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Fire, late frost, nun moth and drought risks in Germany's forests under climate change

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Abstract

Ongoing climate change affects growth and increases biotic and abiotic threats to Germany's forests. We analysed how these risks develop through the mid-century under a variety of climate change scenarios using the process-based forest model 4C. This model allows the calculation of indicators for fire danger, late frost risk for beech and oak, drought stress and nun moth risk. 4C was driven by a set of 4 simulations of future climate generated with the statistical model STARS and with 10 simulations of future climate based on EURO-CORDEX model simulations for the RCP2.6, RCP4.5 and RCP8.5 pathways. A set of about 70000 forest stands (Norway spruce, Scots pine, beech, oak, birch), based on the national forest inventory describing 98.4 % of the forest in Germany, was used together with data from a digital soil map. The changes and the range of changes were analysed by comparing results of a recent time period (1971–2005) and a scenario time period (2011–2045). All indicators showed higher risks for the scenario time period compared to the recent time period, except the late frost risk indicators, if averaged over all climate scenarios. The late frost risk for beech and oaks decreased for the main forest sites. Under recent climate conditions, the highest risk with regard to all five indicators was found to be in the Southwest Uplands and the northern part of Germany. The highest climate-induced uncertainty regarding the indicators for 2011–2045 is projected for the East Central Uplands and Northeast German Plain.

Keywords: forest model 4C, climate scenarios, abiotic and biotic risk

1 Introduction

In 2014, the global surface temperature was 0.74 Kelvin higher relative to the 1951–1980 average (GISTEMP Team, 2015; Hansen et al., 2010). In Germany, the mean annual temperature has risen by about 1.4 K since 1881 (DWD, 2015). This ongoing climate warming poses substantial risks for future forest management to deliver ecosystem goods and services (Duncker et al., 2012, Seidl et al., 2016). Quantitative and qualitative information about risks under climate change are perceived as helpful by forest professionals to adapt forest management plans (Yousefpour and Hanewinkel, 2015) and to meet economic and ecological targets at the stand and at the regional scale (Frank et al., 2015)

Forest disturbances due to fire, insect outbreaks or strong winds have already damaged forests in Europe during the past decades (Seidl et al., 2014). For Europe the contribution of climate change and management effects on forest disturbances varies regionally depending on the disturbance agent Seidl et al. (2011)

These findings at the continental scale are also true at the national scale of Germany. The national forest condition monitoring (as measured by defoliation percentage) gives an aggregated measure for the vitality of the main tree species since 1984. Without allowing for attributing causality to specific disturbances, the data clearly shows that needle-leaf trees (spruce and especially pine) exhibit a positive vitality development, whereas the vitality of broad-leaf trees is declining (oak and especially beech) (BMEL, 2015). The positive vitality development is possibly caused by a recovery from past air pollution (Boxman et al., 1998; Zimmermann et al., 2003). During extremely dry summers such as 1992 and 2003 the fire frequency and fire area clearly increased (about 4900 and 1500 ha) compared with the long-term mean for 1991–2010 (824 ha) (BLE, 2015). Huge damages by a nun moth mass outbreak (*Lymantria monarcha* L.) were observed in Brandenburg (Federal state in Eastern Germany) on about 5500 ha in 2012 and 5880 ha in 2013 (LFE, 2015). The responses to seasonal weather conditions of several defoliator species have been studied at long time scales which help to identify species with higher (e.g. nun moth) and lower risk (e.g. pine beauty (*Panolis flammea*)) potentials (Gräber et al., 2012; Haynes et al., 2014). However, there are still large knowledge gaps due to the complex interactions of climate, different agents and their population ecology as well as regional differences (Haynes et al., 2014; Netherer and Schopf, 2010).

Besides fire and insect dynamics, extreme events such as late spring frost and especially drought and extreme temperatures also impact forest stands and are

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likely to show different dynamics under climate change (Lindner et al., 2014). In 2011, an extreme spring frost event on 3–5 May influenced the spring development of forests in Germany (Kreyling et al., 2012 and Menzel et al., 2015). They found strong leaf damage and a shift backward of the spring development by 7–9 weeks in this year. Kodra et al. (2011) and Rigby and Porporato (2008) concluded that risk of late frost events increases under climate warming scenarios in the 21th century. At the same time, an advanced spring phenology has been reported (Fu et al., 2014; Menzel et al., 2001; Menzel et al., 2006).

Drought and heat during the vegetation period not only lead to growth depression but also trigger mortality which has the potential to turn a forest stand from a carbon sink to a carbon source (Allen et al., 2015; McDowell et al., 2013; McDowell and Allen, 2015). For instance, three to four times higher mortality rates have been reported after the dry summers of 1991 and 2003 in Saxony-Anhalt, a Federal State in the east of Germany (MLU, 2015).

The heat wave of the year 2003 resulted in a reduction of net primary productivity and of ecosystem respiration. Monitoring data of several projects as well as ecosystem modelling experiments indicated that these reductions were not primarily caused by the high temperatures but rather by drought stress (Reichstein et al., 2007). A model-based analysis by Granier et al. (2007) for the year 2003 showed a wide spatial distribution of drought stress over Europe, with a maximum intensity within a large band extending from Portugal to north-east Germany. The growth of beech stands declined not only in 2003 but also in the following year, whereas coniferous stands (spruce and pine) appeared to be less drought-sensitive (Granier et al., 2007). Also Bauwe et al. (2013) stated that severe soil water stress can lead to substantial growth depression. However, they concluded that the pine forests in North-Eastern Germany are far from being seriously threatened by inter-annual climatic variations in the near future.

Albert et al. (2015) analysed drought stress using the water available to plants in the growing season as an indicator. They found that drought risk is a serious issue in parts of eastern Germany, whereas regions in the western part of northern Germany face less drought stress. They ranked the main forest species regarding drought tolerance from Norway spruce (low drought tolerance), to beech, to oaks, to Douglas fir, to pine (high drought tolerance).

Recently, we carried out a first analysis of the potential risk for forests in Germany under the RCP8.5 scenario generated only with the statistical model STARS (Lasch-Born et al., 2015). We found that Germany's forests are likely to experience higher potential risks from fire and nun moth under the warmer and dryer climate projected by STARS driven by RCP8.5. In this paper, we improve the analysis by integrating further risk indices and a much broader variety of climate scenarios. We intend to answer the following questions for the whole forest area of Germany: What are the possible risks of fire, drought, late spring frost and pest outbreaks for forests in Germany in an uncertain future climate? How should the future climate-induced uncertainty of these risks be described? Such an assessment of potential risks provides information for the development of risk reduction strategies in forest management (Albrecht et al., 2015). This information is important because forest management under climate change might have equally strong influence on forest productivity as (a)biotic disturbances (Zell and Hanewinkel, 2015).

