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Forests under climate change: potential risks and opportunities

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Abstract

Climate change will affect forests in Germany through the end of this century. The impacts of climate change on forest productivity, water budget and the associated biotic and abiotic risks are relevant for the forestry sector and its decision makers. We analysed the possible impacts of climate change on Germany's forests using a variety of climate scenarios generated with the regional statistical climate model STARS and the process-based forest growth model 4C. The focus of our analyses was on mono-specific stands of the main tree species Norway spruce (*Picea abies* L. Karst.), Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.), oak (*Quercus robur* L. and *Quercus petraea* Liebl.), and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco). The impacts on net primary production of forest stands are mainly positive for needle tree species and more negative at low elevation, water-limited sites for broadleaved tree species like beech, which is in contrast to the overall tendency of deterioration of the annual percolation rates independent of tree species. The application of a fire danger index and a nun moth risk species index according to Zwölfer indicates that Germany's forests will experience, under the warmer and dryer climate described by RCP8.5, higher potential risks from fire and some specific pest species. An integrated evaluation reflecting the potentials and risks of forests under RCP8.5 for the German natural regions illustrates that the dryer (water-limited) low elevated regions reaching from southwestern to northeastern Germany will benefit less from the assumed climate change than regions in the Northwest and forest sites at higher altitudes, which are mainly temperature limited.

Keywords: forest growth model 4C, climate scenario RCP8.5, forest productivity, forest fire danger, nun moth risk

1 Introduction

The possible impacts of climate change on forests in Germany in the 21st century have been studied since the late 20th century, when early accounts of global change started (e.g. Lasch et al., 1999). A first analysis of the German forest sector under global change (Lindner and Cramer, 2002) focused on the impacts on forest productivity and the forest sector. Köhl et al. (2010) studied the effects of climate change on productivity and species composition in managed forests in Germany in light of potential mitigation strategies. Moshammer et al. (2009) analysed, by means of the process-based model BALANCE and the management-oriented model SILVA, the impacts of climate change in combination with adaptation strategies of management on the regional scale of a forest enterprise, which indicated the possibility of growth losses due to the applied site change scenarios for spruce and pine. On the other hand, Lindner et al. (2010) cited a variety of on larger scale studies that Central European forest production is limited mainly by water availability and the impacts for different species depend clearly on site condi-

tions and assumed regional climate changes. Analyses of expert knowledge (Spathelf et al., 2013) confirmed this statement and asserted risks for forest productivity, especially at low-altitude and dry sites. A model-based analysis on climate change impacts along an elevation gradient in Central Europe indicated, for beech and spruce, declines of growth at lower elevations and significant increase at higher elevations (Hlasny et al., 2011).

The impact on individual tree species that are considered to be particularly vulnerable such as Norway Spruce has been discussed using species distribution models (Kölling et al., 2009). However, these studies only addressed to a limited extent the effects of climate change on disturbance regimes and also mostly ignored climate change impacts on the interaction of the carbon and water balance of forests. Furthermore, they relied on few climate change scenarios without embracing the uncertainty induced in any climate change impact assessment by climate model uncertainty (cf. Reyer et al., 2013).

The impacts of climate change on forest water budgets have been partly treated in other studies but at smaller scales rather than the whole of Germany. For example, regional analyses of climate change impacts on groundwater recharge indicate temporal and spatial

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changes in ground water recharge for the IPCC scenarios A1B and A2 in a small catchment of the Black Forest in Germany (NEUKUM and AZZAM, 2012) without considering the implications for forest productivity. NATKHIN et al. (2012) highlighted the important effects of forest growth dynamics under climate change on groundwater recharge for a lowland region in north eastern Germany. Also the impacts of climate change on disturbances have been studied at the regional level. For regions like Lower Saxon Harz Mountains (OVERBECK and SCHMIDT, 2012) or the Bavarian Forest National Park (FAHSE and HEURICH, 2011) models and studies exist regarding risks of infestation and outbreaks of bark beetle.

Thus, studies combining climate change impacts on different functions of forests like productivity, carbon sequestration, and groundwater recharge as well as on risks due to extreme events and pest species are lacking. Therefore, we aimed to answer the following questions for the whole area of Germany: (1) how do changes in net primary production and timber production interact with changes in the water budget under climate change? (2) What are the possible risks of fire danger or pest outbreaks?

We addressed these questions by using climate scenarios supplied from the regional statistical climate model STARS (GERSTENGARBE et al., 2015) to drive the process-based forest model 4C (BUGMANN et al., 1997), which allows the impacts of changing climate on a variety of forest functions to be analysed as well as estimating risks from disturbances for forests until 2100. The main idea of our study was to evaluate potential risks and opportunities for typical forests all over Germany, to filter out the climatic signal and to account for confounding factors such as changing forest area, species composition, forest dynamics, and age structure during the next 50 years. This approach allowed us to assess potential regional risks and opportunities for forest stands of the economically most important tree species under a variety of climate change scenarios.

2 Method and material

2.1 Model 4C

2.1.1 Overview

Our impact analyses were realised with the process-based forest growth model 4C, which has been developed at the Potsdam Institute of Climate Impact Research and applied in various model-based studies on different regional and temporal scales. The model allows the simulation and analysis of long-term forest behaviour under changing environmental conditions (LASCH et al., 2005). It describes processes at tree- and stand-level, based on findings from eco-physiological experiments, long-term observations and physiological

modelling and includes descriptions of tree species composition, forest structure, and total ecosystem carbon content (for more details: http://www.pik-potsdam.de/~lasch/web_4c/theory/short_desc.htm). The model 4C shares a number of features with gap models, which have often been used for the simulation of long-term forest development. Establishment, growth and mortality of tree cohorts are explicitly modelled on a patch on which horizontal homogeneity is assumed. Water and nitrogen availability affect growth and mortality of trees. The annual course of net photosynthesis is simulated with a mechanistic formulation of net photosynthesis as a function of environmental influences (temperature, water and nitrogen availability, radiation, and CO_2) where the physiological capacity (maximal carboxylation rate) is calculated based on optimisation theory (modified after HAXELTINE and PRENTICE, 1996) and calculation of total tree respiration following the concept of constant annual respiration fraction as proposed by LANDSBERG and WARING (1997). The water and nitrogen availability depends on the soil parameters, the climatic conditions, and the stand development. Because we did not consider nitrogen deposition, the nitrogen availability changes only due to the decomposition processes in the soil, which are affected by soil temperature, soil humidity and the soil pH. The water balance is calculated from potential evapotranspiration (see below), interception, and percolation and varies with species and time.

Currently, the model is parameterised for the five most abundant tree species of Central Europe (European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* L. Karst.), Scots pine (*Pinus sylvestris* L.), oaks (*Quercus robur* L., and *Quercus petraea* Liebl.), and birch (*Betula pendula* Roth)) as well as other tree species like aspen (*Populus tremula* (L.), *P. tremuloides* (Michx.)), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), and black locust (*Robinia pseudoacacia* L.). These parameters are fixed for all applications of the model (see http://www.pik-potsdam.de/~lasch/web_4c/theory/parameter_table_0514.pdf). The regional scale of model application covers single-site analyses including model validation (GUTSCH et al., 2011; REYER et al., 2010; SUCKOW et al., 2001) as well as regional and large-scale analysis of climate change impacts (FÜRSTENAU et al., 2007; REYER et al., 2013).

2.1.2 Potential evapotranspiration according to Turc and Ivanov

The potential evapotranspiration was calculated based on the approach of Turc and Ivanov described in DYCK and PESCHKE (1995) as follows:

For $T >= 5\,°C$:

$$E = 0.00031 \cdot (R + 209) \cdot \frac{T}{T + 15} \cdot C$$

$$C = \begin{cases} 1 + \frac{(50 - H)}{70} & \text{if } H < 50 \\ 1 & \text{if } H \geq 50 \end{cases}$$

and for $T < 5\,°\text{C}$:

$$E = 0.000036 \cdot (T + 25)^2 (100 - H)$$

With

T – daily mean temperature [°C]
E – potential evapotranspiration [mm]
H – relative humidity [%]
R – global radiation [J cm^{-2}]

2.1.3　Fire danger index according to Käse FDI

The model also allows the calculation of a risk index for fire danger according to KÄSE (1969), which is used in similar form by the German Weather Service providing daily values from 1 (no risk) to 5 (very high danger) from the middle of February until the end of September.

The annual fire danger index based on the calculation of the daily fire danger index $I_C(d)$ according to KÄSE (1969) and FLEMMING (1994), which is calculated for days d with $46 \le d \le 274$.

The daily index is defined as

$$I_C(d) = k_p(d) \cdot I_C(d-1)$$
$$+ k_{\text{phen}}(d) \cdot (T_{\max}(d) + 10) \cdot \Delta p(d)$$

with

Δp – air vapour pressure deficit at 13 h of the respective day, calculated from the saturated vapour pressure $p_{s,13}$ at 13 h by (DVWK, 1996):

$$p_{s,13} = 6.1078 \cdot e^{\left(\frac{17.62 \cdot T_{\max}}{243.12 + T_{\max}}\right)}$$
$$p_{13} = p_{s,13} \cdot h_r / 100$$
$$\Delta p = p_{s,13} - p_{13}$$

with

$T_{\max}$ – maximum daily temperature [°C]
h_r – relative humidity

Precipitation modifier, k_p, is defined:

$$k_P(d) = \begin{cases} 0 & \text{if } P(d) \ge 10 \text{ or } C_{\text{snow}} > 2 \\ 0.25 & \text{if } 5 \le P(d) < 10 \text{ or } C_{\text{snow}} = 2 \\ 0.5 & \text{if } 1 \le P(d) < 5 \text{ or } C_{\text{snow}} = 1 \\ 1.0 & \text{else} \end{cases}$$

with

C_{snow} – number of snow days
$P(d)$ – daily precipitation [mm]

Phenology modifier, k_{phen}, is defined:

$$k_{\text{phen}}(d) = \begin{cases} 0.5 & \text{if } d_{\text{end}} < d \text{ and } P(d) \ge 5 \\ 1.0 & \text{if } d_{\text{BB,robinia}} < d < d_{\text{end}} \text{ and } P(d) \ge 5 \\ 2.0 & \text{if } d_{\text{BB,birch}} < d < d_{\text{BB,robinia}} \\ & \quad \text{and } P(d) < 5 \\ 3.0 & \text{if } d < d_{\text{BB,birch}} \end{cases}$$

The day of bud burst for birch $d_{\text{bb,birch}}$ is calculated according to the 4C approach (SCHABER, 2002). The day

of bud-burst for black locust $d_{\text{bb,robinia}}$ is determined with a simple temperature sum model: black locust foliates, when the temperature sum T_{sum} is above a critical value T_{crit} of 537 degree days. That means

$$d_{\text{bb,robinia}} = d \text{ for } d \text{ with } T_{\text{sum}}(d) \ge T_{\text{crit}}$$

and T_{sum} is calculated by

$$T_{\text{sum}}(d) = \sum_{i=1}^{d} T(i).$$

The parameter d_{end} is fixed with the day number of 1 September.

