Forest Growth Projections under Climate Change And Implications for Forest Planning

Cumulative Habilitation Thesis

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by

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Come to the woods, for here is rest. There is no repose like that of the green deep woods.

- *John Muir*

Preface

The scientific foundation of the here presented cumulative habilitation thesis was created while I was working on six research projects at the Northwest German Forest Research Institute, Göttingen, from July 2007 to date.

I herewith express my sincere gratitude to Prof. Dr. Hermann Spellmann, Director of the Northwest German Forest Research Institute and Head of the Department of Forest Growth, and to Prof. Dr. Jürgen Nagel, Head of the Section Forest Growth Modelling and Computer Science at the Northwest German Forest Research Institute, for their tireless commitment to guarantee a productive work environment with versatile inspirations and vivid discussions, and for allowing the scientific freedom in order to pursue my own research strategy.

Göttingen, January 2019

Scope of Habilitation Thesis – List of Publications

The thesis covers the fields of site-sensitive forest growth modelling, predicting forest development applying different silvicultural management strategies under changing climatic conditions, explicitly considering uncertainty, analyzing potential risks and vulnerabilities, deriving conclusions for forest planning including adaptation measures and providing information and methods for decision support. Figure 1 presents an artful wink on the research fields covered.



Fig. 1: Word cloud presenting the key words which define the scope of the habilitation thesis.  *: warming stripes by Hawkins (2018); shown here are the annual mean temperatures in Germany from 1881 to 2017; the colour scale ranges from 6.6°C (dark blue) to 10.3°C (dark red).*

The following eight publications constitute the scientific core of the habilitation thesis:

[I] **ALBERT, M.**, NAGEL, R.-V., SUTMÖLLER, J. AND SCHMIDT, M., **2018**: Quantifying the effect of persistent dryer climates on forest productivity and implications for forest planning – a case study in northern Germany. Forest Ecosystems, 5:33; doi: 10.1186/s40663-018-0152-0.

[II] **ALBERT, M.**, NAGEL, R.-V., NUSKE, R.S., SUTMÖLLER, J. AND SPELLMANN, H., **2017**: Tree Species Selection in the Face of Drought Risk – Uncertainty in Forest Planning. Forests, 8, 363; doi: 10.3390/f8100363

[III] FLECK, S., AHRENDS, B., SUTMÖLLER, J., **ALBERT, M.**, EVERS, J. AND MEESENBURG, H., **2017:** Is Biomass Accumulation in Forests an Option to Prevent Climate Change Induced Increases in Nitrate Concentrations in the North German Lowland? Forests, 8, 219; doi: 10.3390/f8060219

[IV] THIELE, J.C., NUSKE, R.S., AHRENDS, B., PANFEROV, O., **ALBERT, M.**, STAUPENDAHL, K., JUNGHANS, U., JANSEN, M. AND SABOROWSKI, J., **2017**: Climate change impact assessment – A simulation experiment with Norway spruce for a forest district in Central Europe. Ecological Modelling 346: 30–47; doi: 10.1016/j.ecolmodel.2016.11.013

[V] **ALBERT, M.**, LEEFKEN, G., NUSKE, R., AHRENDS, B., SUTMÖLLER, J. AND SPELLMANN, H., **2016**: Auswirkungen von klimatischer Unsicherheit auf die Forstplanung am Beispiel von vier Regionen im norddeutschen Tiefland. Allg. Forst- und Jagdzeitung, 187 (9/10): 161-185.

[VI] **ALBERT, M.**, HANSEN, J., NAGEL, J., SCHMIDT, MAT. AND SPELLMANN, H., **2015:** Assessing risks and uncertainties in forest dynamics under different management scenarios and climate change. Forest Ecosystems, 2:14; doi: 10.1186/s40663-015-0036-5

[VII] **ALBERT, M.** AND SCHMIDT, M., **2012:** Standort-Leistungs-Modelle für die Entwicklung von waldbaulichen Anpassungsstrategien unter Klimawandel. Arch. Forstw. u. Landsch.ökol., 46, 57-71

[VIII] **ALBERT, M.** AND SCHMIDT, M, **2010:** Climate-sensitive modelling of site-productivity relationships for Norway spruce (Picea abies (L.) Karst.) and common beech (Fagus sylvatica L.). For. Ecol. Manage., Vol. 259, Issue 4, 739-749; doi: 10.1016/j.foreco.2009.04.039

1. Background to Forest Growth, Climate change and Forest Planning

From the beginning of sustainable forest management decisions on species cultivation, silvicultural stand treatment and final harvests rely on expectations of future developments (Carlowitz, 1713). Concerning the prediction of prospective forest growth and yield, the central paradigm in forest management to assume constant site conditions has to be revised at least for a stand's lifespan (e.g. Pretzsch, 1992; Skovsgaard and Vanclay, 2008; Smith et al., 2015). In large areas in Central Europe, gradual processes have transformed site quality negatively through exploitation, or positively through, for example, site-enhancing species by reforestation in the last centuries. However, massive nitrogen and sulfur depositions beginning in the 1950s (Schöpp et al., 2003) and the rapidly changing climate affect the primary growing conditions of forests well below a classical rotation period (e.g. Boisvenue and Running 2006; Pretzsch et al. 2014; Kohnle et al. 2014; Aertsen et al. 2014). Consequently, the previously applied static biological laws of growth and yield need to be adapted to account for aggravating transitions in site conditions.

Therefore, it is inevitable to enhance forest growth models site-sensitively (Pretzsch, 1999). In order to quantify site quality, the first shifts in forest growth modelling from phytocentric measures such as the classical site index to geocentric concepts relying on physiographic, climatic and soil-based attributes started in the 1960s (Czarnowski, 1961). One of the first applications were the gap models JABOWA (Botkin et al., 1972) and its advanced version FORET (Shugart and West, 1977). Ecophysiological forest growth models utilize soil and climate variables as predictors as well, e.g. the early North American model formulations FOREST-BGC (Running and Coughlan, 1988) and FORCYTE (Kimmins et al., 1990) as well as German model developments such as the approach by Pfreundt (1988) and Sloboda and Pfreundt (1989) and the models TREEDYN (Bossel, 1994) and 4C (Bugmann et al., 1997). Also, statistical growth models have made intensified use of site variables, in Germany starting with the set of functions to predict height-age curves based on nine soil and climate parameters by Kahn (1994; 1995). Until now, different approaches have been proposed to facilitate site-sensitive statistical growth modelling: (1) direct prediction of site productivity measures, i.e. site index, mean annual increment etc. (e.g. Latta et al. 2010; Nothdurft et al. 2012), (2) prediction of change in site productivity measures (e.g. Yue et al. 2014; Yue et al. 2016), (3) prediction of temporal shifts of height-diameter curves (e.g. Schmidt 2010; Burggraef et al. 2017; Schmidt et al. 2018), and (4) direct prediction of diameter increment and/or height increment, respectively (e.g. Rohner et al. 2017). In this context, the **publications IV, VII and VIII** of this cumulative habilitation thesis introduce a climate-sensitive approach to model site-productivity relationships for selected tree species in Germany.

By applying site-sensitive growth model formulations, the effect of changing site conditions on forest growth can be quantified (Pretzsch, 1999). One major field of application for forest growth models in general is to simulate future developments in light of differing framework conditions (Clark et al., 2001). The main objective of simulation studies is to provide information beyond measurements and observations for forest planning and to support decision making. In order to supply forest planning with management options and to

evaluate the different alternatives, it is necessary to not only project forest growth but also to formulate silvicultural management scenarios (e.g. Gadow 2005; Nuutinen et al. 2006; Pukkala 2016; Braun et al. 2016) and to assess potential abiotic and biotic risks (e.g. Gadow 2000; Bredemeier et al. 2001; Spellmann et al. 2007, 2015). With regard to methodological questions concerning silvicultural management strategies, the **publications II, III, V and VI** highlight the process of scenario formulation and the technical challenges in the implementation within a forest growth simulation framework. In the **publications I, II, III, V and VI**, risk assessment is addressed using drought stress and windthrow as examples. A more comprehensive view on the application of forest growth simulation frameworks in general is given in the **publications I, IV, V and VI**.

One crucial issue when providing forest planning with decision support is to account for the inherent uncertainty in climate projections (e.g. Yousefpour and Hanewinkel 2016). While forest planning always had to decide on a basis of incomplete information, projections of climate change bear an intrinsic uncertainty where climate scenarios cannot be assigned any probability of occurrence (Foley, 2010). The uncertainty in climate projections when used for forest planning raises two concerns, i.e. to build confidence in the projections (Knutti and Sedlácek 2012; Baumberger et al. 2017) and to communicate the degree of uncertainty for proposed recommendations (Kandlikar et al., 2005). In this context, the **publications I, II, V and VI** point out how climate projection uncertainties can be anticipated by applying several climate scenarios. This is a compromise between adequate computational workload and sufficient consideration of possible projection uncertainties.

In the end, it is the goal of forest growth projections under climate change taking risks and uncertainties into account in order to derive recommendations for forest planning. Ultimately, adaptation measures can be identified and implemented into practical forestry to counter or at least diminish the negative effects of climate change, if necessary (e.g. Lindner 2000; Brang et al. 2008; Lindner et al. 2010; Schelhaas et al. 2015; Yousefpour et al. 2017). The **publications I, II, V, VI, and VII** demonstrate, for selected regions in northern Germany, which conclusions can be drawn from predictions of forest development under climate change and how this information supports forest management and forest planning in decision making. Additionally, a newly developed instrument, the three-dimensional ecogram, to aid in the tree species selection process under climate change, is introduced in **publication VII**.

Figure 2 summarizes the connections of the different fields of research in forest growth projections under climate change and decision support in forest planning. Furthermore, it is illustrated how the publications of the cumulative habilitation are assigned to the different topics.