2 Method and material

2.1 Model 4C and risk indicators

The analysis of climate change impacts on abiotic and biotic threats was carried out with the process-based forest dynamics model 4C (FORESEE – FORESt Ecosystems in a Changing Environment) for all forested areas in Germany. 4C has been developed to describe the forest behaviour on tree and stand level under changing environment (Bugmann et al., 1997; Lasch et al., 2005; Reyer et al., 2014). Using the daily meteorological parameters of temperature, precipitation, relative humidity, global radiation, wind speed and air pressure, the model simulates growth, mortality, and regeneration as well as carbon and water balances of tree cohorts (classes of trees with equal characteristics), which describe a forest stand. 4C includes a detailed soil model describing physical and chemical soil processes in defined layers on a daily time step. Transport of water in the multi-layered soil is calculated by a simple percolation model (Grote and Suckow, 1998) and controlled by a model-specific water conductivity parameter (Glugla, 1969; Koitzsch, 1977) depending on the soil texture. Root uptake of water is limited by the plant available water and the transpiration demand of all trees.The water demand of tree cohorts depends on the potential evapotranspiration, calculated according to Turc/Ivanov (Dyck and Peschke, 1995), the interception evaporation and the unstressed stomatal conductance. The amount of precipitation and the percolation rate determine the water supply for each tree. The drought stress index (DSI) describes the relation between water demand and water supply of a simulated forest during the vegetation period. It is calculated annually as one minus the average daily ratio of water supply and water demand of all tree cohorts of a forest stand (Reyer et al., 2010; Reyer et al., 2014) and varies from 0 (no drought stress) to 1 (maximum drought stress). This index depends on species type as well as on the stand dynamics and site conditions and will be considered here only for deciduous forests (DSI_{dec}).

The model contains calculations of risk indicators for drought stress (drought stress index DSI), fire danger (fire danger index FDI) and the risk of Nun moth (*Lymantria monacha* L.) outbreak (nun moth risk index NMRI) (Lasch-Born et al., 2015). Further, we define

Table 1: Overview of the historical climate data and climate scenarios applied in this study (for the GCM and RCM see Jacob et al. (2014).

GCM / RCM	Historical runs	RCP2.6	RCP4.5	RCP8.5
Observation data / STARS	x	2 x[1]	x	x
ICHEC-EC-EARTH / KNMI-RACMO22E	x		x	x
ICHEC-EC-EARTH / SMHI-RCA4	x	x	x	x
MOHC-HadGEM2-ES / SMHI-RCA4	x		x	x
MPI-M-ESM-LR / MPI-CSC-REMO2009	x	x	x	x

[1]two different temperature trends (mean and high) within the RCP

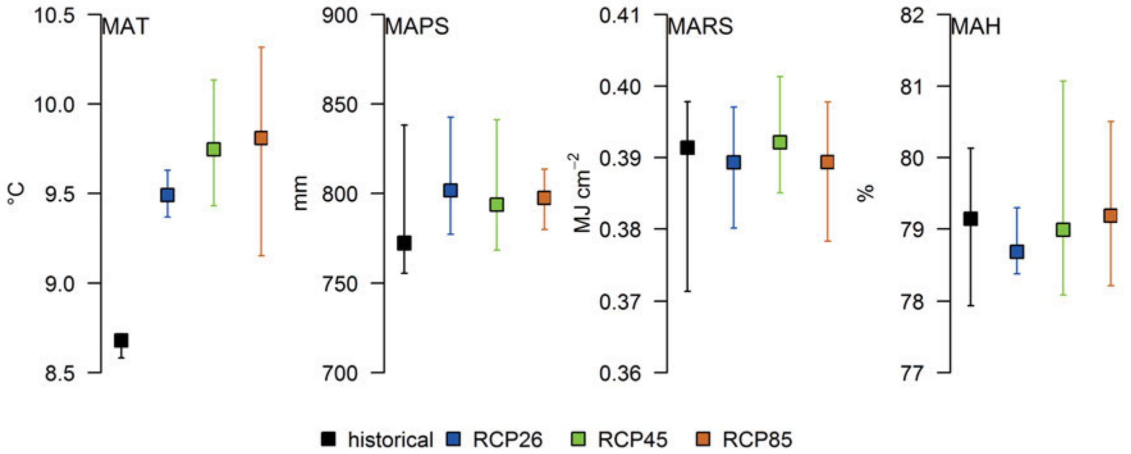

Figure 1: Mean annual temperature (MAT), mean annual precipitation sum (MAPS), mean annual global radiation sum (MARS), and mean annual relative humidity (MAH) averaged over the time period 1971–2005 (historical) and over the years 2011–2045 for each of the RCP scenarios and averaged over all sites and all models. The whiskers indicate the minimum and maximum values.

a risk index for late frost for deciduous tree species in the following way: First, the species-specific day of bud burst is modelled according to Schaber and Badeck (2003). Next, the number of years is counted in which a late frost event (minimum temperature below zero) occurs one day or more after the day of bud burst. This number of years is divided by the total number of considered years and results in the late frost index (LFI) which is greater than or equal to zero (no late frost) and less than or equal to one (late frost occurring every year after bud burst).

2.2 Climate data and climate scenarios

To representing past climate, we applied a homogenized climate data set for Germany (Gerstengarbe et al., 2015) derived from 180 climate stations and 1038 precipitation stations of the observation network led by the German Weather Service (DWD). For consistency, daily meteorological variables recorded at the climate stations were spatially interpolated to stations where only the precipitation was measured. Altogether, data at 1218 stations are used for simulations of the observation period from 1971 to 2010. The basic concept is roughly described by Österle et al. (2006).