The daily fire hazard level is then calculated as follows. If $I_C(d)$ is less equal 500 the fire alert level is one, if it is greater than 500 and less equal 2000 the level is two, if it is greater than 2000 and less equal 4000 the level is three, if it is greater than 4000 and less equal 7000 the level is four, and if $I_C(d)$ is greater than 7000 the fire alert level is five.

2.1.4　Nun moth risk index NRMI

The model 4C calculates an index for the risk of nun moth (*Lymantria monacha* L.) mass outbreaks according to ZWÖLFER (1935). The nun moth risk index describes the annual risk of appearance or mass outbreaks of nun moth (*Lymantria monacha* L.). ZWÖLFER (1935) developed a thermal index on the basis of experiments about the influence of hydrothermal conditions on the survival and reproduction ability of nun moth. He investigated the impact of temperature on the different life stages of nun moth and determined three parameters for each life stage whereas the nine life stages were split into thirteen phases according to the relation between month and life stage (see Table 1):

p – parameter
T_0 – minimum temperature of the stage (°C)
r – number of days of the phase

For the first stage, egg (hatch period), ZWÖLFER (1935) calculated under wet saturated atmosphere (relative humidity of 100 %) $p = 65$ and $T_0 = 4.9$. He assumed for the life stage larva I no clear influence of the relative humidity within the range 40–100 %. The data for the following stages (larva II, III, IV, V) were collected for a relative humidity of 70–80 % (Table 1). Therefore, the index does not allow statements under dry climate conditions.

A thermal constant T_{tot} of the whole life stage was derived from these data as a sum of the parameters p of the different life stages. ZWÖLFER (1935) stated

$$T_{\text{tot}} = 1240 \pm 40.$$

From the observations of the phenology of the life stages of nun moth he defined for each phase a mean number of days r (Table 1). Using the local monthly means of temperature for the period April until September T_i ($i = 4, \ldots, 9$) which are assigned to the 13 phases $T_m(j)$

Table 1: Parameters of the nun moth life stages; T_m – related monthly mean temperature for the calculation of T_{sum}, $T_4, \ldots, T_9$ – monthly mean temperature from April until September.

Life Stage	Phase	p	T_0	r	Month	T_m
Egg (hatching period)	1	65	4.9	30	IV	$T_m(1) = T_4$
	2			3	V	$T_m(2) = T_5$
Larva I	3	217	3.2	17	V	$T_m(3) = T_5$
Larva II	4	84	5.7	8	V	$T_m(4) = T_5$
Larva III	5	84	7.2	3	V	$T_m(5) = T_5$
	6			6	VI	$T_m(6) = T_6$
Larva IV	7	90	7.6	10	VI	$T_m(7) = T_6$
Larva V	8	132	7.8	14	VI	$T_m(8) = T_6$
Larva VI	9	197	6.0	18	VII	$T_m(9) = T_7$
Pupa	10	130	8.4	13	VII	$T_m(10) = T_7$
	11			2	VIII	$T_m(11) = T_8$
Egg (embryo of next generation)	12	240	6.8	29	VIII	$T_m(12) = T_8$
	13			30	IX	$T_m(13) = T_9$
Sum		**1239**				

$(j = 1, \ldots, 13)$ (Table 1) a local annual temperature sum T_{sum} is calculated in the following way:

$$T_{sum} = \sum_{j=1}^{13} r(j) \cdot (T_m(j) - T_0(j))$$

T_m – related monthly mean temperature [°C]

The annual nun moth risk index is defined as following:

$$NMRI = \frac{T_{sum}}{T_{tot}}$$

ZWÖLFER (1935) stated that if NMRI is less than one, the required temperature sum for the whole life cycle is not available. If the value NMRI = 1 is reached, then the minimum temperature limited distribution area is given. The index allows the presentation of the northern horizontal distribution border but also of the vertical border. The southern distribution border is estimated for a NMRI value of 1.5–1.6. The distribution area of nun moth is characterises by NMRI values less than 1.6 and greater than 1.0. Typical areas for mass outbreaks of nun moth are characterised by NMRI values varying from 1.1 to 1.4 as long-term mean.

2.2 Data

2.2.1 Climate data and scenarios

The simulations were driven by daily climate time series of temperature, precipitation, relative humidity, global radiation, air pressure and wind speed for the past and the future. For the past time period 1981–2010 data from 1218 stations in Germany were used (see GERSTEN-GARBE et al., 2015). The climate scenario projections for the time period 2031–2060 are based on the Representative Concentration Pathways (RCP) scenario 8.5 of

the IPCC. The maximum (4.97 °C), minimum (2.36 °C) and median (4.01 °C) of temperature trend for Germany during 2011–2100 was determined from 21 different General Circulation Models (GCM) of the CMIP5 program driven by RCP8.5. These three trends were used to assemble new meteorological data sets from historical meteorological data by STARS (GERSTENGARBE et al., 2015). STARS is able to simulate a large number of such data assemblies per given temperature trend called realisations. The statistical characteristics of temperature and precipitation for the base period and the three RCP8.5 scenarios are given in Table 2.

We used 100 realisations in each case of the three RCP8.5 trend scenarios, all in all 300 realisations. The CO_2 concentration time series for the RCP8.5 scenarios was selected from the Extended Concentration Pathways by MEINSHAUSEN et al. (2011) with an increase of concentration to 603 ppm in 2060.

2.2.2 Soil data

The simulation sites (grid cells) were linked with the soil data base BÜK 1000 (BGR, 2004). Information of soil texture, physical and chemical soil parameters are given per soil horizon. The parameters are taken directly from this soil data base and processed in the model 4C. The nitrogen availability is calculated from the C/N ratio of the soil and is used for all tree species in the same way.

2.3 Simulation concept and analyses

The model simulations were realised on a grid (0.11 ° × 0.11 °) with 4183 sites corresponding to each grid cell, in Germany assuming a hypothetical forest stand at each site. The corresponding soil from the BÜK 1000 is assigned to each grid cell and the meteorological station closest to each grid cell was determined using Thiessen

Table 2: Statistical characteristics (minimum, maximum and mean value over all grid cells and all realisations in the case of RCP8.5) of the climate data for the base period and of the low, medium and high RCP8.5 scenario; T – temperature, P – precipitation.

	1981–2010			2031–2060								
				RCP8.5 low			RCP8.5 medium			RCP8.5 high		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
T [°C]	5	11.7	8.9	5.7	13	9.9	6.6	13.8	10.6	7.1	14.3	11.1
P [mm]	456	2452	816	424	2692	802	407	2519	794	393	2499	778

Table 3: Characteristics of simulated forest stands for 1981 and for 2010 as average over all considered 4183 sites; N – number of trees, DBH – diameter at breast height, HO – height of 100 highest trees, BA – basal area, LAI - leaf area index.

Tree species	N [ha^{-1}]	DBH [cm]	HO [m]	LAI [m^2 m^{-2}]	BA [m^2]	Volume [m^3 ha^{-1}]
1981						
Spruce	1294	21.5	24.5	9.8	46.9	494.8
Pine	1125	19.2	19.8	4.2	32.6	337.9
Douglas fir	446	30.5	26.2	7.3	32.6	238.8
Beech	1128	15.6	20.3	5.3	21.6	189.9
Oak	978	17.0	19.8	2.8	22.1	196.7
2010						
Spruce	475	32.2	29.9	5.8	39.2	646.9
Pine	407	36.1	28.2	4.2	41.5	656.2
Douglas fir	200	44.9	33.9	5.1	33.3	404.8
Beech	464	25.7	28.2	6.3	24.0	363.4
Oak	430	28.7	25.6	3.4	28.5	390.1

polygons. We derived monospecies, 55 year old forest stands of medium site index of Scots pine, Norway spruce, Douglas fir, European beech or oak from yield tables (LEMBCKE et al., 2000; SCHOBER, 1987; WENK et al., 1984) (see Table 3, 1981). We assumed that these stands represent medium aged forest stands in their most productive state (RYAN et al., 1997), where main silvicultural measurements are realised (RÖTZER et al., 2010). The management of these stands was derived from the yield tables based on stem number development. The final state of the stands averaged over all sites under the recent climate is given in Table 3 (2010), as well. This approach allowed us to simulate typical forest stands but it also means that we simulated forests at sites where stands of the assumed species may not be present today, or where no forests is growing at all. Thus, we rather provide an overall picture of the productivity of the species in relationship to water budget and risks of fire or pest outbreaks under varying climate conditions rather than predictions for concrete, existing forests.

