutrient content in forest soils Can. J. Forest Res. 23 1026–32
Federer C A, Vörösmarty C and Fedketa B 2003 Sensitivity of annual evaporation to soil and root properties in two models of contrasting complexity J. Hydrometeorol. 4 1276–90
García-Santos G, Bruijnzeel L A and Dolman A J 2009 Modelling canopy conductance under wet and dry conditions in a subtropical cloud forest Agric. Forest Meteorol. 149 1565–72
Gardiner B, Pirzadeh H, Huseini S, Kaminuma K, Mitchell S J, Peltola H and Ruel J C 2008 A review of mechanistic modelling of wind damage risk to forests Forestry 81 447–63
Gardiner B, Peltola H and Kellomäki S 2000 Comparison of two models for predicting the critical wind speeds required to damage coniferous trees Ecol. Modelling 129 1–23
Gardiner B A, Stacey G R, Belcher R E and Wood C J 1997 Field and wind tunnel assessments of the implications of respawning and thinning for tree stability Forestry 70 233–52
Gerakis A and Bear B 1999 A computer program for soil textural classification Soil Sci. Soc. Am. J. 63 807–8
Hammel K and Kennel M 2001 Charakterisierung und Analyse der Wasserzu- und -abflussverhältnisse von Waldstandorten in Bayern mit dem Simulationsmodell BROOK90 Forsch. Forschungsberichte München. 185 148
Howard D M and Howard P J A 1993 Relationships between CO2 evolution, moisture content and temperature for a range of soil types Soil Biol. Biochem. 25 1537–46
IPCC 2007 Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B A Bovel, M Tignor and H L Miller (Cambridge: Cambridge University Press) p 996
Jackson R B, Canadel J, Ehleringer J R, Mooney H A, Sala O E and Schulze E D 1996 A global analysis of root distributions for terrestrial biomes Oecologia 108 389–411
Jansen M et al 2008 Anpassungsstrategien für eine nachhaltige Waldbewirtschaftung unter sich wandelnden Klimabedingungen—Entwicklung eines Entscheidungsunterstuzungssystems, ‘Waldu und Klimawandel’ (DSS-WuK) Fortschrivth 79 131–42
Kaminuma K, Kitagawa K, Saito S, Yazawa H, Kajikawa T and Mizunaga H 2009 Root anchorage under the combined condition of wind pressure and intensive rainfall: tree-pulling experiments with controlled soil water content Proc. 2nd Int. Conf. Wind Effects on Trees Albert-Ludwigs-University of Freiburg (Germany) ed H Mayer and D Schindler
Keuler K, Will A, Raddeke K and Wolfit M 2007 Hinweise zur Nutzung von CLM-Ergebnissen CLM-Workshop und Kontaktforum
Lautenschlager M, Keuler K, Wunram C, Keup-Thiel E, Schurbeta M, Will A, Rockel B and Boehm U 2009 Climate Simulations with CLM. Data Stream 3: European Region MPI-M/MaxD. World Data Center for Climate (1) doi:10.1594/WDC/CLM/C20_1/D3; (2) doi:10.1594/WDC/CLM/C20_2/D3; (3) doi:10.1594/WDC/CLM/A1B_1/D3; (4) doi:10.1594/WDC/CLM/A1B_2/D3; (5) doi:10.1594/WDC/CLM/B1_1/D3; (6) doi:10.1594/WDC/CLM/B1_2/D3
Leckebusch G C, Ulbrich U, Froehlich L and Pinto J G 2007 Geophys. Res. Lett. 34 L05703
Lehnardt F and Brechtel H M 1980 Durchwurzelungs- und Schüttförmel von Waldbeständen verschiedener Baumarten und Altersklassen bei unterschiedlichen Standortverhältnissen Allg. Forstl. Jagd-Z. 151 120–7
Nicoll B C, Gardiner B A, Rayner B and Peace A J 2006 Anchorage of coniferous trees in relation to species, soil type and rooting depth Can. J. Forest Res. 36 1871–83

Panferov O and Sogachev A 2008 Influence of gap size on wind damage variables in a forest Agric. Forest Meteorol. 148 1869–81

Peltola H, Gardiner B, Kellomaeki S, Kolstroem T, Laessig R, Moore J, Quine C and Ruel J C 2000 Wind and other abiotic risks to forests introduction Forest Ecol. Manag. 135 1–2

Peltola H, Kellomaeki S, Vaeisaenen 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 Can. J. Forest Res. 29 647–61

Quine C P and Gardiner B A 2007 Understanding how the interaction of wind and trees results in windthrow, stem breakage and canopy gap formation Plant Disturbance Ecology: The Process and the Response ed E Johnson (Burlington, VT: Academic) pp 103–55

Raissi F, Müller U and Meesenburg H 2009 Ermittlung der effektiven durchwurzelungstiefe von forststandorten GeoFakten 9 1–7

Richter A, Adler G H, Fahnak M and Eckelmann W 2007 Erläuterungen zur Nutzungsdifferenzierten Bodenübersichtskarte der Bundesrepublik Deutschland im Maßstab 1:1 000000 (BUK 1000 N, Version 2.3) Hannover p 53

Rockel B, Will A and Hense A 2008 The regional climate model COSMO-CLM (CCLM) editorial Meteorol. Z. 12 347–8

Schelhaas M J, Kramer K, Peltola H, van der Werf D C and Wijdevem S M J 2007 Introducing tree interactions in wind damage simulation Ecol. Modelling 207 197–209

Schöber R 1995 Ertragstafeln wichtiger Baumarten bei verschiedener Durchforstung. 4. Aufl. Sauerländer Frankfurt am Main p 166

Sogachev A, Menzhulin G, Heimann M and Lloyd J 2002 A simple three dimensional canopy—planetary boundary layer simulation model for scalar concentrations and fluxes Tellus B 54 784–819

Stathers R J, Rollerson T P and Mitchel S J 1994 Windthrow Handbook for British Columbia Forests (Victoria, BC: British Columbia Ministry of Forests) p 32 Working Paper 9401

Vygodskaya N N, Groisman P Ya, Tchebakova N M, Kurbatova J A, Panfyorov O, Parfenova E I and Sogachev A F 2007 Ecosystems and climate interactions in the boreal zone of Northern Eurasia Environ. Res. Lett. 2 045033

Walse C, Berg B and Sverdrup H 1998 Review and synthesis of experimental data on organic matter decomposition with respect to the effect of temperature, moisture, and acidity Environ. Rev. 6 25–40

Wildung R E, Garland T R and Buschbom R L 1975 The interdependent effects of soil temperature and water content on soil respiration rate and plant root decomposition in arid grassland soils Soil Biol. Biochem. 7 373–8