We used an ensemble of 14 climate simulations at the regional scale based on statistical- and dynamical downscaling approaches (Table 1) using three RCP (Representative Concentration Pathway) scenarios (RCP2.6, RCP4.5 and RCP8.5). Simulations with the STAtistical Resampling Scheme (STARS) (Orlowsky et al., 2008) were generated by prescribing a scenario-specific seasonal temperature mean for every decade which was derived from an ensemble of 30 GCMs (Global Circulation Models) (Taylor et al., 2012). The STARS simulations provide selected representations (1) at the lower bound of temperature increase of the RCP8.5 scenario, (2) at the mean of temperature increase of the RCP4.5 as well as (3) at the upper bound and mean of temperature increase of the RCP2.6 scenario. The bias-corrected simulations of the different dynamical RCMs (Regional Climate Model) were generated within the EU-project IMPACT2C (Gobiet et al., 2015; Vautard et al., 2014). The simulation matrix for the GCM/RCM combination shown in Table 1 is a part of the whole EURO-CORDEX initiative (Jacob et al., 2014). They are available for the time period 1971–2005 (historical runs) and 2011–2100 (scenario runs) with a spatial resolution of $0.25° \times 0.25°$. Due to inconsistencies in dew point temperature throughout the scenario periods, an additional bias correction based on quantile mapping, was carried out.

The climate data (Fig. 1) averaged on national scale indicate a high variability of e.g. temperature (RCP8.5) and also of relative humidity (RCP4.5) across the different climate datasets. Mean annual temperature will rise by 0.4 to 1.7 K by the middle of the century compared to

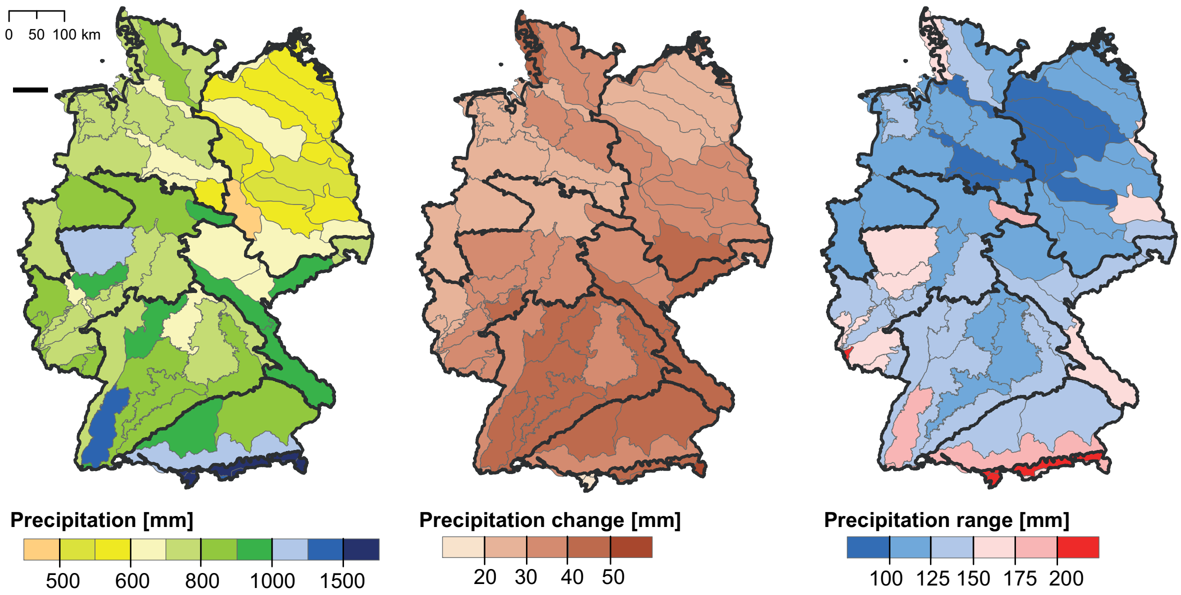

Figure 2: Precipitation conditions across Germany averaged for different natural regions. Observed precipitation sum averaged for 1971–2005 (left), averaged change of precipitation over 14 scenarios (center) and range of precipitation change averaged over 14 scenarios (right) for the period 2011–2045.

1971–2005, depending on the RCP used (see also Supplement Table 1). The mean annual precipitation sum will increase slightly according to all RCPs, whereas in global radiation and relative humidity no consistent trend across RCPs can be detected. The variation of precipitation change as well as the average range of precipitation change over all scenarios is relatively small in the Lowlands and clearly higher in the mountain area (Fig. 2).

2.3 Forest stands

Aiming at a comprehensive representation of Germany's forest, we selected all stands of the major tree species from the German national forest inventory BWI[2] (BMELV, 2005). Namely, we selected about 21000 Norway spruce (*Picea abies* L.) stands, 15000 Scots pine (*Pinus sylvestris* L.) stands, 2000 Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands, 16000 common beech (*Fagus sylvatica* L.) stands, 11000 oak (*Quercus robur* L. and *Quercus petraea* Liebl.) stands, along with 4500 birch (*Betula pendula* Roth) stands to represent broadleaf trees with low life span.

To each stand, we assigned a soil type of the digital soil map BÜK 1000 (BGR, 2004), a land use unit of the land cover map CORINE 2000 (DLR-DFD, 2004) to aggregate from point to forest area, a climate station according to the PIK data set and a grid cell of the CORDEX data. In total, 69393 mono-species stands representing 10.37 million hectare (98.2 % of the BWI[2] plots) were thus initialized to be simulated with 4C.

The whole initialisation process encompasses three main working steps. (1) From the BWI[2]-plot data, we determined the tree species with its observed mean age. (2) To this information, we added the age-dependent and species-specific stand information (mean height, mean diameter, and mean basal area) of the specific federal state where the plot is located. (3) We initialised 4C which includes empirically derived distribution functions of height, diameter, and stem number from these combined information. After these three steps we ended up with 69393 artificial monospecific forest stands with a close-to-reality distribution in terms of species occurrence and stand characteristics (mean diameter, mean height, basal area, and growing stock). The management of all stands consists of an annual thinning with an intensity based on annual harvested timber statistics available for tree species, age class, and federal state (from BWI[3], Thünen-Institut, 2012). In addition, a federal state- and species-specific rotation length has been defined. Once the rotation length is reached, the whole stand is harvested and regenerated with 2000 saplings per hectare of the same tree species.