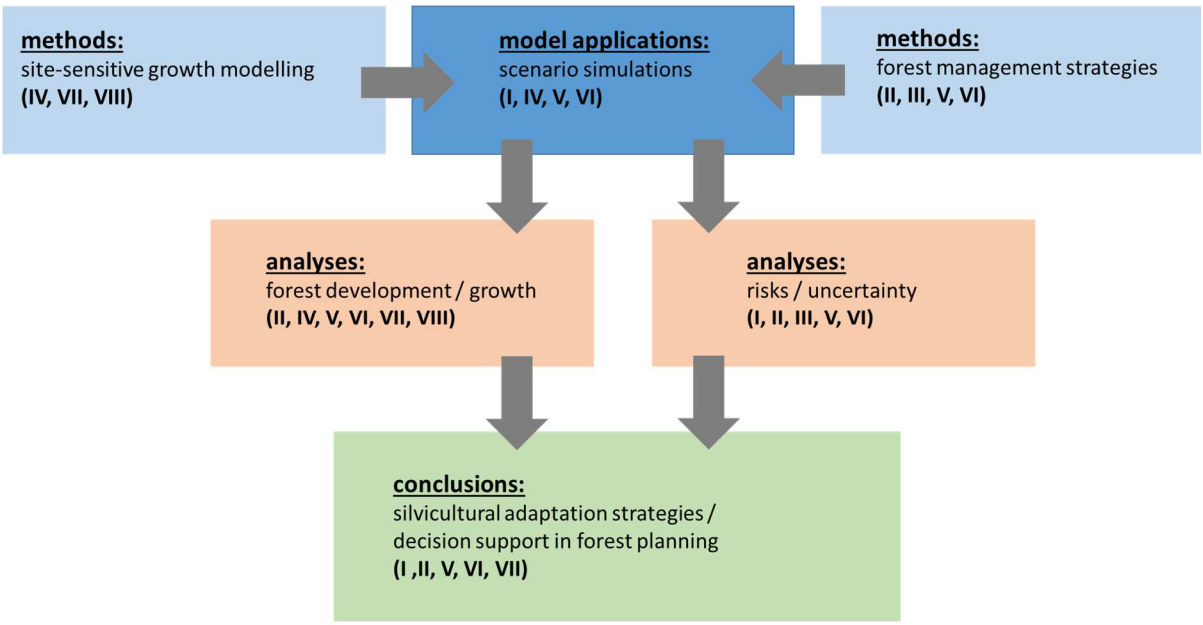


Fig. 2: Fields of research in forest growth projections under climate change and decision support in forest planning. Publications of the cumulative habilitation assigned to the different topics (in brackets).

The eight publications of the cumulative habilitation pursue three major goals: (1) development of a climate-sensitive site-productivity model and methods to project forest growth under climate change, (2) analysis of the effects of site alterations due to climate change and nitrogen deposition on stand productivity and on risks applying scenario simulation taking uncertainty into account, and (3) deriving recommendations for adaptive forest planning to avoid or reduce the negative impact of climate change.

2. Concepts in Forest Growth Projections

The manifold model formulations applied in forest growth research can be categorized into four groups: (1) statistical growth models, (2) process-based approaches, (3) hybrid formulations, and (4) gap models (Weiskittel et al., 2011). Statistical models straight forwardly correlate explanatory variables to the desired target variable using observational data. The primary field of application is to predict future forest stand development over time in order to provide decision support for forest management and planning (Mohren and Burkhart, 1994). Process-based models reproduce key physiological processes. Thus, growth predictions are rather causal in contrast to the correlative character of statistical models (Bontemps and Bouriaud, 2013). Therefore, system analysis within the meaning of understanding forest growth and exploring key determinants and their effects on trees and forests is the main purpose of process-based models. Hybrid model formulations are characterized by statistical growth equations with either physiologically derived covariates or physiologically derived modifiers. Thus, hybrid models can overcome a common limitation of statistical approaches, i.e. unsatisfactory sensitivity to environmental changes, as well as a deficiency of process-based models, i.e. precise predictions on an area-wide forest stand level. As hybrid models make use of the advantages of both statistical and process-based approaches, their applicability is well suited for system evaluation and predictions for management purposes (e.g. Peng et al. 2002). Gap models, on the other hand, disintegrate a forest into small tree groups of similar traits (Shugart and West, 1977). Bugmann (2001) points out four underlying assumptions which characterize the gap model concept: (1) the tree groups of similar traits, i.e. same age and successional stage, constitute a patch and the sum of all patches makes up the entity of a forest; (2) each patch is assumed horizontally homogeneous; (3) leaf area is regarded as one disk at the top of the tree group; (4) no interaction between the patches exists. The design of the gap model approach enables investigation on long-term ecological processes especially for forest species succession.

Each model group has their own advantages and disadvantages (cf. Weiskittel et al., 2011). However, in view of modelling forest growth under climate change and to provide decision support for forest management and planning, further on, the focus will be on climate-sensitive statistical approaches. From the point of view of the Northwest German Forest Research Institute, three reasons for selecting a statistical growth model formulation are paramount: (1) the already existing statistical forest growth model framework (Hansen and Nagel, 2014), (2) the available extensive data base of long-term experimental growth and yield plots as well as the data from the German National Forest Inventory and state forest inventories, and (3) decision support for practical forest management and planning needs precise estimates of growth and yield measures based on easily and area-wide available site-specific input data, i.e. observations from forest inventories and site mapping. While it is logical to pursue the development of existing models, also the data-base at hand, mainly collecting traditional growth and yield measures, is best suited for statistical modelling. Furthermore, process-based as well as hybrid approaches usually require initialization data which is normally not available area-wide and has not an appropriate spatial resolution necessary for forest management purposes.

2.1 Site-sensitive Forest Growth Models

Forest growth dynamics already have undergone significant changes in the past decades with serious implications for forest productivity in central Europe and in many other parts of the world (e.g. Spiecker et al., 1996; Hasenauer et al., 1999; Pérez et al., 2005; Boisvenue and Running, 2006; Bontemps et al., 2009; Kohnle et al., 2014; Pretzsch et al., 2014; Charru et al., 2017). Different external factors have caused these changes, for example rising temperatures and correspondingly longer growth periods commonly have a positive effect on forest growth in central Europe (e.g. Kerkhoff et al., 2005; Laubhann et al., 2009; Brandl et al., 2018), whereas reduced precipitation along with increasingly dryer conditions has a negative effect on productivity (e.g. Hanson and Weltzin, 2000; Zang et al., 2011). Furthermore, forest growth might have accelerated due to rising nitrogen depositions (e.g. Egli et al., 1998; Vries et al., 2006), or it might have benefited from declining sulphur deposition (e.g. Hauck et al., 2012; Kolár et al., 2015) or rising CO_2 concentrations (e.g. Körner et al., 2005). All these potentially rapidly changing factors call for site-sensitive forest growth models.

Four different methodological approaches to account for a changing environment in statistical forest growth predictions are conceivable: (1) a direct estimate of site index (e.g. Monserud et al., 2006; Nothdurft et al., 2012; Antón-Fernández et al., 2016; model construction in **publications VII and VIII** and application of the method in **publication IV**) which is further used as a predictor in, for example, height growth equations (e.g. Nagel, 1999; Hansen and Nagel, 2014), (2) estimation of the change in site index within a certain time period (e.g. Yue et al., 2014; 2016), (3) estimation of the temporal shift of the height-diameter relationship within a forest stand (e.g. Schmidt, 2010; Schmidt et al., 2018; applications of the method in **publications I, III, V, and VI**), and (4) a direct estimate of tree increment (e.g. **supplementary publication 6**; Rohner et al., 2017).

The problem definition for **publication VIII** comprises the development of a site index model which is sensitive to soil and climate parameters (cf. also **supplementary publication 10**). One important requirement for the modelling approach is its applicability to refine the well-established single-tree growth models of the Northwest German Forest Research Institute to climate change conditions (cf. Hansen and Nagel, 2014). It is hypothesized that modelling site index as a function of soil and climate variables requires a wide gradient of environmental conditions to distinguish between the individual factors affecting site index. Furthermore, it is hypothesized that a generalized additive model (GAM) is the adequate statistical approach to depict linear and non-linear effects on the response variable (Hastie and Tibshirani, 1990). This conjecture is confirmed, for example, by Aertsen et al. (2010). Finally, the underlying assumption of the modelling approach states that, in principle, the state-for-time substitution, i.e. the effects of today's environmental conditions at a certain location on site index are transferable to a different location where these environmental conditions are expected to occur in the future, holds true. Therefore, **publication VIII** builds on a rich source of yield data from the state forest inventory of the Lower Saxony State Forest Enterprise covering 9,474 plots stocked with European beech (*Fagus sylvatica* L.) and 16,552 plots with Norway spruce (*Picea abies* (L.) Karst.). The time-dependent values of the explanatory climate variables and the nitrogen deposition are converted to means for the

constant reference period 1961 to 1990 retaining the spatial variability. Thus, the modelling approach is a classical space-for-time substitution (Pickett, 1989). Furthermore, we apply the general GAM methodology of Wood (2000; 2004; 2006) which is implemented in the R-library *mgcv*. Two features make the methodology of Wood so appealing, i.e. non-linear effects on the response variable are identified using penalized regression splines without any assumption on the underlying form of the function and, moreover, multi-dimensional effects as, for example, a spatial trend can be modeled applying a two-dimensional isotropic penalized thin-plate regression spline.

The core results of **publication VIII** can be summarized as follows: The key environmental determinants to predict site index are identified (Tab. 1). It is important to note that both models for Norway spruce and European beech include a temperature and a precipitation variable, as well as soil nutrients, nitrogen deposition and a spatial trend. The soil parameter available water capacity (here denoted as available soil moisture asm) is a direct explanatory variable for site index of Norway spruce, while for beech it is combined with precipitation and evapotranspiration to form the variable water balance. All explanatory variables are highly significant and the effects on site index are biologically feasible.