We simulated all stands for 30 years with the observed climate, 1981–2010, and with all realisations of the three RCP8.5 climate scenario data for the period 2031–2060 always using the same stand initialisation as a starting point. Thus, we did not consider transient dynamics of the forest stands but only the dynamics of the 30-year period under the scenarios in comparison with the recent 30-year period. We began by assuming a constant CO_2 concentration of 380 ppm for all simulation runs in the past and future. We then ran the simulations using historical data of CO_2 concentration and the CO_2 concentrations of RCP8.5 given by the Extended Concentration Pathways (MEINSHAUSEN et al., 2011) (increasing CO_2). This approach allowed us to focus first on pure climate change effects on the considered key variables and second on the additional effects of changing CO_2 concentration.

We focused our analyses on the productivity of the forest stands as indicated by the average net primary production (NPP) and the average stem increment (SI). Linear regressions of mean absolute NPP changes and mean absolute SI changes (averaged over all 300 realisations and comparing base period 1981–2010 and scenario period 2031–2060) while accounting for site elevation were carried out for each species using the least squared method and a F-test to analyse the significance of the linear trends with the statistical package R (R DEVELOPMENT CORE TEAM, 2008). The effects on water budget were examined using the average annual percolation rate. Risks to forest stands by fire were calculated with the fire danger index (FDI) and the risk by pest species with the nun moth risk index (NMRI). We calculated statistical parameters of the focus variables over all simulation runs within the model and with the statistical package R.

2.4 Integration of impacts

We developed an approach for the investigation of the potential risks and opportunities for different so-called

natural regions in Germany (see Fig. 1 in ESM). We integrated the impacts of the climate change scenario on the annual NPP, the annual stem increment, the annual percolation rate, the fire danger and the nun moth risk using a simple approach of rescaling the following variables

- I_1 - absolute NPP change per species in 2031–2060 (S) compared with 1981–2010 (B)
- I_2 - absolute stem increment (SI) change per species in S compared with B
- I_3 - percolation rate per species in S
- I_4 - Fire danger index (FDI) in S
- I_5 - Nun moth risk index (NMRI) in S.

To combine all indicators in an overall risk indicator all indicators were rescaled to a range from 0 to 1. At first we defined:

P_{ijk} – averaged (over all stands of the region) values for each indicator I_k per region j and species i

M_{ik} – maximum of all values P_{ijk} for each species i and indicators I_k ($k = 1, \ldots, 3$) over all regions j

m_{ik} – minimum of all values P_{ijk} for each species i and indicators I_k ($k = 1, \ldots, 3$) over all regions j

i – number of species ($i = 1, \ldots, 5$)

j – number of natural regions ($j = 1, \ldots, 7$)

k – number of Indicators ($k = 1, \ldots, 5$)

In the case of NPP change, SI change and percolation rate (indicators $I_1 - I_3$) we rescaled for each species and each region the values averaged over region and period to a scale from 0 (minimum value) to 1 (maximum value). We determined linear functions for each species i and each indicator I_k ($k = 1, \ldots, 3$):

$$f_{ik}(P_{ijk}) = a_{ik} + b_{ik}P_{ijk}.$$

calculating the parameters a_{ik} and b_{ik} (Table 4) as follows:

$$b_{ik} = \frac{1}{(M_{ik} - m_{ik})}$$
$$a_{ik} = 1 - b_{ik}M_{ik}$$

For each region j ($j = 1, \ldots, 7$) we calculated averages R_{jk} for each of the three indicators I_k ($k = 1, \ldots, 3$) over all five species:

$$R_{jk} = \frac{1}{5} \sum_{i=1}^{5} f_{ik}(P_{ijk})$$

In the case of the variables FDI and NMRI (indicators I_4, I_5) we determined linear functions

$$f_k(P_{ijk}) = a_k + b_k P_{ijk}$$

whereas the averaged values P_{ijk} for the indicators I_4 and I_5 per region j over all stands of the region are independent of the species or only relevant for pine stands respectively. The parameters a_k and b_k of the

Table 4: Parameters of the rescaling functions.

Indicator	Species	a_{ik}	b_{ik}
I_1 NPP change	Spruce	−0.9545	2.2727
	Pine	−0.9420	1.4493
	Douglas fir	−0.7121	1.5152
	Beech	−0.2468	1.2987
	Oak	−1.0727	1.8182
I_2 stem increment change	Spruce	−0.9528	0.9434
	Pine	−0.8287	0.5525
	Douglas fir	−0.5680	0.8000
	Beech	−0.0072	0.7246
	Oak	−0.7568	0.9009
I_3 Percolation rate	Spruce	−0.1045	0.0008
	Pine	−0.0989	0.0008
	Douglas fir	−0.1250	0.0008
	Beech	−0.0931	0.0008
	Oak	−0.1305	0.0008

function f_k for a region (I_4 (FDI): $a_k = -1.7241$, $b_k = 1.1494$; I_5 (NMRI): $a_k = -2.0$, $b_k = 2.0408$) were calculated with the assumption that both for maximum FDI and also for maximum NMRI the function value is one (high risk)

$$R_{jk} = f_k(P_{ijk}) \quad j = 1, \ldots, 7.$$

Now, values $R_{jk} = 1$ ($j = 1, \ldots, 7$) indicate the maximum simulated positive NPP change ($k = 1$), maximum simulated positive stem increment change ($k = 2$), maximum percolation rate ($k = 3$), minimum FDI ($k = 4$), and minimum NMRI ($k = 5$) over all regions.

Subsequently, we calculated per region for each recalculated indicator or index R_{jk} the danger index

$$R_{jk}^* = 1 - R_{jk}$$

according to the assumption that the danger index $R_{jk}^* = 0$ indicates no or very low risk (maximum increments or percolation rates or minimum FDI and NMRI) and $R_{jk}^* = 1$ indicates a very high risk. The aggregated impact index is calculated for each region j by averaging the five danger indices R_{jk}^*.

3 Results

3.1 Net primary production

Under constant CO_2 concentration the average annual net primary production of the five considered tree species for the base period (Fig. 1, upper row) indicates a regional variability caused by site specific soil and climate conditions. Independent of tree species, sites at higher altitudes show higher productivity than low elevation sites with an exception of the temperature-limited sites (Alps). The absolute change of annual NPP in the scenario period compared with the base period
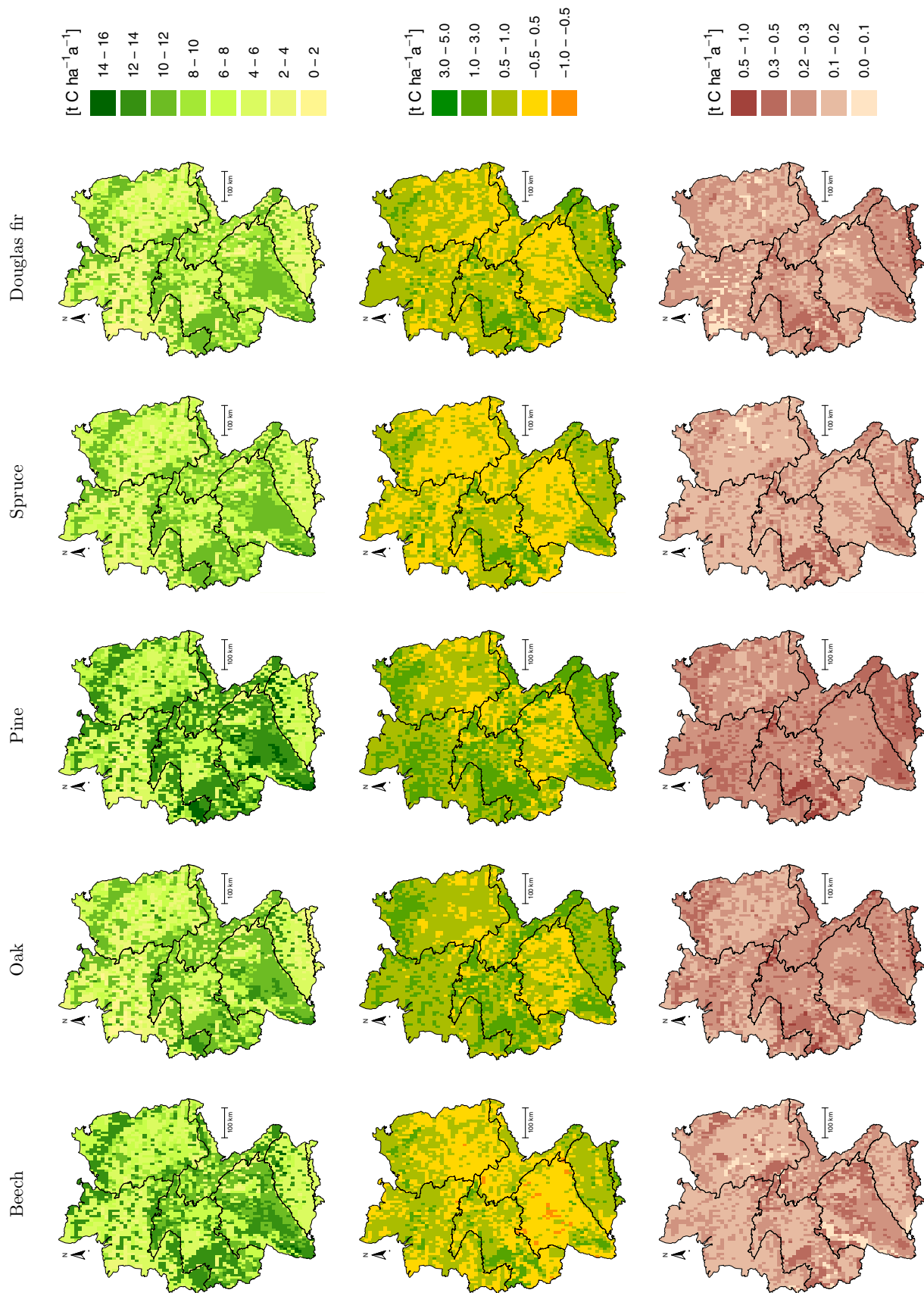
Figure 1: Mean annual NPP of the stands for 1981–2010 (upper row), change of mean annual NPP for 2031–2060 in comparison to 1981–2010 (middle row), standard deviation of mean annual NPP change (lower row) for the 30 year period over 300 realisations (constant CO_2)

Table 5: Mean, maximum and minimum of averaged relative changes of NPP in 2031–2060 compared with 1981–2010.