2.4 Simulation concept and statistical analysis

All forest stands were simulated from climate of the observational data set and the historical model runs for the time period 1971–2005 (5 model runs). Furthermore, the model 4C was applied to all forest stands with the climate scenario data for the time period 2011–2045 (14 model runs). Subsequently we compared the risk indicators at each plot averaged over the time period 2011–2045 with the averaged values for 1971–2005. We calculated the relative changes for the indices FDI, NMRI, DSI_{dec} and the absolute changes for LFI for beech (LFI_{beech}) and oak (LFI_{oak}) separately. For each

Table 2: Results averaged on national scale for late frost risk for beech and oak for 1971–2005 and 2011–2045 (averaged over all nation-wide averages per scenario). The date is given in parenthesis.

	Simulation with observed data 1971–2005 average	Simulation with historical model runs 1971–2005 average	Average changes simulated across 14 scenarios 2011–2045		
			average	minimum	maximum
Beech					
Number of years with late frost	15	12	−2	−4	0
Day of bud burst	120 (30.4)	120	−3	−5	−1
Late frost index (LFI_{beech})	0.43	0.35	−0.06	−0.11	0.00
Oak					
Number of years with late frost	12	8	−1	−4	1
Day of bud burst	126 (6.5.)	126	−4	−7	−1
Late frost index (LFI_{oak})	0.33	0.22	−0.03	−0.12	0.04

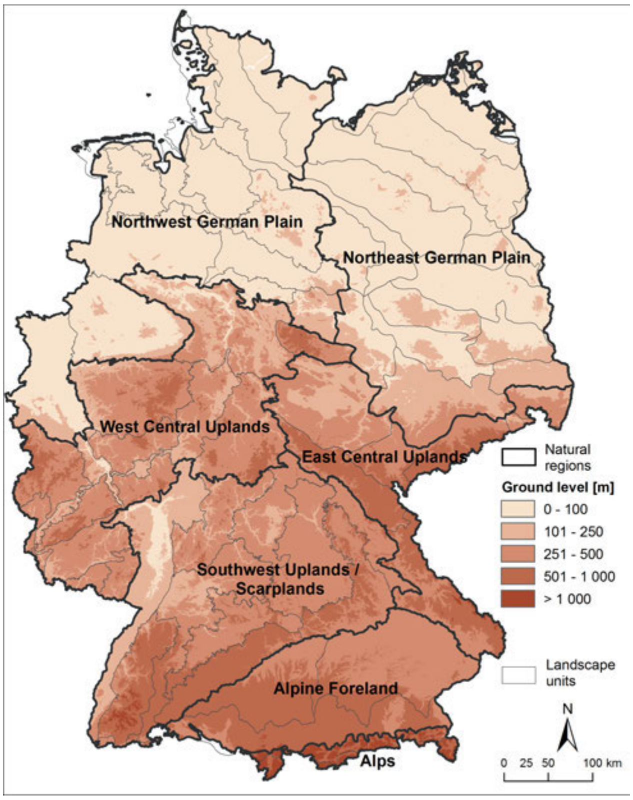

Figure 3: Natural regions and sub-regions according to Ssymank (1994).

plot we analysed the mean change and the range (maximum minus minimum) of the changes over the 14 scenarios as a measure of uncertainty (climate-induced uncertainty). For spatial aggregation we used the so-called natural regions and sub-regions (Ssymank, 1994) in Germany which classifies the territory according to geological, hydrological and soil properties (see also Lasch-Born et al., 2015, Fig. 3). The natural regions are subdivided into sub-regions, which we use also for aggregation by calculating averages of change and range over all sites and scenarios per sub-region.

Furthermore, we attempted to integrate the five risk indicators as follows. We ranked them in two ways: 1) in terms of their "relevance" expressed as regional mean values for 1971–2005 and 2) in terms of their "uncertainty" expressed as the range of change per natural region. A rank of seven denotes the highest value of a risk indicator, a value of one denotes the lowest value of the risk indicator. We then averaged all rank values (LFI_{beech}, LFI_{oak}, FDI, NMRI, DSI_{dec}) for each natural region and in terms of their relevance and uncertainty. In this way, we can classify changes in climate change risks to forest ecosystems in the natural regions according to their relevance and uncertainty.

3 Results

3.1 Results at national scale

The late frost risk decreases for beech and oak on average over all 14 scenarios by 6 and 3 %, respectively (Table 2). This reflects a decrease of two (beech) and one (oak) years with late frost events in the period of 35 years. The range of the changes in late frost risk for beech indicates a clear decreasing late frost risk, whereas for oak the range varies −12 to +4 %. For both species the day of bud burst shifts to an earlier date, but the number of years with late frost decreases.

Fire danger, nun moth risk and drought stress of deciduous tree species increase on average under climate change (Table 3). The FDI varies from a small decrease to an increase of about 10 % depending on the scenario. The nun moth risk index increases for all scenarios whereas the change of the drought stress again varies from a small decrease to an increase of about 4 %.

A comparison of the results for the recent time period indicates a slightly lower risk of fire and higher drought risk for the simulations with historical model runs. There is a clear difference in the number of years with late frost and late frost risk between the simulation with observation data and with data from historical model runs. The differences reflect the deviations of the historical model runs from the observation climate data.

Table 3: Results averaged on national scale for the fire danger index (FDI), the nun moth risk index (NMRI) and the drought stress index (DSI_{dec}).

	Simulation with observed data 1971–2005 average	Simulation with historical model run 1971–2005 average	Average changes simulated across 14 scenarios 2011–2045 average [%]	Range [%]	Min. [%]	Max. [%]
FDI	1.89	1.79	+4.21	10.47	−0.75	9.72
NMRI	1.11	1.12	+14.69	14.61	7.59	22.20
DSI_{dec}	0.06	0.08	+1.78	4.62	−0.53	4.09