*Tab. 1: Formulae of site-productivity models for spruce and beech, adjusted coefficient of determination and standard error (SE) (from **publication VIII**).*

	R_{adj}^2	SE [m]
spruce:		
$SI_i = \alpha_1 + nut_i^T \beta_1 + f_1(prec_i) + \alpha_2 * cep_i + f_2(asm_i) + f_3(temp_i) + f_4(Ndep_i) + f_5(lon_i, lat_i) + \varepsilon_i$; $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ [1]	0.39	2.3
beech:		
$SI_i = \alpha_1 + nut_i^T \beta_1 + f_1(wb_i) + f_2(temp_i) + \alpha_2 * cNdep_i + f_5(lon_i, lat_i) + \varepsilon_i$; $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ [2]	0.34	2.9

with:

SI_i	= site index (mean stand height at age 100) at inventory point *i* [m],
nut_i^T	= indicator vector for soil nutrient class,
β_1	= parameter vector corresponding to nut,
$prec_i$	= precipitation sum in growing season (GS) [mm],
ep_i	= potential evapotranspiration in GS [mm],
cep_i	= centered potential evapotranspiration in GS [mm],
asm_i	= available soil moisture [mm],
$temp_i$	= mean temperature in GS [°C],
$Ndep_i$	= mean annual nitrogen deposition [eq/ha/a],
$cNdep_i$	= centered mean annual nitrogen deposition [eq/ha/a],
lon_i	= longitude (location parameter),
lat_i	= latitude (location parameter),
wb_i	= water balance in GS [mm] (*with* $wb_i = prec_i - ep_i + asm_i$),
ε_i	= random error term,
α_1, α_2	= regression coefficients,
$f_1 \ldots f_4$	= one-dimensional penalized regression splines,
f_5	= two-dimensional penalized regression spline describing a spatial trend.

The model performance is tested along a precipitation as well as a temperature gradient for sensitivity (Figures 3 and 4). Along the gradients, the site-productivity models are applied under a climate change scenario, i.e. the conditions of scenario A1B in the dry variant in the period from 2041 to 2050 (IPCC, 2007). The change in site index then is analyzed by comparing the predicted site index values for this future period to model predictions under conditions of the reference period 1961 to 1990.

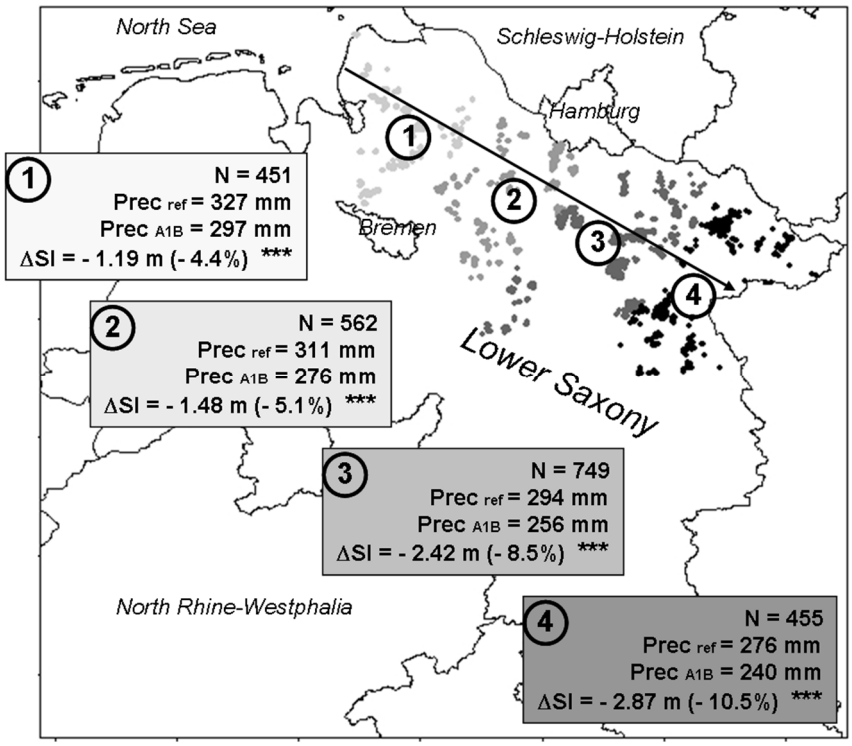


*Fig. 3: Effects of the precipitation gradient along four regions in Lower Saxony, Germany (N = number of spruce plots; $Prec_{ref}$ = mean precipitation sum in growing season in respective region for the reference period 1961 to 1990; $Prec_{A1B}$ = precipitation sum in growing season in respective region for the period 2041 to 2050 under scenario A1B – dry variant; ΔSI = change in mean site index of spruce plots in respective region) (from **publication VIII**).*

As an example in the overall evaluation of model performance, the sensitivity analysis along the precipitation gradient clearly shows that the site-productivity model for Norway spruce is capable to reflect the spatial and temporal trends (Fig. 3). It renders feasible causal projections. The same holds true for the site-productivity model for European beech along the temperature gradient (Fig. 4).

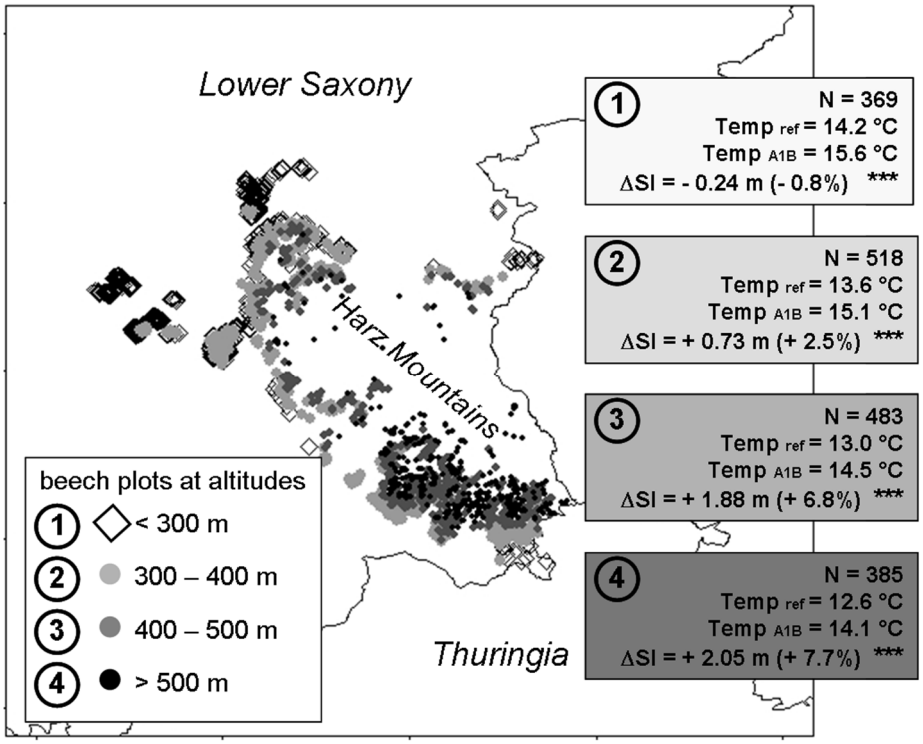


*Fig. 4: Effects of the temperature gradient along four altitude classes in the Harz Mountains, Lower Saxony, Germany (N = number of beech plots; $Temp_{ref}$ = averaged mean temperature in growing season for the reference period 1961 to 1990; $Temp_{A1B}$ = averaged mean temperature in growing season for the period 2041 to 2050 under scenario A1B – dry variant; ΔSI = change in mean site index of beech plots in respective altitude class) (from **publication VIII**).*

The results from **publication VIII** lead to the following core conclusions:

(1) The novel approach to model site index site-sensitively using GAM is well capable to be used under climate change conditions. In the models, the major environmental determinants affecting site index, i.e. climate and soil parameters, are statistically significant. All partial effects are biologically feasible. The advantage of the presented site index models is that partial effects of single predictors on the dependent variable are quantified and estimated confidence intervals help to account for prediction uncertainty.

(2) The coefficient of determination shows that 39 % of the variation in site index can be explained for Norway spruce and 34 % for European beech. However, to put these numbers into perspective it needs to be considered that this first modelling approach has some flaws, i.e. the response variable is an estimate itself, and the climate parameters as well as the nitrogen deposition are model predictions which are further downscaled to the respective plot location. In addition, fixed average values for the reference period 1961 to 1990 are used. Recently, a method of dynamic balancing over the stand's actual life-span was tested (Schmidt, 2018). Furthermore, the gradient of today's climatic conditions in Lower Saxony lacks certain parameter combinations, e.g. warm and concurrently wet sites. Extreme site conditions which are especially necessary for

predictions under climate change are also not well represented in the data set. Thus, enlarging the parameterization to all of Germany will improve the current models (c.f. **publication VII**).

(3) The space-for-time substitution in the context of climate change impact studies is currently under debate (e.g. Yue et al., 2016). Basically, the three underlying assumptions, i.e. the gradient is causal and deterministic, environmental conditions and tree growth are in equilibrium at the given sites, and spatial growth response equals dynamic growth in time when site factors change in the same order, are crucial but not totally refuted, yet. Also, the concern about potential confounding in the space-for-time substitution should be considered, since gradient studies often lack a randomization and interspersion of treatments in the meaning of manipulated experiments (Hurlbert, 1984). In our case, treatments could be forest management regimes, for example. However, the large number of observations, the spatial extent of the gradients and a mix of different inventories, at least for the German-wide models in **publication VII**, contradict confounding concerning treatments and spatial or temporal factors. Thus, unambiguous recommendations to unrestrictedly replace time-for-space approaches with state-space approaches based on long-term longitudinal data cannot be given yet (Albrecht et al., 2017).