NPP change [%]					
constant CO_2	Spruce	Pine	Douglas fir	Oak	Beech
mean	8.8	12.5	12.7	13.9	6.9
minimum	−4.7	−4.6	−4.2	−7.1	−10.6
maximum	34.5	104.9	69.6	84.2	34.2
increasing CO_2					
mean	25.4	27.9	34.9	30.8	21.0
minimum	11.9	10.2	13.5	10.1	4.0
maximum	52.8	165.2	102.1	133.9	47.4

Table 6: Mean, maximum and minimum of averaged relative changes of annual stem increment in 2031–2060 compared with 1981–2010.

Stem increment change [%]					
constant CO_2	Spruce	Pine	Douglas fir	Oak	Beech
mean	8.2	13.4	13.3	14.4	7.1
minimum	−24.5	−6.6	−9.2	−10.9	−19.0
maximum	150.7	116.6	76.1	94.9	41.2
increasing CO_2					
mean	27.6	30.6	32.8	32.8	24.2
minimum	−9.1	9.5	6.5	13.1	−2.0
maximum	339.7	186.5	158.0	158.0	58.2

Table 7: Mean, maximum and minimum of relative change of averaged annual percolation for 2031–2060 compared with 1981–2010.
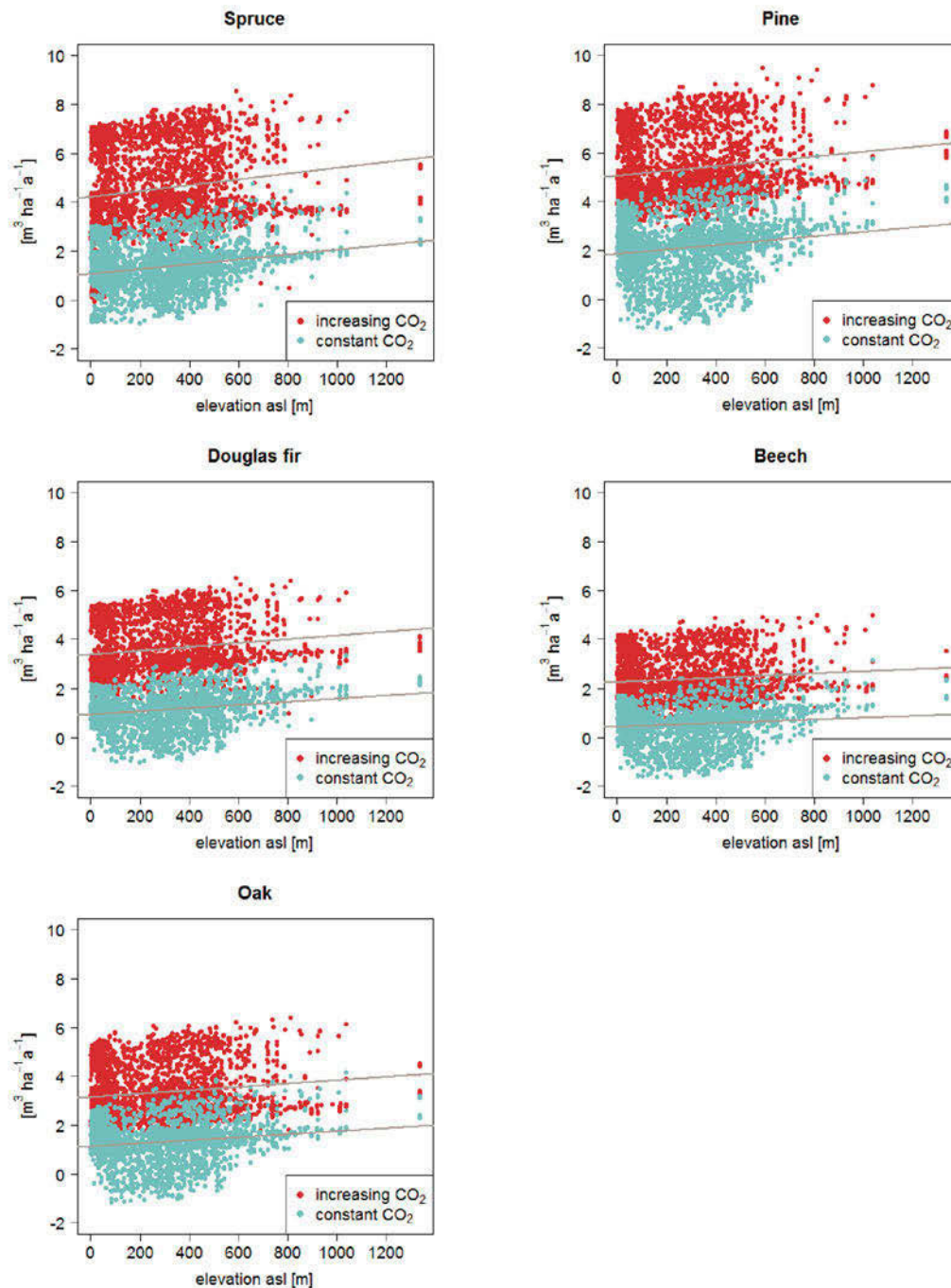
Percolation rate change [%]					
constant CO_2	Spruce	Pine	Douglas fir	Oak	Beech
mean	−19.4	−20.1	−17.7	−17.6	−19.2
minimum	−86.6	−83.5	−83.6	−77.5	−82.5
maximum	12.4	13.3	10.3	14.0	11.2
increasing CO_2					
mean	−12.6	−12.3	−12.8	−11.9	−12.0
minimum	−77.8	−74.1	−74.4	−68.5	−74.1
maximum	51.1	72.9	30.4	26.3	30.4

(Fig. 1, middle row) is highest for pine and oak stands with NPP changes up to 3–5 t C ha^{-1} a^{-1} and lowest for beech stands, where at most sites the NPP change varies around zero and for some sites it is negative. The percentage change in annual NPP on average for all sites is highest for oak and Douglas fir and lowest for beech. For all tree species, there are sites where, under some of the 300 realisations, the relative NPP change is negative (Table 5 minimum value) while on the other hand there are site and realisation combinations which lead to a very high increase in annual NPP, especially for pine and oak.

The standard deviation per stand of NPP changes for all of the 300 realisations of the RCP8.5 scenario seems to be higher for pine than for the other species and lowest for spruce (Fig. 1, lower row). Regionally, the lowest standard deviation is found for the regions of lower altitude in the Northeast and Northwest German Plain, while the highest values are for the regions at higher altitude (Alps, Harz Mountain, low mountain ranges).

Simulations with increasing CO_2 concentration resulted in clearly higher absolute and relative changes in annual NPP (see Table 5 and ESM, Fig. 2). All changes are positive. The distinctions between species are similar to the simulation results with constant CO_2. The range of annual NPP shifted to higher values for all species and all site/scenario combinations. The variability of the standard deviation is clearly lower than under constant CO_2 and is highest in the Alps and lowest mainly on Northeast German Plain (ESM, Fig. 2, lower row).

3.2 Stem increment

The simulated average annual stem increment for the considered species with constant CO_2 assumption vary regionally and between the species similar to the annual NPP (see ESM, Fig. 4) in the base period 1981–2010. The relative changes of stem increment in 2031–2060 compared with 1981–2010 are lowest for beech stands and highest for oak and pine stands (Table 6), with potential annual stem increment decreases for all species at some sites. The standard deviation of stem increment change is also lowest for the Douglas fir stands and highest for spruce and pine. The regional variability of standard deviation of stem increment change differs

clearly between the species. Considering annual stem increment change versus elevation of the sites indicate a significant trend for this relation (Fig. 2), which is also the case for the relation between mean annual NPP change and elevation.

3.3 Percolation rate

Analysing the results under the constant CO_2 assumption, we assert that the average annual percolation rates for the base period have a very high regional variability, which is driven by the annual precipitation sum (Fig. 3, upper row). As GERSTENGARBE et al. (2015) described, Germany is currently divided into an area with precipitation below 700 mm (eastern Germany and the lee side of the low mountain range in the middle of western Germany) and a precipitation rich remaining area. The resulting variability in percolation is obviously higher than the variability caused by tree species. With some exceptions, most notably oak in northwestern Germany, all species show a reduction of annual percolation in the time period 2031–2060 (Fig. 3, middle row), with regions with high percolation have higher change rates and higher standard deviations. The average change in percolation rate varies between −17.6 and −20.1 % (varying from −58 to −63 mm on average per species) depending on tree species, with maximum decrease of 86.6 % (Table 7).

Assuming increasing CO_2 the simulated annual percolation rates for 1981–2010 are very similar to the annual percolation rates with constant CO_2 (see ESM,

Figure 2: Absolute averaged changes of annual stem increment [m³ ha⁻¹ a⁻¹] in 2031–2060 (and averaged over all 300 realisations per site) compared to 1981–2010 with significant trends (p≤0.001) for all species

Fig. 6). The changes in annual percolation rate for 2031–2060 are clearly lower than under constant CO_2 for all species and vary from -11.9% to -12.8% (-39 to -47 mm) on average (Table 7).