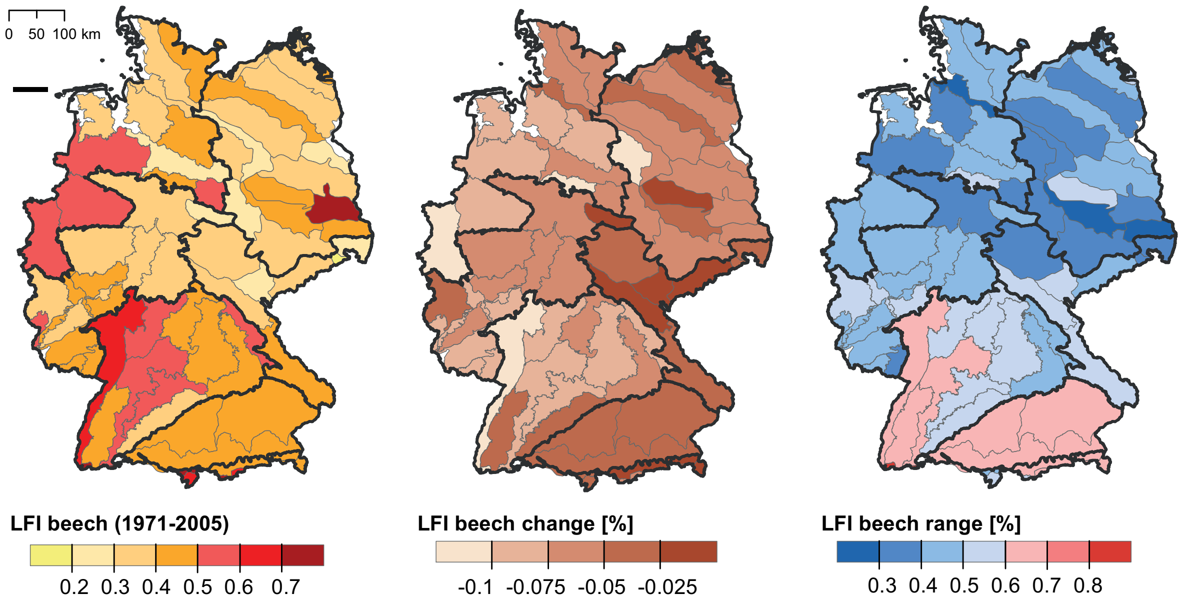

Figure 4: Late frost index for beech under recent climate (1971–2005), left, averaged changes 2011–2045 (centre), and averaged range for 2011–2045 (right) for the sub-regions of the natural regions.

3.2 Results at regional scale

The late frost risk for beech is highest in the Alps, Alpine Foreland, and Southwest Uplands and lowest in the East Central Uplands (0.35 on average) under recent climate conditions (Fig. 4 left) and decreases in all natural regions on average over all scenarios. The greatest decrease is simulated for the northwest German Plain (−0.08 on average) and the least is simulated for the Alps. The Alps and Alpine Foreland show the highest range of change while ranges are lowest for the Northeast and Northwest German Plain (see Supplement Table 2).

For oaks the results indicate a higher risk of late frost in the southwest Uplands and the northwest German Plain (0.38 on average) and a lower risk in the east Central Uplands (0.27 on average) under recent climate conditions. On average over all scenarios the late frost risk decrease is at its greatest for the northwest German Plain (−0.04) and is least for the Alpine Foreland (Fig. 5). The ranges did not differ much between the regions in this case. Only in one sub-region of the Northwest German Plain does the late frost risk increase on average for 2011–2045 (see Supplement Table 2).

Under recent climate conditions the fire danger is highest in parts of the Northeast German Plain whereas it is lowest in the Alps and the Alpine Foreland (Fig. 6, left). The averaged changes over 14 scenarios vary from an increase by 3.6 % for the Alps to 4.54 % for the East Central Uplands. The range is highest in the Northeast and Northwest German Plain (see Supplement Table 3).

The simulated average drought stress for deciduous tree species is relatively low at the regional level under recent climate. It is very low in the Alps and Alpine Foreland and higher in the southwest Uplands and parts of the northeast German Plain for 1971–2005 (Fig. 7, left). The changes under the 14 scenarios are very small and vary mostly from 0 to 3 % (see ESM Table 4). The range of changes is highest for the Northwest and Northeast German Plain, which is already among the regions with the highest drought stress index under recent climate conditions (Fig. 7, left). The precipitation under recent climate is especially low in the Northeast German Plain and under the future scenarios, the change of precipitation is low with the smallest range (Fig. 2).

The risk of nun moth appearance and mass outbreak is highest in the Northeast German Plain (1.19 on aver-

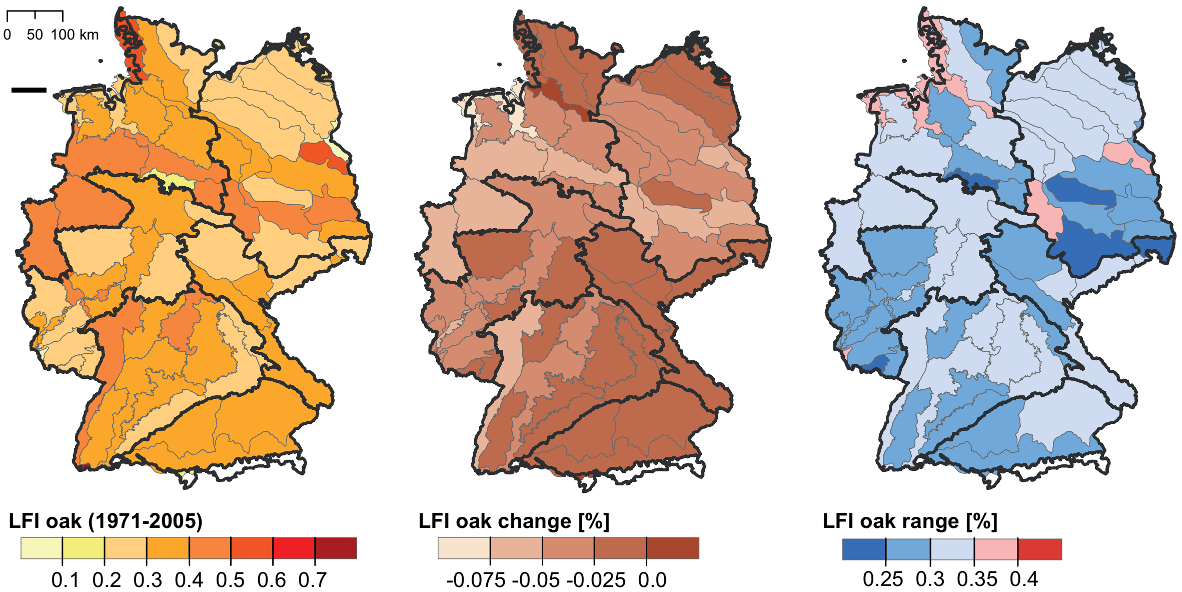

Figure 5: Late frost index for oak under recent climate (1971–2005), left, averaged changes for 2011–2045 (centre), and averaged range for 2011–2045 (right) for the sub-regions of the natural regions.