The preliminary site-productivity models of **publication VIII** are determinedly refined, applying the same GAM approach, however, expanding the gradient for climatic conditions to the whole of Germany (**publication VII**). Thus, the task for **publication VII** is to develop a first German-wide applicable site-sensitive site-productivity model on the grounds of the preliminary models and to include additional tree species, i.e. next to Norway spruce (*Picea abies*, [L.] Karst) and European beech (*Fagus sylvatica*, L.) also oak (*Quercus spec.*), Scots pine (*Pinus sylvestris*, L.) and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco).

The main results in **publication VII** concerning the site-productivity models yield two model formulations (cf. also **supplementary publication 8**). The first model is developed for European beech, oak, Norway spruce and Scots pine:

$$SI_i = \alpha_1 + nut_i^T \beta + f_1(Temp_i) + f_2(CWB_i) + f_3(awc_i) + f_4(Ndep_i) + f_5(lon_i, lat_i) + \varepsilon_i \quad [3]$$

with $\mathbf{SI}_i$=site index (mean stand height at age 100) at inventory point *i* [m], $\mathbf{nut}_i^{\mathbf{T}}$=indicator vector for classified soil nutrients, $\boldsymbol{\beta}$=parameter vector corresponding to nut, $\mathbf{CWB}_i$=climatic water balance in growing season [mm], $\mathbf{Temp}_i$=temperature sum in growing season [°C], $\mathbf{Ndep}_i$=mean annual nitrogen deposition [eq/ha/a], $\mathbf{awc}_i$=available water capacity with regard to 1,4m soil depth [mm], $\mathbf{lon}_i\mathbf{,lat}_i$=Gauss-Krüger-coordinates, $\boldsymbol{\alpha}_1$=regressions coefficient (intercept), $\mathbf{f}_1$, $\mathbf{f}_2$, $\mathbf{f}_3$, $\mathbf{f}_4$=one-dimensional penalized regression splines, $\mathbf{f}_5$=two-dimensional penalized regression spline describing a spatial trend.

A separate two-stage model needs to be formulated for Douglas-fir. The predictor variables show a high correlation for Douglas-fir because of the much smaller data base (cf. Tab. 2). Thus, in order to warrant a biologically feasible model behaviour, it is necessary to model the effects of the climate variables Temp and CWB in a first model stage. The effects

are then transferred as offsets into the second model stage, which also includes soil nutrients, nitrogen deposition and a spatial trend as predictor variables:

first model stage:

$$SI_i = \alpha_1 + f_1(Temp_i) + f_2(CWB_i) + \varepsilon_i \quad [4.1]$$

second model stage:

$$SI_i = \alpha_1 + nut_i^T \beta + \hat{f}_1(Temp_i) + \hat{f}_2(CWB_i) + f_4(Ndep_i) + f_5(lon_i, lat_i) + \varepsilon_i \quad [4.2]$$

with $\hat{f}_1$, $\hat{f}_2$ = effects parameterized in the first model stage [4.1] and transferred to the second model stage [4.2] (all other labels see above).

In comparison to the preliminary models of **publication VIII**, the final Norway spruce model shows a considerable improvement while the model fit for European beech is slightly worse (Tab. 2).

*Tab. 2: Characteristics of model quality (N=number of plots; se=standard error) (from **publication VII**, modified).*

	N	R^2	se [m]	bias [m]
Norway spruce	57,094	0,44	3,1	-7,3e-14
Europ. beech	35,864	0,31	3,4	1,6e-14
Scots pine	35,104	0,45	2,6	-4,0e-15
oak	20,666	0,33	3,1	-9,0e-17
Douglas-fir	4750	0,40	5,0	8,7e-15

Figure 5 demonstrates the application of the site-productivity model for Scots pine on all plots of the German National Forest Inventory and all plots of the State Forest Inventory of Lower Saxony currently stocked with Scots pine.

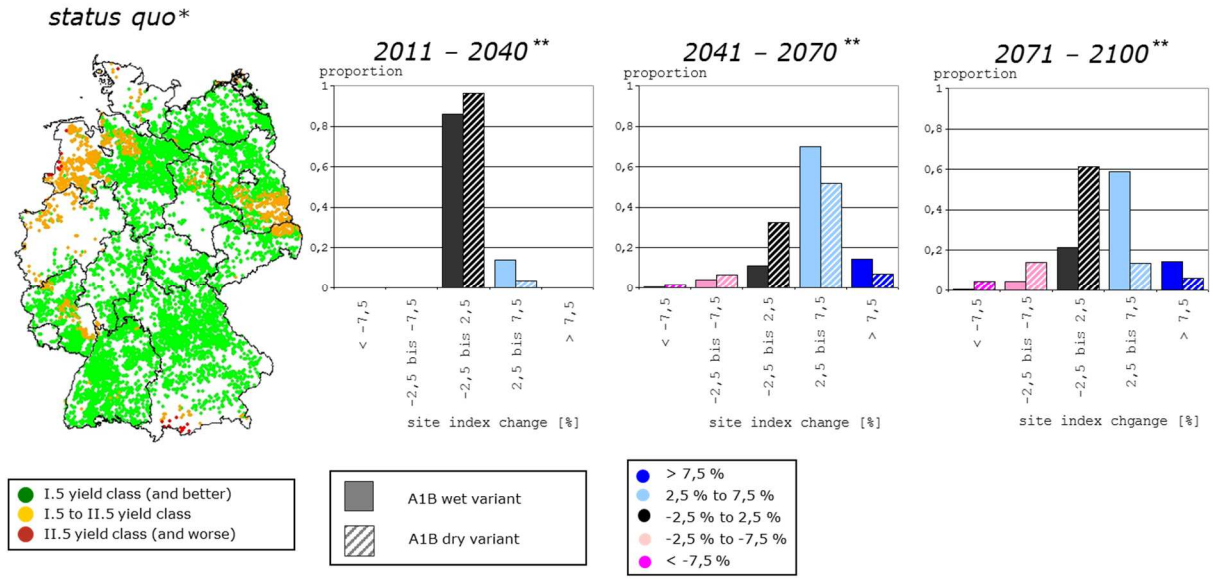


Fig. 5: Projection of relative change of site productivity for Scots pine under the climate scenario A1B in the wet (solid bars) and dry (crosshatched bars) variant for three projection periods (graphic shows projections of the A1B dry variant in the period 1981 to 2010; ** reference value for changes are the status quo values of the A1B wet and dry variant, respectively). Climate parameters are modelled using WETTREG. Projection is made nationwide for all plots of the National Forest Inventory and the State Forest Inventory of Lower Saxony which are currently stocked with Scots pine (from **publication VII**).*

The climate-sensitive site-productivity models of **publication VII** form the integral forest growth model part in the novel complex dynamic simulation model system *DSS-WuK* (decision support system forest and climate change (in German: *Wald und Klimawandel*)) of **publication IV**. The major goal when starting work on *DSS-WuK* was to build a model system which couples several independent submodels to describe forest-climate interactions, i.e. the fields of soil and climate, forest growth and productivity, abiotic and biotic hazards and the economic implications (**publication IV, supplementary publication 12**). While **publications VII** and **VIII** focused on developing a climate-sensitive site-productivity model which projects site index according to among others soil and climate variables, the problem definition for **publication IV** is to integrate the site-productivity model into an existing forest growth model. As a convenient approach, we use the well-established single-tree growth functions *TreeGrOSS* by Nagel (2011). As the function to predict height increment applies site index as a predictor, it is hypothesized that by updating the site index values for each 5-year prediction period using estimates from the site-productivity model adequate climate-sensitive projections of forest growth can be realized.

Publication IV yields two main results looking at the forest growth part. First, the site-productivity model of **publication VII** proves highly sensitive in the simulation of Norway spruce stands in model region Arnsberg under two climate scenarios B1 and A1B in the period 2011 to 2100 (Fig. 6). As a reference, site index is predicted for the period 1971 to 2000 applying the 20th century reconstruction (C20) with anthropogenic forcing.

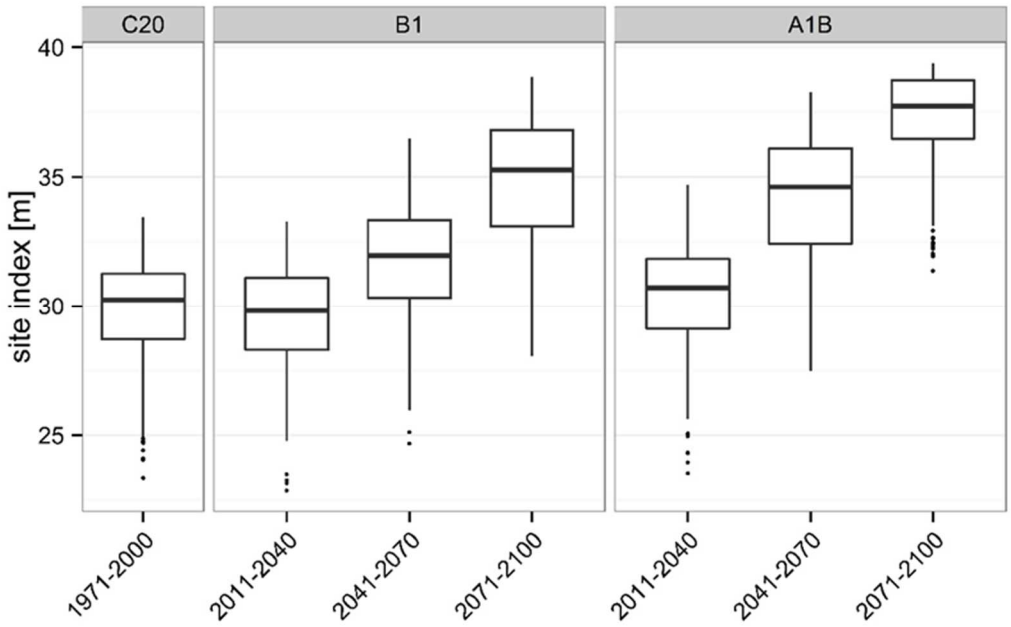


*Fig. 6: Box-Whisker plots (median, 25th and 75th percentile, 1.5 interquartile range, outliers) of the projected site index values applying the site-productivity model from **publication VII** for climate periods of the C20 reference and two climate scenarios B1 and A1B (from **publication IV**).*

Second, the climate effect on forest development can be distinguished when comparing stand characteristics among the two different climate scenarios B1 and A1B (Tab. 3). As the same silvicultural management rules are applied in both simulation runs, the differences in quadratic mean diameter, height of trees with quadratic mean diameter and basal area primarily stem from different climatic conditions.