3.4   Forest fire danger

The applied forest fire danger index FDI indicates two main regions of highest fire risks for the period 1981–2010, one in eastern Germany and another in southwestern Germany (Fig. 4, left). Under the RCP8.5 realisations for 2031–2060 the forest fire risk clearly increases

in these regions by about half grade on the scale between 1 and 5. The regions with a FDI above 2 become larger (Fig. 4, middle). Only in the Alps, the Alpine Foreland, and in a small region in northwestern Germany the FDI does not change. The standard deviation over the 300 realisations shows the highest values in the region with highest value of FDI. On average the fire risk clearly increases from 1981–2010 to 2031–2060 (Table 8). Analysis of the number of days with highest fire danger classes 4 (high risk) and 5 (very high risk) confirms the results in Fig. 4, with highest number of days in both classes
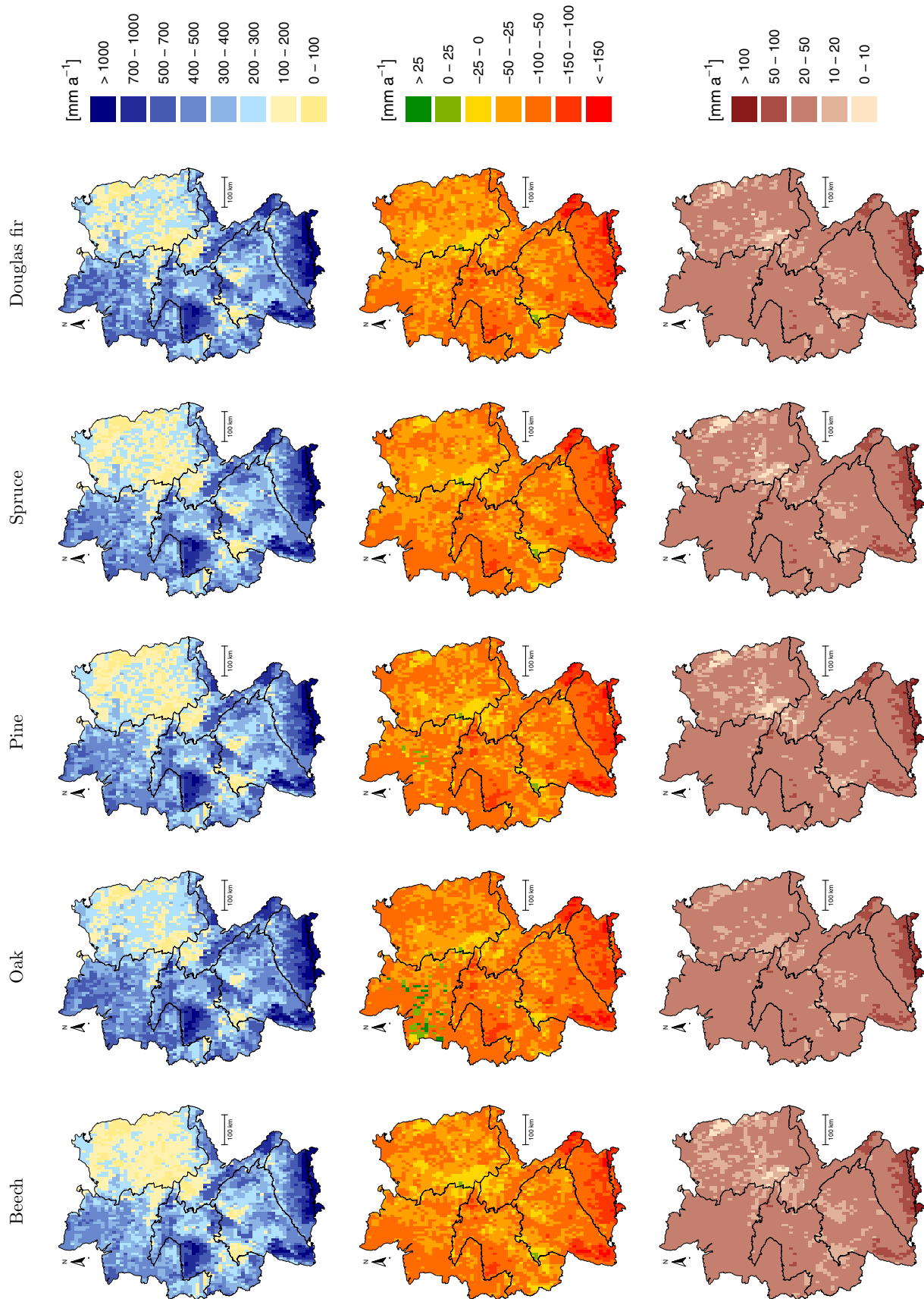
Figure 3: Mean annual percolation of the stand for 1981–2010 (upper row), change of mean annual percolation for 2031–2060 in comparison to 1981–2010 (middle row), and standard deviation of mean annual percolation change (lower row) for the 30 year period over 300 realisations (constant CO_2)
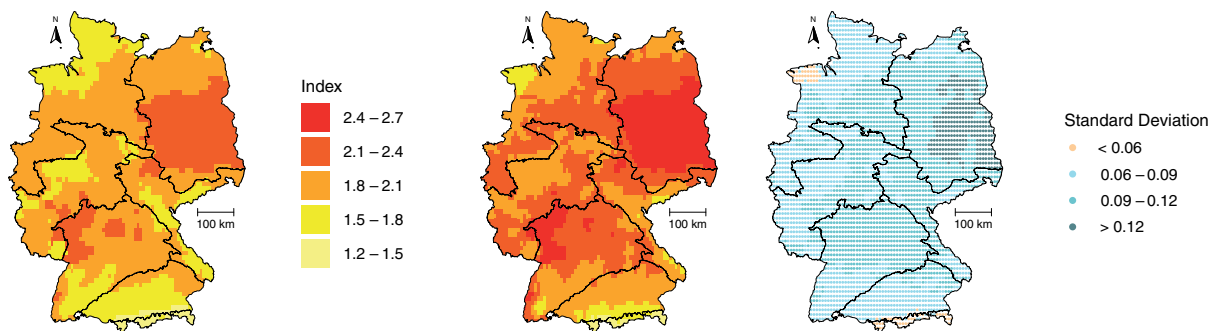
Figure 4: Mean annual fire danger index for the period 1981–2010 (left) and 2031–2060 (centre) and standard deviation for 2031–2060 over the climate scenario realisations (right)
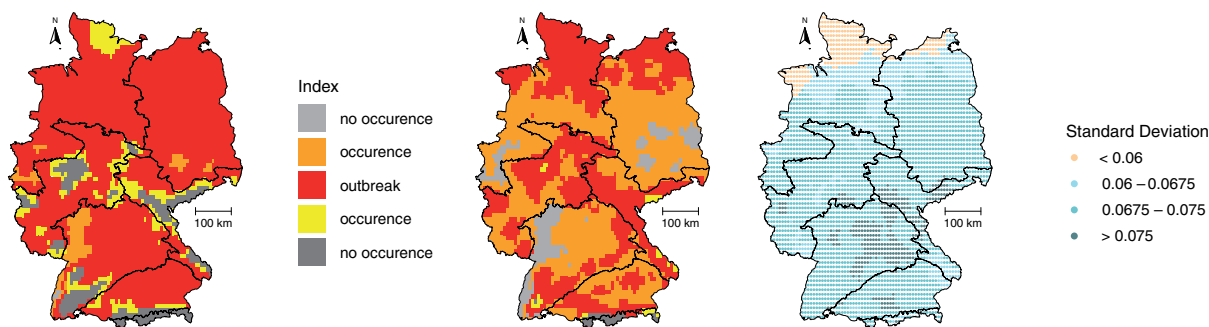
Figure 5: Mean annual nun moth risk index for the period 1981–2010 (left) and 2031–2060 (centre) and standard deviation over the climate scenario realisations (right); dark grey colour indicate the lower range of absence, the light grey indicate the upper range of absence due to high temperatures

Table 8: Statistics of average fire danger index for 1981–2010 and 2031–2060 (RCP8.5).

	1981–2010	2031–2060
minimum	1.33	1.37
mean	1.92	2.14
maximum	2.38	2.84

found in the Northeast German Plain and Southwest Uplands under recent climate (Table 9). For these regions the number of days with fire risk class 4 increases by 8 and 7 days, respectively, using RCP8.5. On average for all of Germany the number of days with class 4 increases by 4 days but with class 5 only by 1 day. The maximum values for both classes are especially high in the Northeast German Plain.

3.5   Nun moth risk

The risk of nun moth mass outbreak according to the nun moth risk index NMRI is currently very high as indicated by the results for 1981–2010 (Fig. 5, left). Only regions with higher altitude (Alps and low mountain ranges with an exception in the Southwest) are not endangered by the occurrence or mass outbreak of nun moth. This picture clearly changes under the realisations of RCP8.5 for 2031–2060. In large parts of Germany the NMRI exceeds the upper threshold (1.4) of

the index, which possibly indicates, that nun moth outbreaks will not happen (Fig. 5, middle). Areas without risk of outbreaks in 1981–2010 will become endangered by this event and in some small regions the index will exceed 1.6 (Northeast Germany, south of West German Uplands, light grey colour), which indicates that mainly the temperature conditions are not favourable for nun moth occurrence. The standard deviation of mean NMRI over the 300 realisations is very low in the northern part of Germany and a little bit higher in some regions of higher altitude and in eastern Germany (Fig. 5, right). On average the nun moth index increases by more than 17 % (Table 10), but the minimum value for both periods is below 1, due to the existence of regions without any nun moth risk.

3.6   Integration

A low value of the aggregated impact index indicates very low risks and high opportunities as shown for the Alps natural region followed by the Alpine Foreland (Fig. 6, Table 1, ESM). Otherwise, an impact index near one describes lower opportunities regarding productivity and percolation (as an indicator for the regional water balance) and higher risks, as can be stated for the warmest and driest regions under the RCP8.5 scenario: Southwest Uplands/ Scarplands and the Northeast Plain. These regions are hot spots of climate impacts on forestry with higher potential risks and lower potential opportunities than the other natural regions.