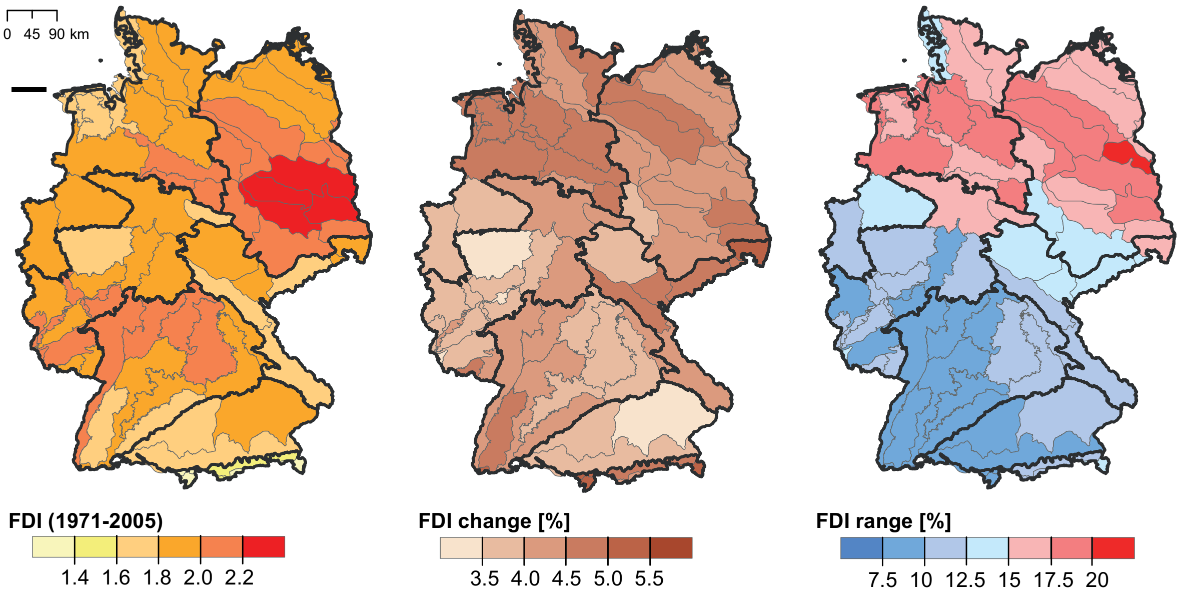

Figure 6: Fire danger index under recent climate (1971–2005), left, averaged changes for 2011–2045 (centre), and averaged range for 2011–2045 (right) for the sub-regions of the natural regions.

age) and lowest in the Alps (0.75) under recent climate conditions (Fig. 8, left). The grey color indicates that a region is climatically not suitable for nun moth outbreaks at present. This is the case at most sites of higher elevation. The highest relative increase is found in the Alps (about 26 %) and the Eastern Central Uplands (17 %). The range of changes is also highest in the Alps (about 37 %) and the Eastern Central Uplands (19 %) whereas the ranges are lowest in the Northwest German Plain (13 % on average) (see Supplement Table 3).

The integrated analysis of all five risk indicators for the natural regions in terms of their relevance and uncertainty shows that in the Southwest Uplands risk indicators are most relevant, i.e. the risk is highest under recent climate conditions (1971–2005) (Table 4). The aggregated risks are least relevant in the Alps and Alpine Foreland. The uncertainty regarding the five indicators given by the range over the 14 climate scenarios is highest in the East Central Uplands and lowest in the Alpine Foreland and the West Central Uplands.

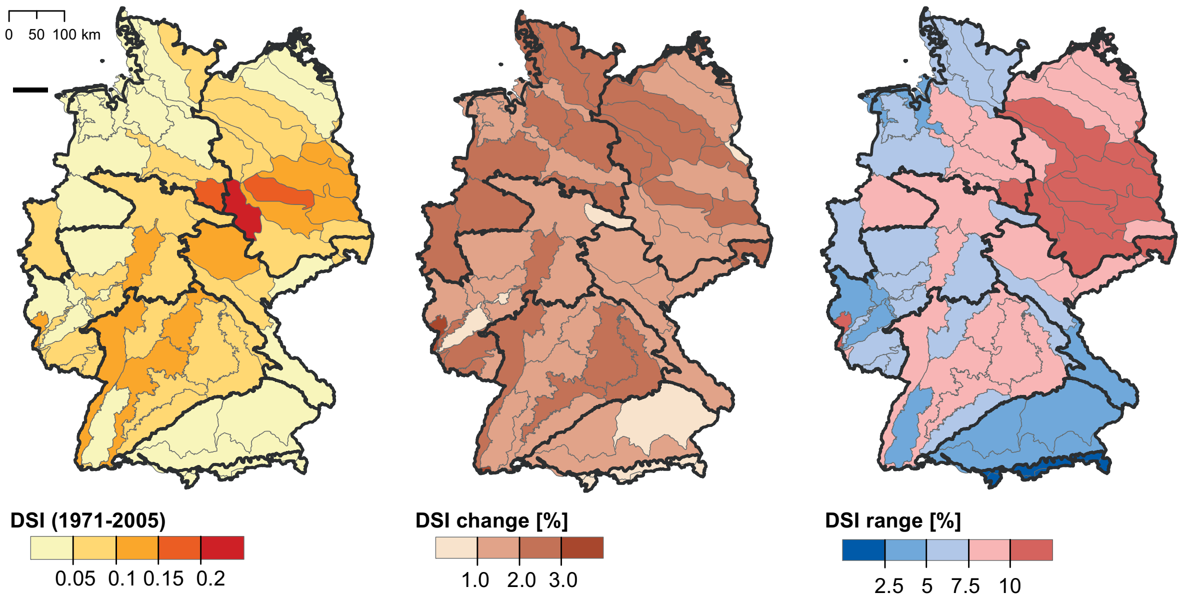

Figure 7: Drought stress index for deciduous species under recent climate (1971–2005), left, averaged changes 2011–2045 (centre), and averaged range for 2011–2045 (right) for the sub-regions of the natural regions.