*Tab. 3: Stand characteristics at the end of 30-year simulation periods for each age class and climate scenario B1 and A1B averaged over all 462 stands. As a reference the values predicted under C20 for the period 1971 to 2000 are listed. Mqd: mean quadratic diameter, Hq: height of tree with mean quadratic diameter, BA: Basal area (from **publication IV**).*

Age class [years]	Climate period [year]	Stems/ha [N]		Mqd [cm]		Hq [m]		BA/ha[m^2]	
		B1	A1B	B1	A1B	B1	A1B	B1	A1B
30 – 60	1971-2000	786		24.5		15.8		34.3	
	2011-2040	795	800	24.5	24.5	15.8	15.8	34.6	34.7
	2041-2070	681	653	27.8	28.5	17.8	18.5	37.3	38.7
	2071-2100	634	636	29.5	30.9	19.6	21.6	41.2	45.9
60 – 90	1971-2000	376		37.8		24.8		41.5	
	2011-2040	375	375	37.8	37.8	24.7	24.7	41.4	41.4
	2041-2070	319	322	39.1	39.0	24.1	24.3	37.1	37.4
	2071-2100	288	284	42.3	42.9	26.0	26.9	38.9	39.9
90 – 120	1971-2000	268		45.1		29.5		42.6	
	2011-2040	269	270	45.1	45.1	29.5	29.5	42.8	42.9
	2041-2070	239	229	45.6	45.7	28.4	28.7	39.2	37.6
	2071-2100	227	234	45.1	45.0	27.0	27.3	36.1	37.2

One potential shortcoming of the concept to simply update the site index values when using *TreeGrOSS* for climate-sensitive projections of forest development is that the basal area increment function is not site-sensitive. Thus, basal area increment is only indirectly influenced by changing climate conditions in the growth model. However, internal analysis proved that the predictor variable crown surface area, depending on the climate-sensitively estimated tree height, sufficiently replicates the climate effect in the basal area increment function (cf. **publication I** for details on the interaction between growth functions for tree height increment and basal area increment).

Publication VII in combination with **publication VIII** and **publication IV** (see also **supplementary publications 8, 10 and 12)** reaches following profound conclusions:

(1) For the first time, German-wide site-sensitive models to predict site index of five major tree species under changing environmental conditions are available.

(2) The nationwide gradients of climatic conditions do not necessarily yield a much better model fit. However, slightly different predictor variables (temperature sum in the growing season instead of mean temperature in the growing season; climatic water balance in the growing season instead of precipitation sum in the growing season) and a wider array of climatic combinations (e.g. wet-cold and wet-warm etc.) result in more stable and biologically feasible partial effects (cf. Fig. 2 to 5 in **publication VIII** and Fig. 1a to 1d in the **supplementary publication 8**).

(3) In combination with the single-tree growth functions of *TreeGrOSS*, the site-productivity models enable climate-sensitive predictions of forest development.

2.2 Silvicultural Management Strategies in Forest Growth Scenarios

Forest growth simulators consist of a second core sector next to the elementary growth functions, i.e. routines to describe and project silvicultural treatments and harvesting (e.g. Alder, 1979; Sterba et al. 1995; Pretzsch, 2001; Hansen and Nagel, 2014). As with forest growth modelling different conceptual approaches to reproduce silvicultural management operations are utilized (Söderbergh and Ledermann, 2003). The simulations of forest development in **publications I, III, IV, V** and **VI** all rely on the growth simulator *WaldPlaner*[1] with a spatial resolution of individual trees (Hansen and Nagel, 2014). Thus, in the following, the focus will be on single-tree thinning and harvesting algorithms.

When modelling silvicultural management operations at tree level, the four characteristics of thinning and harvesting operations need to be considered, i.e. they are normative, intrinsically fuzzy, multi-criterical and spatially explicit (Kahn, 1995a; Daume et al., 1998). The normative character refers to the underlying authoritative guidelines of best practice in forest management. Thinning and harvesting decisions are intrinsically fuzzy as it is an expert valuation rather than a decision based on precise quantitative information. Thinning and harvesting actions are classical multi-criteria decisions since they are influenced by different properties of a tree to be potentially removed and of its surrounding trees' attributes. Finally, on the single-tree level, each thinning and harvesting decision is spatially explicit as only the near vicinity of the respective tree to be removed is relevant. In practice, these four characteristics are simultaneously considered, however, it is crucial to also take them into account in the modelling approach.

Basically, the modelling concepts can be classified into three groups. First, deterministic – or analytical in the nomenclature of Söderbergh and Ledermann (2003) – thinning and harvesting algorithms reflect the underlying theory of the corresponding silvicultural management strategy without fitting a model on observational data. This group can further be divided into result-oriented approaches which identify thinning and harvesting trees directly, i.e. the thinning result is predicted, and decision-driven approaches which project why a tree is chosen for removal, i.e. the thinning process is modelled (Daume and Robertson, 2000). The A-value method by Johann (1988) constitutes a typical example for deterministic result-oriented thinning models as the trees to be removed as competitors of a crop tree are identified based on their diameter at breast height (dbh), the dbh and height of the crop tree, the distance between crop tree and competitor and the A-value defining the thinning intensity. Another demonstrative example of the deterministic result-oriented approach is given in the *WaldPlaner* simulation framework featureing several rule sets to reproduce different normative thinning and harvesting types (Hansen and Nagel, 2014; technical implementation of different silvicultural management scenarios and application within the *WaldPlaner* simulation framework in **publications I, III, IV, V,** and **VI**). The heuristic thinning model *ThiCon* by Daume (1998) serves as an example for deterministic decision-driven approaches as sets of thinning rules describing a forester's way of reasoning when selecting a

[1] *WaldPlaner* is a software solution to simulate forest development for multiple forest stands simultaneously. The growth routines are based on the forest growth library *TreeGrOSS*.

tree for removal are optimized to achieve the defined thinning targets (cf. Albert (2002) and Albert and Guericke (2003) for applications of *ThiCon*). One of the outstanding advantages of the deterministic decision-driven approach is the easily accomplishable reverse transformation of the customized thinning rule set into thinning instructions for practical application in the forest. As the forester's way of reasoning is emulated, the derived instructions will contain most of the relevant information which is especially crucial in the light of potential variation among foresters when marking trees for thinning and even among comparable markings of one forester (Albert, 2006). All deterministic modelling approaches have in common that a distinct thinning and harvesting strategy is projected, be it normative guidelines or customized algorithms to achieve defined silvicultural and management targets.

Second, statistical – or designated as empirical by Söderbergh and Ledermann (2003) – thinning and harvesting models are parameterized based on data from observed thinning operations. Numerous contributions present statistical thinning and harvesting models, e.g. probabilistic formulations by Vanclay (1989), Albert (1999), Ledermann (2002), Pukkala et al. (2015), to name but a few. The explanatory nature of statistical models in contrast to deterministic models becomes obvious when looking at, for example, Vanclay's (1989) approach to model the probability of a tree to be removed applying logistic regression analysis. Depending on species groups, Vanclay identified the tree's dbh, time since last logging in the stand, two factors indicating if the tree's dbh exceeds the cutting and retention limits as explanatory variables and the coefficients express the magnitude of the variables' explanatory power. Thus, when fitting models to observational data, underlying relationships can be explored and the effects of different influencing factors on thinning and harvesting decisions can be quantified.

Third, hybrid approaches consist of a deterministic part, e.g. a thinning rule set, and an empirical part, e.g. observational data being used to specify and refine the rule set. Kahn (1995a), for example, projects thinning decisions by applying a fuzzy logic controller, i.e. tree attributes are passed to a set of thinning rules and an inference engine transforms all information into values of thinning priority. As a combination of statistical and deterministic elements, hybrid models have one primary advantage, i.e. in comparison to purely statistical formulations they offer a higher flexibility to integrate deviations in management strategies by modifying the thinning rules based on data input (cf. Weiskittel et al., 2011, p.253).

The overall goal of simulation studies is to project forest development within certain environmental, economic and social barriers (Pretzsch, 2001, p.85). However, the purpose of the pursued forest development simulation strongly affects the choice of the thinning and harvesting model. Different model philosophies serve different aims such as implementation of silvicultural guidelines in forest management practice via decision support (e.g. Battles et al., 2007), timber supply assessments to estimate the short- to medium-term availability of merchantable wood under different management scenarios (e.g. Rüther et al., 2007), long-term impact studies under changing framework conditions such as climate change, globalization or shifts in land use (e.g. Braun et al., 2016; Jandl et al., 2018; **publications I, III, IV, V** and **VI** as well as **supplementary publications 1, 2, 4** and **5)**, and optimization studies striving to identify the best management strategy (e.g. Nuutinen et al., 2006; Buongiorno and Zhou, 2015; Pukkala, 2015, 2018).