Table 9: Statistic of the number of days with highest fire danger classes 4 and 5 for the natural regions and Germany.

| | 1981–2010 | | 2031–2060 | | | | | | |
| | class 4 | class 5 | | class 4 | | | class 5 | | |
Region	mean	mean	minimum	mean	maximum	minimum	mean	maximum
Alps	4	1	1	4	11	0	1	5
Alpine Foreland	9	5	6	13	25	0	5	16
Northeast German Plain	17	13	13	25	42	4	17	43
Northwest German Plain	13	8	7	17	31	1	8	24
East Central Uplands	13	7	8	18	33	1	8	24
Southwest Uplands	14	9	10	21	35	3	11	29
West Central Uplands	13	8	9	18	32	2	9	25
Germany	14	9	9	19	33	2	10	28

Table 10: Statistics of the nun moth risk index for 1981–2010 and 2031–2060 (RCP8.5).

	1981–2010	2031–2060	change [%]
minimum	0.57	0.72	26.32
mean	1.2	1.41	17.50
maximum	1.63	1.94	19.02

4 Discussion

4.1 Productivity: NPP and stem increment

The simulated mean annual NPP for the period 1981–2010 shows a similar picture for all species (Fig. 1, upper row, and in ESM Fig. 2, upper row). The NPP is higher in the southwestern regions of higher altitude (without Alps) and substantially lower in the northeastern and northwestern regions and in the southern regions of lower altitude. This regional variability corresponds with results of TUM et al. (2011), simulated with the model BETHY/DLR. However, the simulated maximum values of NPP for the specific tree species differ clearly. A comparison with data from the German National Forest Inventory (BWI[2]) as given by PRETZSCH (2010) or simulated values by TUM et al. (2011) and RÖTZER et al. (2010) is not appropriate because of our special simulation approach assuming forest stands of a specific age at all cells of our base grid (see chapter 4.3, Simulation concept and analyses). The mean annual NPP (Fig. 1 and ESM, Fig. 2, 3) and also annual stem increment (ESM, Figs 4, 5) indicate differences between the species. For spruce and Douglas fir the annual NPP is very similar as well as in the case of stem increment for oak and beech. Highest annual NPP and stem increments were simulated for pine. These results may be biased. While the relations between stem increment change and elevation (Fig. 2) as well as between NPP change (ESM, Fig. 3) and elevation are significant for all species, both relations indicate a broad variety over site condition on low elevation, especially for pine. The high changes of stem increment for pine may be caused by a more or less unrealistic assumption of pine forests being on very
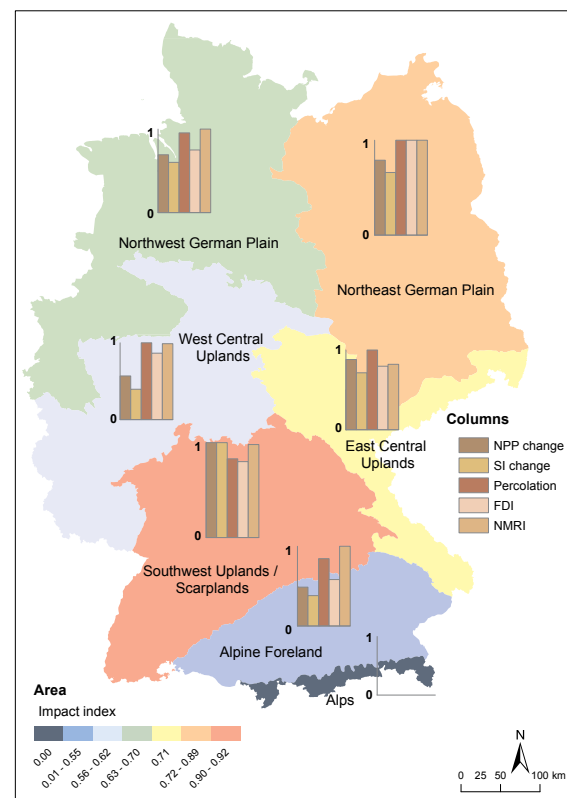
Figure 6: Regional specific aggregated impact indexes for 2031–2060 (coloured areas of natural regions). Each chart per region gives the values of the 5 impact variables NPP change, stem increment change, percolation, FDI, and NMRI.

productive sites, which are not water and nutrient limited. Furthermore, we used a pine stand derived from the yield table of LEMBCKE et al. (2000), which is representative for a pine stand in eastern Germany.

The simulation results with all realisations of RCP8.5 under constant CO_2 concentration show that annual NPP change in 2031–2060 compared with 1981–2010 is mainly positive or insignificant ($\pm 0.5\,t\,C\,ha^{-1}\,a^{-1}$) for the needle tree species, which is similar to results for

stem increment (Fig. 1, middle row). Beech stands lose at some sites because of warmer and dryer climate, especially during summer months; only a few sites show a clear increase in NPP (with higher precipitation also for 2031–2060) and stem increment. These results are comparable with REYER et al. (2013) and MORALES et al. (2007). The impact of future climate on annual NPP change strongly differ between sites (Fig. 1, middle row) characterised by different changes in temperature and precipitation. Higher increases can be stated for all species in the Northwest and lower increases in the Northeast and at lower altitudes in southern Germany. Model analyses by HLASNY et al. (2011) projected an increase in growth for beech, oak and spruce excepting beech forest at lower altitude, with a shift of beech production optimum to higher elevations. This corresponds with our beech productivity projections without CO_2 fertilisation for lower and higher altitudes (Fig. 2, ESM: Fig. 3). In contrast, LEVESQUE et al. (2013) showed from tree ring analyses that spruce is highly vulnerable to water deficits at dry sites, which is in accordance with a few spruce stands of low altitude (Fig. 2) simulated with constant CO_2 concentration.

If we assume increasing CO_2 concentration for 2031–2060, the results for annual NPP change show mainly increases for all species in all regions (see ESM, Fig. 2, middle row), which is caused only by the CO_2 fertilisation effect. This effect is caused mainly by the formulation of the CO_2-effect in 4C and also other similar process-based models. These models disregard acclimation of physiological processes to elevated CO_2 as well as nutrient limitations that may limit future CO_2 fertilisation (KÖRNER, 2006; REYER et al., 2013; TEMPLER, 2013).

The stem increment change is also higher than with constant CO_2 concentration. The lowest increases and changes $(1–3\,m^3\,ha^{-1}\,a^{-1})$ were simulated for beech and clearly higher increases for the needle tree species stands. Generally, increases in annual NPP were caused by longer vegetation periods due to earlier bud burst (BADECK et al., 2004) and higher temperatures at non water-limited sites in the case of constant CO_2 and the fertilisation effect of the increasing CO_2, which confirms results of MORALES et al. (2007) and REYER et al. (2013).

Positive NPP and stem increment changes for most species and sites independent of CO_2 scenario are on the one hand an indication for increasing harvest yield if changing age structure is not considered. On the other hand they may be a hint for increasing carbon stocks in the German forests as stated by KÖHL et al. (2010).

4.2 Percolation rate

The analysis of the RCP8.5 scenario by GERSTENGARBE et al. (2015) describes, besides increasing annual temperatures, a trend to lower annual precipitation especially in the summer months. Both trends lead to decreasing climatic water balance. These climatic conditions are the main cause of percolation losses in all

regions and on average over all of Germany independent of the species type. Considerable regional variations exist depending mainly on precipitation and temperature variations and variations between the species. The latter variations depend on the simulated stand type, since the foliage biomass of the stands and their leaf area index influence the elements of forest water balance such as interception, evapotranspiration, and the resulting percolation. However, regional variations have a much stronger impact on the water balance than the species type (Fig. 3). Regions with high precipitation like the Alps and the Black Forest in southwestern Germany have higher percolation rates for all species and the change rate is also high. In contrast to this, for regions with low precipitation, especially in eastern Germany, the maps in Fig. 3 show only low percolation for 1981–2010, as stated also by a simulation study for a region in northeastern Germany by NATKHIN et al. (2012), and low change rates for 2031–2060, with corresponding standard deviations. The lower absolute change rates as simulated for northeastern Germany disguises the fact that the very low percolation rates for 1981–2010 in this region were greatly reduced. The relative change rates of percolation decrease in this region up to about $-80\,\%$, as given in Table 7. CONRADT et al. (2012) also simulated strong changes of groundwater recharge in the Elbe river catchment, which partially covers the Northeast German Plain, under climate scenarios generated by STARS.

The decrease in annual percolation rate for the RCP8.5 scenario corresponds very well to the decrease of precipitation sum during the summer months (June, July, August) of about $18\,\%$ on average in Germany (GERSTENGARBE et al., 2015).

The effect of climate change on annual percolation rates with increasing CO_2 under the RCP8.5 realisations correspond with the statement of MORALES et al. (2007) on the enhancement of the efficiency of photosynthesis and water use by increasing CO_2 concentration. The decrease of percolation rates is clearly less on average for Germany compared with the simulations with constant CO_2 and also the maximum decreases in percolation are about $10\,\%$ lower.

4.3 Risks

Our simulations show that the FDI is very high currently in areas with high temperatures and low precipitation (Northeast German Plain, South of West German Uplands), which is also indicated by a negative annual climatic water balance (see GERSTENGARBE et al., 2015). This corresponds with the valuation that the eastern Federal states of Germany are among the most dangerous forest fire regions in Europe (HIRSCHBERGER, 2012). Considering the simulated fire danger risk with all realisations of RCP8.5 it appears that nearly all realisations show a decrease of climatic water balance during the meteorological summer time (June, July, August), which is relevant to fire danger (GERSTENGARBE et al., 2015). This results in a clear increase of fire risk in

northeastern Germany and other regions. Nevertheless, an increasing fire risk does not mean increasing number of fires or area of fires due to modern observation methods like satellite-based early-warning systems applied e.g. in the Federal state of Brandenburg. However, it underlines the requirement of better observation and prevention techniques.