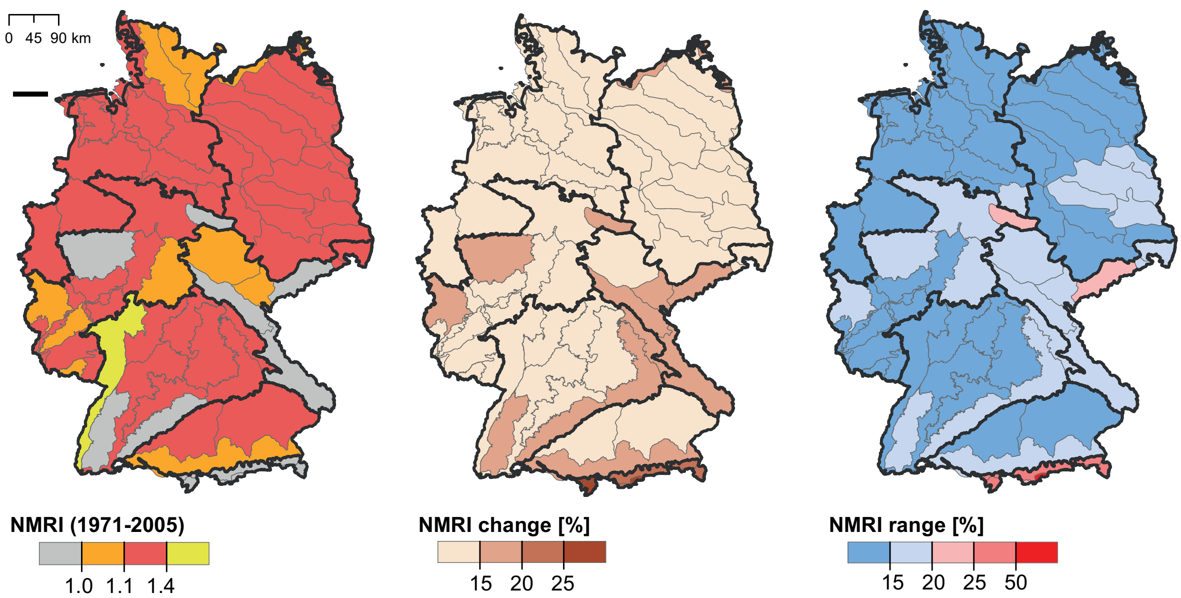

Figure 8: Nun moth risk index under recent climate (1971–2005), left, averaged changes for 2011–2045 (centre), and averaged range 2011–2045 (right) for the sub-regions of the natural regions.

Table 4: Integrated analysis of the five risk indicators for each natural regions regarding their relevance (1971–2005) and uncertainty (2011–2045), see text for further explanations.

	Relevance	Uncertainty
Northwest German Plain	5.20	4.20
Northeast German Plain	5.20	5.00
West Central Uplands	4.40	3.60
East Central Uplands	3.20	5.40
Southwest Uplands	5.60	4.40
Alpine Foreland	4.20	3.60
Alps	2.80	4.20

4 Discussion and conclusion

This study provides the first comprehensive analysis of biotic and abiotic risks to German forest ecosystems under climate change. Risks of fire, drought and insect outbreaks were shown to increase strongly by the middle of the century under the assumed climate projections, whereas risks of late spring frost will gradually decrease. Combining the risk measures in terms of relevance and uncertainty revealed that changes in risk indicators to be strongest for the Southwest Uplands and most uncertain for the East Central Uplands.

Late frost risk

The variation of late frost risk under climate change is still highly debated. Kodra et al. (2011) analysed climate model simulations and stated that extreme cold events are likely to persist across each land continent even in 21st century. Augspurger (2013) found an increase of spring damage risk for 20 species in a forest in Illinois during the last 124 years. Our findings support a decreasing risk of late frost damage in the future, continuing the trends found by Scheifinger et al. (2003) who analysed late frost events in Europe over the period from 1951 to 1997 and showed that the risk of late frost damage for plants decreased during the last decade as compared to the previous decades. The approach presented here represents a step forward as it assesses the probability of occurrence of early frost events via a multitude of climate scenarios.

Our results revealed an overall slight decrease of years affected by late frost risk for beech from 15 years to 13 years and oak from 12 to 11 years for the analysed 35 years period. Although there is broad variation among the climate models (one year increase to four years of decrease) and also the sites, the general trend points toward decreasing risk. This finding is in line with current observations of a more intensive lengthening of the frost-free period compared to the lengthening of the growing season in Germany for 1951–2000 (Menzel et al., 2003).

Our simple analysis regarding late spring frost risk indicates that only at some special sites beech did face increasing risks. Apart from that a decrease was simulated for beech and oak under the variety of climate scenarios, which confirms results of Bennie et al. (2010) for northwest Europe on the projected decrease of exposure to frost risk.

However, it needs to be stated that the frost risk approach applied here is conservative, in the sense that all temperature events below 0 °C after the day of bud burst are considered as potential risk events. Not all these events will have a severe impact physiologically, as on the microscale each phase of bud burst is restricted by its own lethal temperature (Lenz et al., 2013). Thus, it seems that frost risk is decreasing in the future in Germany.

Risk of fire

We simulated the highest forest fire risk under recent climate for the Northeast German Plain, which corresponds with observational data (BLE, 2015). Furthermore, the Federal state of Brandenburg, situated within this natural region, has often been characterised as the region in Germany with highest fire risk (Hirschberger, 2012; Kaulfuss, 2011). The projected overall increase in fire risk is relatively high and uncertain as indicated by higher ranges for the northern part of Germany. This is due to the high variability of annual precipitation sums among the scenarios, ranging from 830 mm to 910 mm (averaged annual precipitation for 2011–2045). Holsten et al. (2013) analysed the predictive performance of a variety of fire danger indices in Germany with recent climate and projections. They found that the fire danger index used here performed well when compared to observations, echoing findings of Badeck et al. (2004).

Drought stress

The changes in drought stress under the climate scenarios compared to the recent climate period are caused mainly by regional temperature and precipitation changes. The temperature increase leads to higher evapotranspiration and the magnitude, seasonal distribution and direction of precipitation changes then determine if the climatic water balance of a region turns negative and increased drought stress occurs. In the Northeast German Plain the annual precipitation increased on average by 30 mm with a range of about 100 mm (varying from −20 to +83 mm on average) in this region, which is relatively high in comparison to the recent annual precipitation (500–600 mm). Here, the simulated range of about 20 % indicates a high uncertainty of future precipitation and leads to a relatively high uncertainty in drought stress, which was also found by Gutsch et al. (2016) with another set of climate scenarios.