The **publications I, III, IV, V** and **VI** all constitute impact studies applying different silvicultural management scenarios within forest growth simulations in the context of climate change. The task in **publication VI** (cf. also **supplementary publication 1**) is to construct contrasting scenarios to cover a broad range of silvicultural management paths (these scenarios are also used either as an ensemble of three or as a standalone application in **publications I, III** and **V** and **supplementary publications 1, 2** and **5**). The different management strategies then are further applied to project forest development in four case study regions, Diepholz, Uelzen, Fläming and Oder-Spree, in the north German lowlands. It is hypothesized that, based on the current state of forests in a region, only widely varying management scenarios generate differences in forest structures strong enough, in the long run, to facilitate impact analyses of a changing climate conditional on forest management (cf. Lindner, 2000). The forest growth simulation framework *WaldPlaner* provides multiple rule sets to project different silvicultural management regimes. Next to the actual formulation of management regimes it is an ambitious assignment to technically transfer the defined characteristics of the management strategies into the *WaldPlaner* system. However, various variables allow for flexible adjustments of the rule sets. Furthermore, it is possible to differentiate stand treatment within one management scenario by defining treatment groups and assigning each stand to a certain group (cf. Hansen and Nagel, 2014, p.93). Thus, on a regional basis, not every stand is treated the same. Table 4 gives an overview of the characteristics of the defined three silvicultural management strategies.

*Tab. 4: Characteristics of selected control variables defining the three silvicultural management strategies reference, biodiversity and climate protection and the according nature conservation rule set (from **publication VI**).*

	Control variable	**Reference (baseline)**	**Biodiversity**	**Climate protection**
Nature Conservation:	*unmanaged area*	status quo	5 % of forest area	status quo
	area under flora-fauna-habitat (FFH) directive	45 % of the FFH-area as natural habitat type	100 % of the FFH-area as natural habitat type	45 % of the FFH-area as natural habitat type
	deadwood (m³/ha)	20	40	20
	habitat tress (N/ha)	3	10	3
Species conversion:	*selection of future stand type*	dominating deciduous species	tree species of potential natural vegetation (pnv)	dominating conifer species
Thinning:	*thinning intensity*	variable over time: high, moderate, low	moderate	variable over time: high, moderate, low
	thinning type	thinning from above	thinning from above	thinning from above
	start of thinning (defined by stand height)	12 – 16 m	12 – 16 m	11 - 15 m
	limit of thinned volume per cut (m³/ha)	max 70 (Douglas-fir max 100)	max 50 (Douglas-fir max 100)	max 70 (Douglas-fir max 100)
Harvest:	*target diameter (cm)*	oak 70, beech 60, spruce 45, pine 45, Douglas-fir 70	all species + 5 cm, in FFH-areas +10 cm except spruce -5 cm, Douglas-fir -10 cm	all species -5 cm
	limit of harvested volume per cut (m³/ha)	max 100 (Douglas-fir max 120)	max 70 (max 100 for all species not included in pnv)	max 100 (Douglas-fir max 120)

In **publication V** and **VI**, we apply three contrasting management scenarios, i.e. a reference scenario reproducing today's close-to-nature silvicultural practices in Germany (baseline), a biodiversity path aiming at increasing the area of potential natural vegetation, and a climate protection scenario with the goal to maximize CO_2 sequestration in standing volume and wood products. As evident from Table 4, the silvicultural management formulations go well beyond prescriptions of thinnings and harvesting alone. Multiple criteria also characterize nature conservation aspects and species conversion. The technical implementation of the control variable *area under flora-fauna-habitat (FFH) directive*, for example, required an extensive beforehand spatial analysis of the forest- and the FFH-layer to deduce the future nature conservation state of each single forest stand within each of the four case study regions. Equally important is the assignment of future forest stand types conditional on the current stand type as well as site characteristics according to the specification in each management scenario (details on the assignments are given in the supplementary information in **publication V**; see also **publication II**).

Looking, for example, at the development of standing volume (Fig. 7) and prescribed yield index (Fig. 8) the results prove the high variability between the management scenarios as well as significant effects arising from different underlying climate scenarios. Regarding the

climate scenarios, **publications I, II, III, V** and **VI** all apply three climate scenarios based on *RCP 8.5* (Moss et al., 2010; van Vuuren et al., 2011). The three projections are calculated using the global circulation models *INM-CM4* (Volodin et al., 2010), *ECHAM6* (Stevens et al., 2013) and *ACCESS1.0* (Bi et al., 2013). The regional climate model *STARS* (Orlowsky et al., 2008) further downscales the realizations of the global circulation models to Germany. In the period 2051 to 2070, the projected temperature based on *INM-CM4* shows a 1.1°C deviation from today's (1991 to 2010) mean annual temperature for the north German lowlands. *ECHAM6* exhibits a 1.6°C deviation and *ACCESS1.0* 2.7°C. Therefore, these three climate scenarios are labelled minimum, median and maximum climate run.

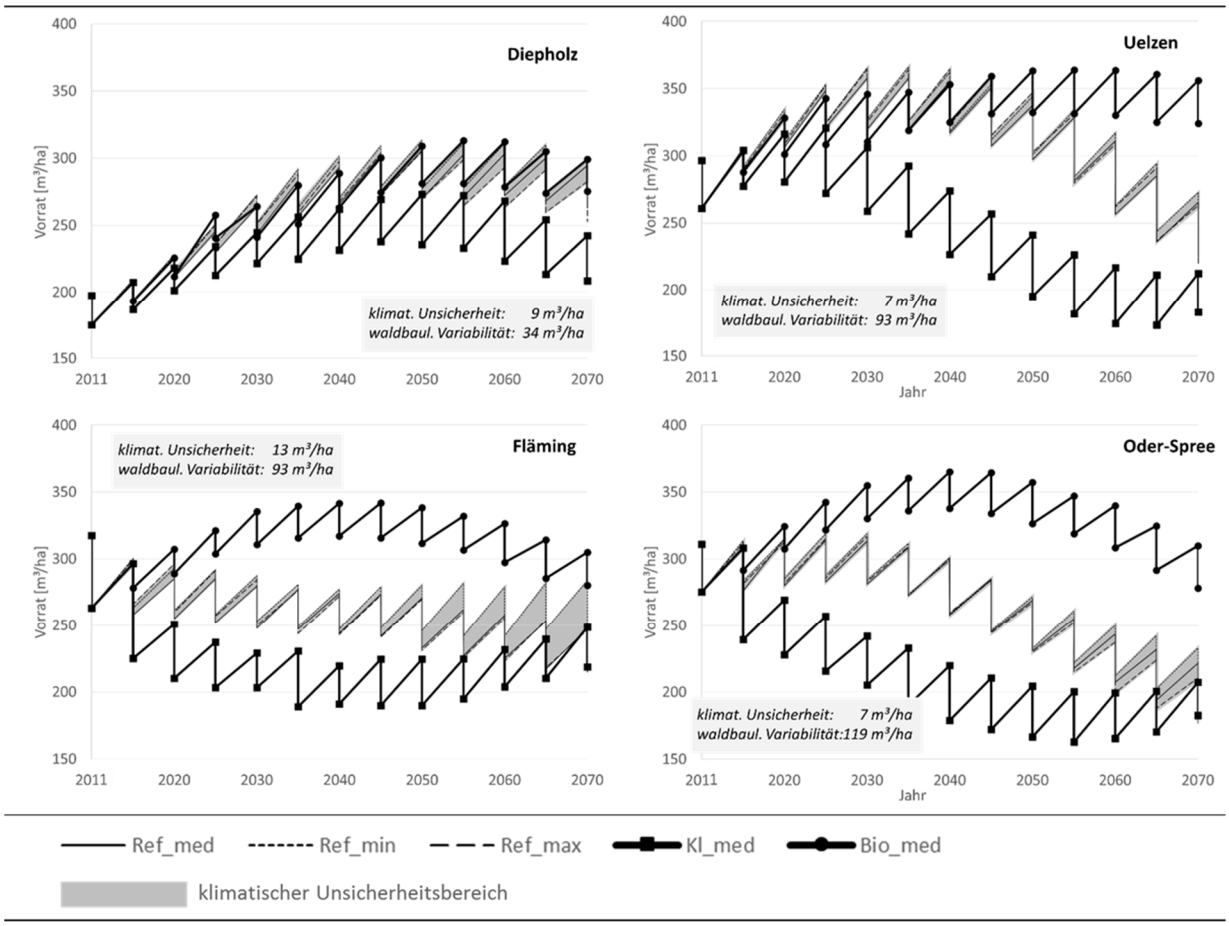


*Fig. 7: Development of standing volume and removed volume in the four case study regions under three silvicultural management scenarios (reference=Ref, biodiversity=Bio, climate protection=Kl) with Bio and Kl projected under median climate run (med) and Ref projected under minimum (min), median (med) and maximum climate run (max) (from **publication V**).*

The mean variability in standing volume (designated as *waldbauliche Variabilität* in Fig. 7)[2] in the projection period 2011 to 2070 between the contrasting management scenarios varies from 34 m³/ha up to 119 m³/ha, depending on region. Furthermore, the mean range of climatic uncertainty lies between 7 m³/ha and 13 m³/ha (designated as *klimatische Unsicherheit* in Fig. 7).

[2] For a detailed derivation of the climate uncertainty value and the management variation value please refer to **publication V**.