Currently, the risk of nun moth occurrence and outbreak is very high in Germany, especially in the northeast (MÖLLER et al., 2007). The nun moth is a serious pest species in Central Europe, which defoliates mainly pine and spruce and prefers regions with less precipitation. Our results confirm that in the future climate-driven nun moth risk will increase. This is in line with reported studies. An increase in bark beetle damage has been observed in the period 1950–2000 in Europe (SCHELHAAS et al., 2003) and for future drier and warmer conditions a general higher risk of insect and pathogen damage is expected (LINDNER et al., 2008; SEPPÄLÄ et al., 2009). This is particularly relevant for spruce forests. Pine plantations are also high risk areas for catastrophic insect disturbances (APEL et al., 2004). Outbreaks of the Pine-tree lappet (*Dendrolimus pini* L.) are favoured by low precipitation (about 500–600 mm of mean annual precipitation) and warm temperatures on dry sites. Also a higher population density of the beetle *Phaenops cyanea* F. has been associated with warmer and drier summers (LOBINGER and MUCK, 2007). Broad-leaved trees may also be increasingly attacked by insects, as has been reported for oak processionary moth (*Thaumetopoea processionea*) (BRÄSICKE and WULF, 2011).

Disturbances are not only a result of climatic drivers but also influenced by other factors such as management history or topography. For the period 1958–2011, SEIDL et al. (2011) found that climatic and non-climatic drivers have an equal share in determining a higher amount of disturbances in Europe's forests. It is also important to consider that we looked at two specific types of disturbances as examples of climate driven disturbances and interpreted them in isolation. In reality however, disturbances are linked, e.g. storm damage provides breeding material for bark beetle outbreaks and drought-stressed trees are more susceptible to insect damage (WERMELINGER, 2004). Furthermore, the interactions between different disturbance agents and different environmental changes further complicate the comprehensive assessments of risks. There is little knowledge about complex interactions but assessments of single disturbance agents already show that the importance of catastrophic disturbances may increase in the future. Storm damage for example has increased, especially in the two recent decades, and currently amounts to 8 Million m^3 timber per year (MAJUNKE et al., 2008). It is however unclear whether this increase is related to climate change and different methods have led to different conclusions (FRÖHLICH, 2011). Future changes in wind speed are hard to project, but regional studies using GCM and RCM data point to an increase in gust speeds in northern Germany, while no clear signal has been found for southern Germany (FRANK et al., 2010). It is important to note that wind is only one element of storm damage and other factors such as the amount of days with frozen soil also influence the susceptibility to wind damage and are likely to be altered by climate change.

4.4 Integration

Our integration of opportunities and risks for forests in Germany points out the regions where forests experience stronger negative or positive impacts under the RCP8.5 scenarios. The dryer (water-limited) low elevated regions reaching from southwest to northeastern Germany benefit less from the assumed climate change than regions in the northwest and forest sites at higher altitudes, which are mainly temperature limited. This overall view confirms statements about the vulnerability of Germany's forests in the framework of a vulnerability study of Germany under climate change (ZEBISCH et al., 2005).

In our first attempt of integration we averaged all rescaled indicators with equal weight to an overall index. The idea behind this approach is to combine all climate change impacts, whether perceived as risk ("negative impacts") or as opportunity ("positive impacts") from an anthropocentric perspective. This delivers an overall view of the changes expected under climate change in a region and allows the comparison of regions regarding expected changes from current characteristics. In the future, the approach could be further developed; e.g. the indicators could be weighted depending on the aim of the study or combined in another way.

5 Conclusion

Our integration effort provides a ranking of the German natural regions regarding risks and opportunities of forests under climate change and assists in detecting vulnerable forest regions. Furthermore, our results, although not explicitly considering adaptation of forest management practices, can be used to discuss adaptation to climate change. The main adaptation options that are being emphasised by the German national adaptation strategy are forest conversion from monospecies (coniferous) stands to site-adapted mixed forests, changing tree species or provenances, insertion of non-native tree species such as Douglas fir, risk-spreading, proactive and reactive measurements to cope with calamities, monitoring and water retention measures (BMU, 2008).

List of abbreviations

B base time period 1981–2010
CMIP5 Coupled Model Intercomparison Project Phase 5 of IPCC
ESM electronic supplementary material
FDI fire danger index

GCM General Circulation Model
IPCC Intergovernmental Panel on Climate Change
NMRI nun moth risk index
NPP net primary production
RCP Representative Concentration Pathways
S scenario time period 2031–2060
SI stem increment
STARS regional statistical climate model

References

Apel, K.-H., M. Auswirth, M. Rös, M. Wenk, 2004: Schadgebiete der wichtigsten nadelfressenden Forstschadinsekten der Kiefer und Risikobewertung von Waldgebieten für das Nordostdeutsche Tiefland. – Beitr. für Forstwirtsch. und Landsch.ökol. **38**, 14–18.

Badeck, F.W., A. Bondeau, K. Bottcher, D. Doktor, W. Lucht, J. Schaber, S. Sitch, 2004: Responses of spring phenology to climate change. – New Phytol. **162**, 295–309.

BGR, 2004: Nutzungsdifferenzierte Bodenübersichtskarte der Bundesrepublik Deutschland 1:100.000.000 (Wald-BÜK 1000). – Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.

BMU, 2008: Deutsche Anpassungsstrategie an den Klimawandel. Die Bundesregierung, Retrieved 2013. – Aavailable at http://www.bmu.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/das_gesamt_bf.pdf

Bräsicke, N., A. Wulf, 2011: Die Waldschutzsituation 2010 in der Bundesrepublik Deutschland. – J. f. Kulturpfl. **63**, 61–68.

Bugmann, H., R. Grote, P. Lasch, M. Lindner, F. Suckow, 1997: A new forest gap model to study the effects of environmental change on forest structure and functioning. – In: Mohren, G.M. J., K. Kramer, S. Sabate (Eds.): Impacts of Global Change of Tree Physiology and Forest Ecosystem. Proceedings of the International Conference on Impacts of Global Change on Tree Physiology and Forest Ecosystems, held 26–29 November 1996, Wageningen. – Kluwer Academic Publisher, Dordrecht, 255–261.

Conradt, T., H. Koch, F.F. Hattermann, F. Wechsung, 2012: Spatially differentiated management-revised discharge scenarios for an integrated analysis of multi-realisation climate and land use scenarios for the Elbe River basin. – Reg. Envir. Chang. **12**, 633–648.

DVWK, 1996: Ermittlung der Verdunstung von Land- und Wasserflächen. DVWK – Merkblätter zur Wasserwirtschaft 238/1996. – Wirtschafts- und Verlagsgesellschaft Gas und Wasser mbH Bonn. Bonn, 134 pp.

Dyck, S., G. Peschke, 1995: Grundlagen der Hydrologie. – Verlag für Bauwesen GmbH. Berlin, 536 pp.

Fahse, L., M. Heurich, 2011: Simulation and analysis of outbreaks of bark beetle infestations and their management at the stand level. – Ecol. Model. **222**, 1833–1846.

Flemming, G., 1994: Wald Wetter Klima – Einführung in die Forstmeteorologie. – Deutscher Landwirschaftsverlag. Berlin, 136 pp.

Frank, C., K. Grebhan, C. Kottmeier, M. Kunz, R. Lux, H. Mayer, S. Mohr, M. Rauthe, B. Ruck, D. Schindler, J. Schönborn, 2010: Strategien zur Reduzierung des Sturmschadensrisiko für Wälder (Verbundprojekt RESTER) innerhalb des Forschungsprogramms Herausforderung Klimawandel Baden-Württemberg, Meteorologisches Institut der Albert-Ludwigs-Universität Freiburg; Institut für Meteorologie und Klimaforschung, Karlsruher Institut für Technologie; Laboratorium für Gebäude- und Umweltaerodynamik, Institut für Hydromechanik, Karlsruher Institut für Technologie, Freiburg, Karlsruhe, 141 pp.

Fröhlich, D., 2011: Stürmische Gesellen: Lothar, Kyrill & Co. Zur Problematik, die künftige Entwicklung von Winterstürmen abzuschätzen. – LWF aktuell, 38–40.

Fürstenau, C., F. Badeck, P. Lasch, M. Lexer, M. Lindner, P. Mohr, F. Suckow, 2007: Multiple-use forest management in consideration of climate change and the interests of stakeholder groups. – Eur. J. For. Res. **126**, 225–239.

Gerstengarbe, F.W., P. Hoffmann, H. Österle, P. Werner, 2015: Ensemble simulations for the RCP8.5-scenario. – Meteorol. Z. **24**, 147–156, DOI: 10.1127/metz/2014/0523.

Gutsch, M., P. Lasch, F. Suckow, C. Reyer, 2011: Management of mixed oak-pine forests under climate scenario uncertainty. – For. Syst. **20**, 453–463.

Haxeltine, A., I.C. Prentice, 1996: A general model for the light-use efficiency of primary production. – Funct. Ecol. **10**, 551–561.

Hirschberger, P., 2012: Wälder in Flammen. Ursachen und Folgen der weltweiten Waldbrände. WWF Studie, WWF, Berlin, 89 pp.

Hlasny, T., Z. Barcza, M. Fabrika, B. Balazs, G. Churkina, J. Pajtik, R. Sedmak, M. Turcani, 2011: Climate change impacts on growth and carbon balance of forests in Central Europe. – Climate Res. **47**, 219–236.

Käse, H., 1969: Ein Vorschlag für eine Methode zur Bestimmung und Vorhersage der Waldbrandgefährdung mit Hilfe komplexer Kennziffern. Abh. Met. Dienst DDR **Nr. 94, Band XII**, Berlin, 63 pp.

Kindermann, G., S. Schorghuber, T. Linkosalo, A. Sanchez, W. Rammer, R. Seidl, M. Lexer, 2013: Potential stocks and increments of woody biomass in the European Union under different management and climate scenarios. – Carbon Balance Manage. **8**, 20.