Analogous to our results, a simulation experiment with data from an ensemble of nine regional climate models showed an increase in drought stress resulting in a decrease in productivity for western Germany despite the large range of the ensemble data (Rötzer et al., 2013).

As stated by Friedrichs et al. (2009), the growth responses to changes of different climate parameters and the overall response to climate is modulated by differences between species and sites. The drought index used in this study depends not only on climate but also on the site conditions given by the soil characteristics as well as the age and structure of the considered deciduous stands. Furthermore, our approach describes the impact of water availability on carbon allocation in the model 4C with using the ratio of water supply and water demand of a cohort. However, the applied approach of water uptake by roots in 4C, which defines the water supply, was analysed and criticised using tree-ring width data by Gutsch et al. (2015). Here, it could be shown that severe drought stress is underestimated by the approach used in 4C and further improvement in 4C in terms of model formulations and validation of different processes at various time scales is needed. Hence, for regions which are already drought affected, a small negative change in our results could actually point to higher drought related risks.

The influence of the assumed annual management on the water balance of stands in our simulations is very low. In the case of 5 or 10 years harvesting period the annual mortality is higher than in the annual harvesting regime and therefore the stand structures in terms of density are very similar and the water balance of the stands too.

Considering average drought risk over a time period may not identify the full risk caused by drought periods or events. The importance of the frequency and duration of drought periods needs to be investigated. Drought events in Central Europe are likely to occur more frequently and last longer than in the past (Seneviratne et al., 2013).

Nun moth risk

The overall averaged nun moth risk index greater than one indicates only a relatively high risk of nun moth outbreaks in Germany. Vanhanen et al. (2007) stated that a northward shift of this species is likely under climate change conditions but a shift of the southern limit northward and to higher elevation is also possible (Battisti, 2008). The simulated relatively high increase and high range of NMRI due to the climate scenarios is mainly an effect of the temperature increases of the scenarios in 2011–2045. The index is mainly driven by temperature (see Lasch-Born et al., 2015; Zwölfer, 1935). The upward trend is also visible for the mountain regions in the averaged changes of NMRI (Fig. 8 centre) which are clearly greater than in the lowlands. Under recent climate, the NMRI is below one and indicates no occurrence in these areas, which is plausible. The Northeast German Plain is one of the main areas of infestation of nun moth since the 19th century, with a mass outbreak about every ten years (Majunke, 1994). This area is particularly destined for serious mass outbreaks of various phytophagous insect species due to the climatic conditions as well as extensive monocultures of pine (Majunke, 1995).

Assessments of disturbance risk caused by insects in Germany are not very common (Hanewinkel et al., 2011). The impacts of disturbances by insects were analysed for past conditions in the southwest of Germany using long-term time series to derive damage functions (Hanewinkel et al., 2008). Our approach to assess nun moth risk should only be considered as an example of risk assessment for a temperature-dependent forest insect species. The temperature dependence of the index had been evaluated by indoor experiments under artificial conditions and a combined empirical study of occurrences of individuals and mass outbreaks (Zwölfer, 1935). However, its applicability for forecasts on real ecosystems has been questioned in the past (Stellwaag, 1940). While our NRMI indicates potential risks for nun outbreaks, it is important to note that the risk of outbreak could also decrease due to changes in tree species composition. For example, decreasing outbreak frequencies in the south of Germany accompanied by changes in forest tree composition have led to the hypothesis of reduced future risks in particular for pine due to the ongoing forest conversion of coniferous monocultures to broadleaf or mixed forest stands (Lemme, 2012). Similar results have been found for bark beetles on spruce (Temperli et al., 2013) even though in general, climate change is thought to greatly increase the risk of bark beetle outbreaks in Germany and Europe (Wermelinger, 2004; Temperli et al., 2013; Seidl et al., 2014; Maroschek et al., 2015).

Increasing risks to German forests and the way forward

The increases of projected fire danger, drought stress and nun moth risk are in good correspondence with expected climate change impacts for Central Europe (Lindner et al., 2010; Lindner et al., 2014). This is not surprising given the importance of increasing temperatures for these risks. However, the risk indicators used here are not only sensitive to temperature but also to precipitation and relative humidity. The development of both of which is more uncertain in a warming world. Thus, including and combining these indicators into a joint analysis is already an important step forward. However, it is also important to note that only the drought stress indicator is really dependent on the state of the vegetation as simulated with 4C. All the other indicators are quite straightforward calculations from climatic data, though fire damage will not only depend on the climatic fire risk but the state of the forest, e.g. through the availability of fuel. Therefore, it is clear that the use of our indicators does not allow firm conclusions about the actual damage or impacts occurring from these risks. Moreover, we have only considered a selection of possible risks. Future analysis should focus especially on storm risk and also assess in greater detail the risks from bark beetle outbreaks. Also, we have not considered changing snow damage, which may regionally be important, even though it plays a minor role compared to storm damage in Europe (Schellhaas et al., 2003) and its risk is decreasing with rising temperature (Hanewinkel et al., 2008).

Our analysis allowed us to evaluate regionally the different risks and to distinguish regions of higher risk and higher climate-induced uncertainty regarding the considered risks. Especially, the Northeast German Plain has a high ranking in terms of both relevance and uncertainty averaged over all risks (Table 4). Hence, our results can be used to assess the risk integration within the current regional strategies of forest management planning. There is increasing knowledge about evaluation and implementation of potential risk adapted silvicultural measures (Yousefpour et al., 2014). Such measures include harvest dates (Couture and Reynaud, 2011), general risk distribution by applying different silvicultural systems (Kätzel and Höppner, 2011), reducing overaged stocking volume (Härtl et al., 2015) or admixing of tree species (Roessiger et al., 2013).

Further analysis should therefore move towards including the impacts of disturbances directly into the model 4C, especially in the case of insect damage in forests. Such an improved forest model would also allow one to quantify the effects of changing disturbance regimes on forest water and carbon cycling as well as forest resource provision which are central ecosystem services provided by German forests.

Moreover, a model coupling of different disturbances would allow assessing the interaction of different disturbances. This interaction is essential because it will, in the end, determine the vulnerability of German forests to climate change.

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The pdf version (Adobe Java Script must be enabled) of this paper includes an electronic supplement:

Table of content – Electronic Supplementary Material (ESM)

Tables S1, S2, S3, S4