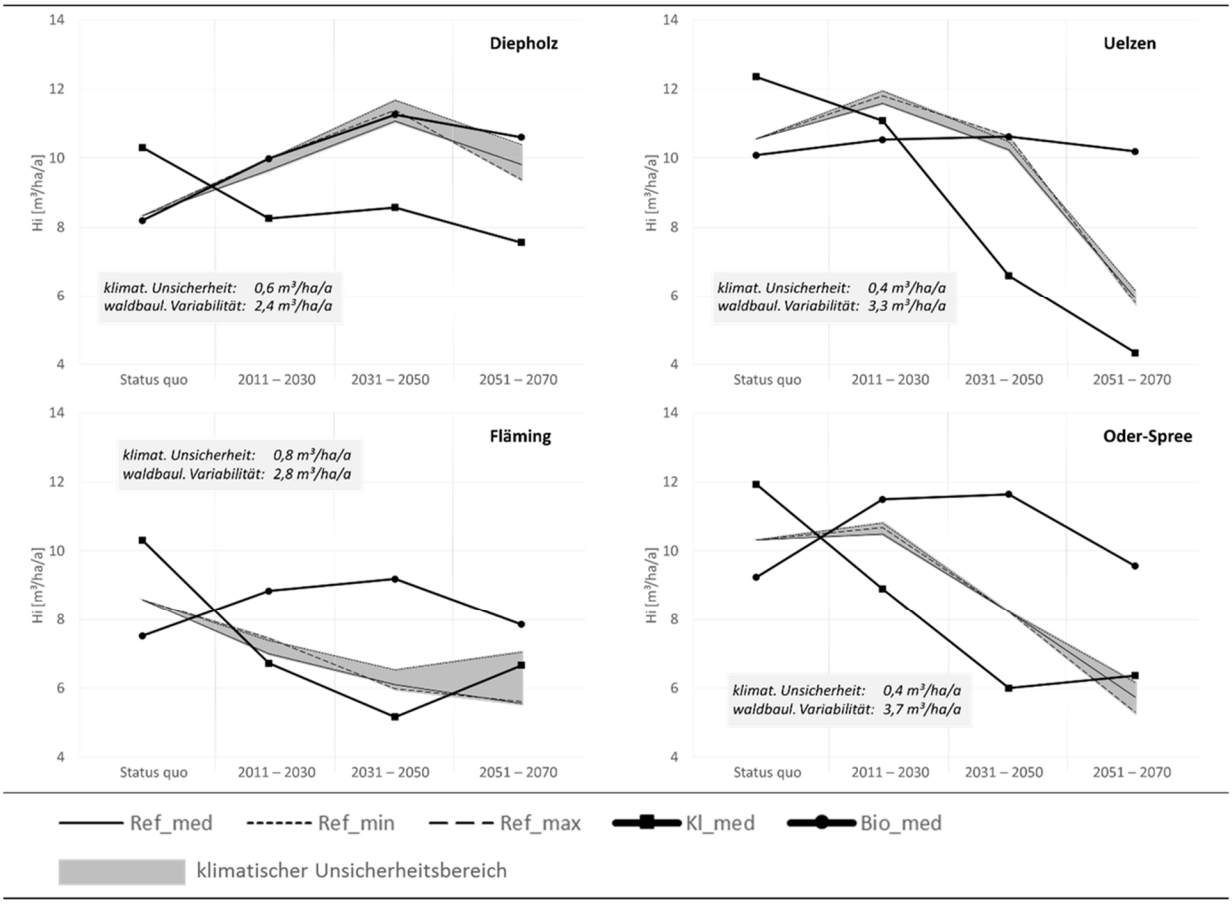


*Fig. 8: Mean values of prescribed yield index by Gehrhardt (1923) for 20-year periods in the four case study regions under three silvicultural management scenarios (reference=Ref, biodiversity=Bio, climate protection=Kl) with Bio and Kl projected under median climate run (med) and Ref projected under minimum (min), median (med) and maximum climate run (max) (from **publication V**).*

The mean variability of the prescribed yield index values due to the different management scenarios is in the range between 2.4 m³/ha/a and 3.7 m³/ha/a (Fig. 8). It emphasizes the contrasting character of the scenario formulations. The climatic variability of mean values up to 0.8 m³/ha/a underlines that the choice of silvicultural management regimes may have a stronger effect than climatic conditions.

Unlike the request for a broad range of potential silvicultural management paths in **publications V** and **VI**, it is sufficient in **publication IV** to apply the standard crop tree selection in combination with selective thinning and subsequent harvesting by target diameter as the unique management strategy for all stands in the study region Arnsberg since it is the primary goal to demonstrate the coupled model system's ability to provide decision support for forest planning under climate change. As in **publications V** and **VI** the management routines are taken from the *TreeGrOSS* system (Nagel, 2011).

At this point, Vanclay's (2014) words of caution shall be mentioned as he advises modellers to be aware of and to reveal the underlying assumptions, to consider alternative modelling approaches and to conduct sensitivity tests to inform decisions. Likewise, Pukkala

et al. (2014) investigate how simplifications or restrictions in the model approach might affect the simulation results. These statements apply to forest growth modelling and replicating silvicultural management regimes alike. As a consequence, limitations of the applied growth model and assumptions on simulation settings are given in all **publications** in detail. Extensive analyses on the models' sensitivity, especially concerning changes in climate, are given in **supplementary publications 5, 8** and **10**.

In summary, **publications IV, V** and **VI** (see also **supplementary publications 1, 2** and **5**) reach the following conclusions regarding the implementation of silvicultural management scenarios in forest growth simulations:

(1) In impact studies, contrasting silvicultural management scenarios are highly suitable to define a decision space with quantified effects on forest dynamics. On that basis, it is possible to assess risks and uncertainties under climate change conditional on forest management regime.

(2) Forest management and planning is always customized to local conditions and landowners' goals. Therefore, actual management plans to the entire forest land of a region will be based on a mixture of the simulated silvicultural management paths. Thus, the simulation results help in the decision process to identify the best mixture of forest management strategies.

(3) In the presented case studies, the variability in forest growth and forest planning parameters due to different silvicultural management regimes significantly exceeds the climatic uncertainty in the simulation results introduced by different climate scenarios. Thus, concluding from the simulation results silvicultural measures are capable to control forest development to a much stronger degree than changing climatic conditions refraining from any tree or forest losses due to risk factors.

3. Concepts in Decision Support for Forest Planning

While the descriptive approach in decision theory mimics humans' actual, and occasionally irrational way of decision making, it is the basis of the prescriptive decision theory to analyze decision problems rationally and provide superior solutions (Dörsam, 2003, p.7). The prescriptive decision theory distinguishes between decision problems under certainty, decision problems under uncertainty in the narrower sense, and decision problems in situations involving risks (Laux, 2002). Decisions under certainty require complete availability of all necessary information. This ideal state can be excluded in association with forest management and forest planning problems. For decisions under uncertainty in the narrower sense, the outcome of alternative actions can be specified. However, it is not possible to assign probabilities to the outcomes (Laux, 2002, p.106). This case is especially apparent when dealing with projections of environmental conditions under climate change. Climate scenarios cannot be assigned any specific probability of occurrence since a considerable amount of uncertainty is left due to the lack of any knowledge that originates from the long time scales and complexity, termed deep uncertainty (Walker et al. 2003; Kandlikar et al. 2005). Finally, Laux (2002, p.121 ff) specifies decision problems involving risks as situations, where the decision maker has a specific perception of the probabilities assigned to certain outcomes. In impact studies on forest development under climate change, as presented in **publications I** to **VI**, the decision problem comprises uncertainty evoked by climate scenarios as well as risk assessments. Thus, further on in **publications I** to **VI**, decision support is always derived under the assumption of intrinsic uncertainty without assigning any specific probability of occurrence.

In forest planning, elements in the process of decision making are defining management goals and preferences on certain attributes, forest data acquisition, generating alternative forest management regimes, obtaining information on the consequences of these alternatives and, finally, the evaluation of the alternatives (Kangas et al. 2008, p.5). In the context of data acquisition from National Forest Inventories, Arnold et al. (2014) discuss how to improve the provisioning of forest inventory data explicitly tailored to the needs of decision makers. Keeney (1992, p.198 ff) assigns the highest importance in decision making to the process of formulating alternatives as it predetermines the search space for a solution to the planning problem. **Publications V** and **VI** cover the step of generating alternative forest management scenarios (cf. chapter 2.2).

At the beginning of a broader use of decision support systems in forest management in the 1980s, the applications dealt with small, well-defined problems, i.e. forest pest management, silvicultural prescriptions, and timber harvesting (Reynolds, 2005). However, the challenges grew with time as holistic solutions to forest ecosystem planning are sought. Among others, Rauscher (1999), Muys et al. (2010) and Segura et al. (2014) provide a comprehensive overview of different models and methods in the context of decision support for forest planning. Muys et al. (2010) claim that forest management increasingly relies on simulations of forest development. This requires accepted and realistic model validation and verification methods based on empirical data. Muys et al. (2010) also provide a descriptive

presentation of the connections between models, simulation tools and decision support systems, which is shown in a modified version in Figure 9.