Köhl, M., R. Hildebrandt, K. Olschofsky, R. Köhler, T. Rötzer, T. Mette, H. Pretzsch, M. Köthke, M. Dieter, M. Abiy, F. Makeschin, B. Kenter, 2010: Combating the effects of climatic change on forests by mitigation strategies. – Carbon Balance Manage. **5**, 8.

Kölling, C., T. Knoke, P. Schall, C. Ammer, 2009: Überlegungen zum Risiko des Fichtenanbaus in Deutschland vor dem Hintergrund des Klimawandels. – Forstarch. **80**, 42–54.

Körner, C., 2006: Plant CO_2 responses: an issue of definition, time and resource supply. – New Phytol. **172**, 393–411.

Landsberg, J.J., R.H. Waring, 1997: A Generalised Model of Forest Productivity Using Simplified Concepts of Radiation-Use Efficiency, Carbon Balance and Partitioning. – For. Ecol. Manage. **95**, 209–228.

Lasch, P., M. Lindner, B. Ebert, M. Flechsig, F.-W. Gerstengarbe, F. Suckow, P.C. Werner, 1999: Regional impact analysis of climate change on natural and managed forests in the Federal state of Brandenburg, Germany. – Environ. Model. Assess. **4**, 273–286.

Lasch, P., F.W. Badeck, F. Suckow, M. Lindner, P. Mohr, 2005: Model-based analysis of management alternatives at stand and regional level in Brandenburg (Germany). – For. Ecol. Manage. **207**, 59–74.

Lembcke, G., E. Knapp, O. Dittmar, 2000: Ertragstafel für die Kiefer (Pinus sylvestris L.) im nordostdeutschen Tiefland. – Ministerium für Landwirtschaft, Umweltschutz und Raumordnung, 82 pp.

Levesque, M., M. Saurer, R. Siegwolf, B. Eilmann, P. Brang, H. Bugmann, A. Rigling, 2013: Drought response of five conifer species under contrasting water availability suggests high vulnerability of Norway spruce and European larch. – Glob. Change Biol. **19**, 3184–3199.

Lindner, M., W. Cramer, 2002: German Forest Sector under Global Change: An interdisciplinary impact assessment. – Forstw. Cbl. **121**, Supplement 1, 3–17.

LINDNER, M., J. GARCIA-GONZALO, M. KOLSTRÖM, T. GREEN, R. REGUERA, M. MAROSCHEK, R. SEIDL, M. LEXER, S. NETHERER, A. SCHOPF, A. KREMER, S. DELZON, A. BARBATI, M. MARCHETTI, P. CORONA, 2008: Impacts of Climate Change on European Forests and Options for Adaptation. Report to the European Commission Directorate-General for Agriculture and Rural Development, European Forest Institute (EFI), Joensuu, 173 pp.

LINDNER, M., M. MAROSCHEK, S. NETHERER, A. KREMER, A. BARBATI, J. GARCIA-GONZALO, R. SEIDL, S. DELZON, P. CORONA, M. KOLSTROM, M.J. LEXER, M. MARCHETTI, 2010: Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. – For. Ecol. Manage. **259**, 698–709.

LOBINGER, G., M. MUCK, 2007: Zunahme des Prachtkäferbefalls in Bayern. – LWF Aktuell **58**, 6–9.

MAJUNKE, C., S. MATZ, M. MÜLLER, 2008: Sturmschäden in Deutschlands Wäldern von 1920 bis 2007. – AFZ-DerWald, 380–381.

MEINSHAUSEN, M., S.J. SMITH, K. CALVIN, J.S. DANIEL, M.L.T. KAINUMA, J.F. LAMARQUE, K. MATSUMOTO, S.A. MONTZKA, S.C.B. RAPER, K. RIAHI, A. THOMSON, G.J.M. VELDERS, D.P.P. VAN VUUREN, 2011: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. – Climate Change **109**, 213–241.

MÖLLER, K., C. WALTER, A. ENGELMANN, K. HIELSCHER, 2007: Die Gefährdung der Gemeinen Kiefer durch Insekten. – In: KÄTZEL, R., K. MÖLLER, S. LÖFFLER, J. ENGEL, K. LIERO (Eds.): Die Kiefer im nordostdeutschen Tiefland - Ökologie und Bewirtschaftung. – MLUV des Landes Brandenburg, Eberswalde, 245–258.

MORALES, P., T. HICKLER, D.P. ROWELL, B. SMITH, M. T SYKES, 2007: Changes in European ecosystem productivity and carbon balance driven by regional climate model output. – Glob. Change Biol. **13**, 108–122.

MOSHAMMER, R., T. RÖTZER, H. PRETZSCH, 2009: Analyse der waldentwicklung unter veränderten Umweltbedingungen – Neue Informationen für die Forstplanung durch Kopplung von Modellen am Beispiel des Forstbetriebs Zittau. – Waldökologie, Landschaftsforschung und Naturschutz, 63–70.

MÜLLER, J., 2009: Forestry and water budget of the lowlands in northeast Germany - consequences for the choice of tree species and for forest management. – J. Water Land Dev. **13A**, 133–148.

NATKHIN, M., J. STEIDL, O. DIETRICH, R. DANNOWSKI, G. LISCHEID, 2012: Differentiating between climate effects and forest growth dynamics effects on decreasing groundwater recharge in a lowland region in Northeast Germany. – J. Hydrol. **448**, 245–254.

NEUKUM, C., R. AZZAM, 2012: Impact of climate change on groundwater recharge in a small catchment in the Black Forest, Germany. – Hydrogeol. J. **20**, 547–560.

OVERBECK, M., M. SCHMIDT, 2012: Modelling infestation risk of Norway spruce by Ips typographus (L.) in the Lower Saxon Harz Mountains (Germany). – For. Ecol. Manage. **266**, 115–125.

PRETZSCH, H., 2010: Forest Dynamics, Growth and Yield. – Springer Berlin, Germany, 664 pp.

R DEVELOPMENT CORE TEAM. (2008). R: A language and environment for statistical computing. – Vienna, Austria: R Foundation for Statistical Computing.

REYER, C., P. LASCH, G.M.J. MOHREN, F.J. STERCK, 2010: Interspecific competition in mixed forests of Douglas-fir (Pseudotsuga menziesii) and common beech (Fagus sylvatica) under climate change – a model-based analysis. – Ann. For. Sci. **67**.

REYER, C., P. LASCH-BORN, F. SUCKOW, M. GUTSCH, A. MURAWSKI, T. PILZ, 2013: Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide. – Ann. For. Sci. **71**, 211–225, DOI:10.1007/s13595-013-0306-8.

RÖHRIG, E., B. ULRICH (Eds.), 1991: Temperate deciduous forests. Ecosystems of the world **7**. – Elsevier, Amsterdam, 636 pp.

RÖTZER, T., J. DIELER, T. METTE, R. MOSHAMMER, H. PRETZSCH, 2010: Productivity and carbon dynamics in managed Central European forests depending on site conditions and thinning regimes. – Forestry **83**, 483–496.

RYAN, M.G., D. BINKLEY, J.H. FOWNES, 1997: Age-related decline in forest productivity: Pattern and process. – In: BEGON, M., A.H. FITTER (Eds.): Advances in Ecological Research, Vol 27. – Elsevier, 213–262.

SCHABER, J., 2002: Phenology in Germany in the 20th century: methods, analyses and models. – University of Potsdam, Dissertation, 148 pp.

SCHELHAAS, M.-J., G.-J. NABUURS, A. SCHUCK, 2003: Natural disturbances in the European forests in the 19th and 20th centuries. – Glob. Change Biol. **9**, 1620–1633.

SCHOBER, R., 1987: Ertragstafeln wichtiger Baumarten. – J.D. Sauerländer's Verlag. Frankfurt a.M., 166 pp.

SEIDL, R., M.-J. SCHELHAAS, M.J. LEXER, 2011: Unraveling the drivers of intensifying forest disturbance regimes in Europe. – Glob. Change Biol. **17**, 2842–2852.

SEPPÄLÄ, R., A. BUCK, P. KATILA, 2009: Adaptation of Forests and People to Climate Change – A Global Assessment Report. IUFRO World Series, IUFRO, Helsinki.

SPATHELF, P., E. MAATEN, M. MAATEN-THEUNISSEN, M. CAMPIOLI, D. DOBROWOLSKA, 2013: Climate change impacts in European forests: the expert views of local observers. – Ann. For. Sci. **7**, 131–137, DOI:10.1007/s13595-013-0280-1, 1-7.

SUCKOW, F., F.-W. BADECK, P. LASCH, J. SCHABER, 2001: Nutzung von Level-II-Beobachtungen für Test und Anwendungen des Sukzessionsmodells FORESEE. – Beitr. Forstwirtsch. u. Landsch.ökol. **35**, 84–87.

TEMPLER, P.H., 2013: Limits on carbon uptake by plants. – Nat. Clim. Chang. **3**, 184–185.

TUM, M., M. BUCHHORN, K.P. GUNTHER, B.C. HALLER, 2011: Validation of modelled forest biomass in Germany using BETHY/DLR. – Geosci. Model Dev. **4**, 1019–1034.

WENK, G., K. RÖMISCH, D. GEROLD, 1984: DDR-Fichtenertragstafel 1984, TU Dresden, Sektion Forstwissenschaft, Tharandt, 64 pp.

WERMELINGER, B., 2004: Ecology and management of the spruce bark beetle Ips typographus–a review of recent research. – For. Ecol. Manage. **202**, 67–82.

ZEBISCH, M., T. GROTHMANN, D. SCHRÖTER, C. HASSE, U. FRITSCH, W. CRAMER, 2005: Klimawandel in Deutschland – Vulnerabilität und Anpassungsstrategien klimasensitiver Systeme Climate Change. – UBA, Dessau, 203 pp.

ZWÖLFER, W., 1935: Die Temperaturabhängigkeit der Entwicklung der Nonne (Lymantria monacha L) und ihre bevölkerungswissenschaftliche Auswertung. – Zeit. f. Angew. Entomologie **XXI**, 333–384.

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