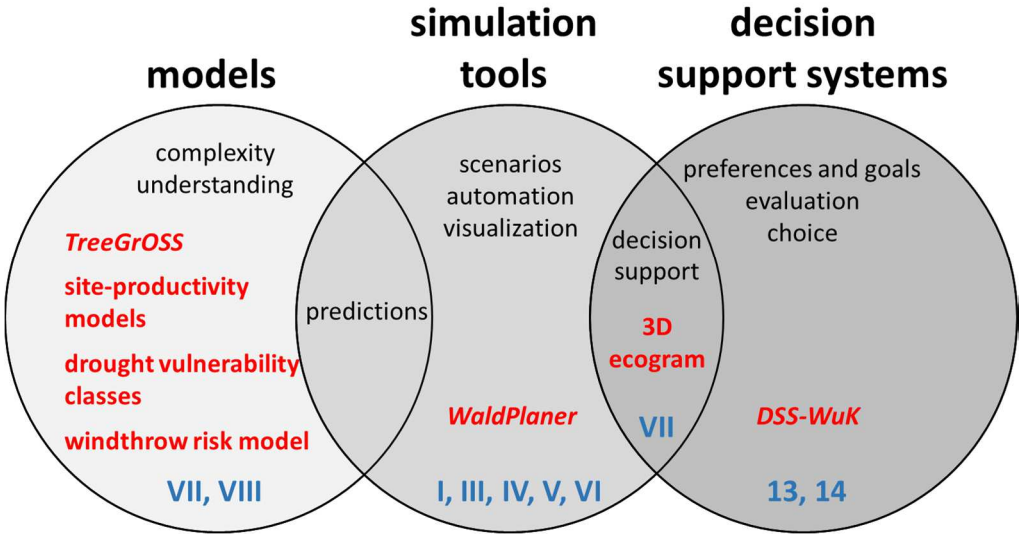


*Fig. 9: Connections between models, simulation tools and decision support systems with their main features; in red: models and tools applied/developed in the course of the habilitation; in blue: corresponding **publications** (modified from Muys et al., 2010).*

Figure 9 illustrates the basic features of models, simulation tools and decision support systems and it points out the models and tools which are applied or developed in the course of the habilitation, including the corresponding **publications**. Models for forest management express the complexity of the real world by fundamental relationships. They foster the understanding of these relationships but do not address any problem solving. The forest growth library *TreeGrOSS* by Nagel (2011) and the site-productivity models of **publications VII** and **VIII** are typical examples for models to assist forest planning by providing predictions. Elements of simulation tools incorporate scenario predictions, automation to a greater or lesser extent and, in most instances, visualization. On this basis, decision support is given, for example, by applying the newly developed three-dimensional (3D) ecograms (**publication VII** and **supplementary publications 7** and **9**). In order to evaluate alternative scenarios and to ultimately choose the best scenario for implementation, information on the decision maker's goals and preferences is needed. Alternatives, goals and preferences as well as the concluding choice define a complete decision support system. **Supplementary publications 13** and **14** present a decision support system for multifunctional forest management on landscape level.

The scope of the habilitation thesis concerning decision support for forest planning encompasses the formulation and technical implementation of alternative forest management regimes (**publication V** and **VI**), the quantification of effects of management scenarios on different indicators (**publication V** and **VI**), the assessment of risks and the quantification of uncertainty (**publications I** to **VI**), the derivation of decision support in the form of adaptation recommendations (**publications I** to **VI**) and the introduction of a new decision support tool (**publication VII**).

3.1 Impact Analysis on Risks and Uncertainties

Generally, simulation studies evaluate future developments under differing framework conditions (Clark et al., 2001). In forest management and planning, simulation studies provide information beyond measurements from forest inventories, observational studies and field experiments. However, simulation studies on possible future forest developments and measurement data from different sources with a retrospective view may complement each other, especially for forest planning issues involving risks and uncertainty (Zhao et al., 2014; Kleinn, 2017).

Forest management decisions are based on expectations of future developments. The foundation for sound decisions are accurate predictions of the expected values. However, forestry has always faced inherent risks and uncertainties, even more today as climate change induces shifts in forest growth potential as well as increasing current and emerging new abiotic and biotic risks (cf. Lindner et al., 2010; Seidl et al., 2011). Thus, simulations on forest development either have to incorporate feedback effects of risks and uncertainties (e.g. Boychuk and Martell, 1996; Buongiorno and Zhou, 2015) or a comprehensive vulnerability analyses and uncertainty assessments have to complement the prediction of forest development afterwards refraining from feedback effects (e.g. Overbeck et al., 2012; Thiele and Nuske, 2016; **publications I, III, IV, V** and **VI**).

Analogous to the classification of thinning and harvesting models, the different risk model approaches can be divided into deterministic methods, e.g. drought vulnerability classes (Spellmann et al., 2007) and the wind risk and snow damage model by Peltola et al. (1999), and statistical formulations, e.g. the wind damage risk model by Schmidt et al. (2010) and the bark beetle infestation risk model by Overbeck and Schmidt (2012). Although a wide variety of single risk models for forest ecosystems exist (cf. Hanewinkel et al. (2011) for a first overview), the disturbance dynamics in response to climate change are still not fully understood (Seidl et al., 2017).

The impact analyses in **publications I** through **VI** all focus on selected risk factors, thus being far from a comprehensive vulnerability analysis. However, as drought risk is seen as one major risk factor under climate change for forestry in the north German lowlands (Spellmann et al., 2007; Kätzel and Höppner, 2011; **supplementary publications 1, 2, 3, 4** and **7**), the implications arising from dryer conditions for forest management and planning serve as a prominent example in risk analysis in **publications I, II, V** and **VI**. In addition, the hazard of wind damage is studied in **publication VI**. The climate uncertainty as another crucial factor in deriving adaptation measures and in providing decision support is of outstanding importance in the impact analyses of **publications I, II, V** and **VI**.

The major goal in **publication I** is to quantify the effect of persistent dryer climates on future forest productivity. The research hypothesis asks for a simulation method to assess the long-term effect of reduced future water availability on forest growth. The approach is straight forward as we apply the simulation framework *WaldPlaner* and project forest development under constant climate conditions (baseline) and three climate scenarios in two regions in the

north German lowlands until 2070. As indicators for a climatic effect we compare mean single-tree volume increment, periodic volume increment and mean annual increment at biological rotation age (MAI_{max}) under constant climate and climate scenarios. Representative for the entire analysis, Figure 10 presents the results for MAI_{max}.

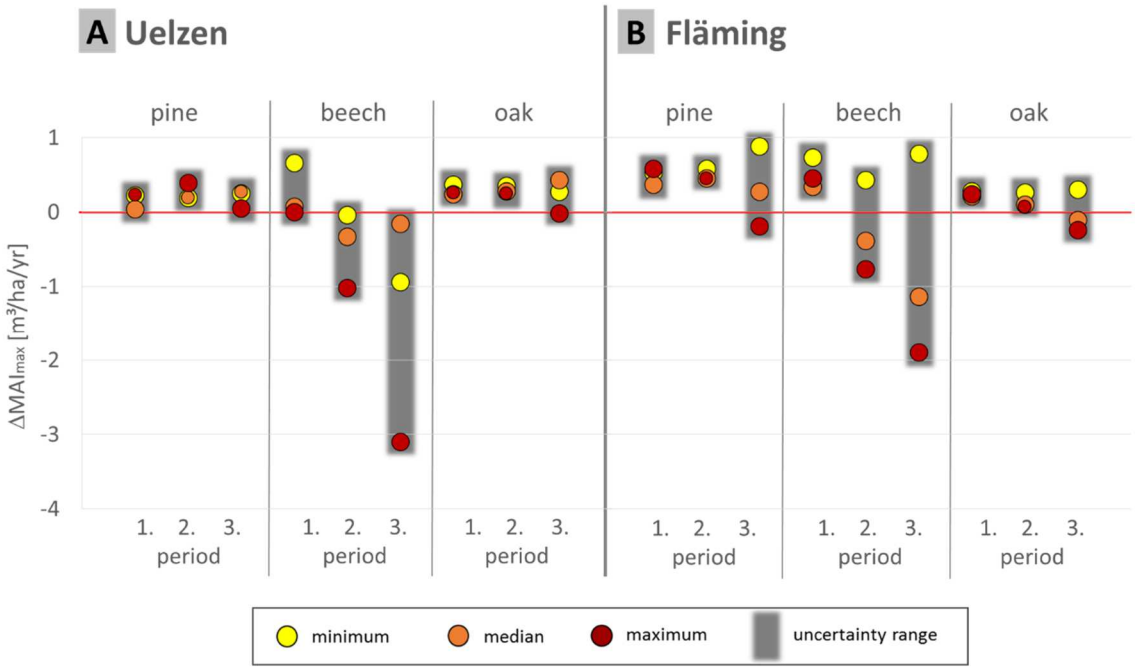


*Fig. 10: Deviation in mean annual increment at biological rotation age (MAI_{max}) between three climate scenarios (minimum, median and maximum) and the baseline scenario for Scots pine, European beech and oak for ages 81 and older in Uelzen (A) and Fläming (B) in the first (2011-2030), second (2031-2050) and third (2051-2070) projection period (from **publication I**).*

As background information, it is important to know that a significant temporal trend exists with decreasing water availability and, additionally, there is a significant projected decrease in water availability from minimum to median and maximum climate scenario. Figure 10 illustrates how persistent dryer climates affect MAI_{max} of Scots pine, European beech and oak differently. Furthermore, the uncertainty range due to different climate scenarios increases with time, most obvious for European beech. Also, regional differences are noticeable, especially in the third projection period, e.g. deviations in MAI_{max} for beech are negative under each climate scenario in Uelzen while in Fläming under minimum climate scenario positive deviations are projected.

Publication I yields four core conclusions:

(1) Growth simulations are an adequate method to quantify the effect of future persistent dryer climates on forest productivity for forest planning issues. A reliable, site-sensitive growth model is an imperative prerequisite.

(2) The presented method to assess the long-term effect of climate change on forest productivity is ideal to complement the expert-knowledge based drought vulnerability

assessment which is applied in forest planning in northwestern Germany today (cf. Spellmann et al., 2007; **supplementary publication 3**).

(3) The reliability of the results can be judged based on the reported uncertainty ranges. Robust decisions are possible, when all results are unidirectional, i.e. displaying all positive or all negative deviations in MAI_{max} under each climate scenario. For a deeper examination on how robust a decision is to adapt to climate change, comprehensive sensitivity analyses should be applied (Dessai and Hulme, 2007; Yousefpour et al., 2017; Radke et al., 2017).

(4) Based on the simulation results profound and differentiated recommendations on adaptation measures can be given for different species and regions.

In contrast to **publication I**, which quantifies the effect of drought vulnerability on forest productivity directly, **publications III, V** and **VI** incorporate retrospective vulnerability analyses after projecting forest development climate-sensitively. The principal objective of **publication III** is the analysis of the interaction between different silvicultural management strategies and nitrate concentration in seepage water. Concerning forest management, it is hypothesized that different silvicultural management strategies will have a considerable effect on nitrate leaching from forests since tree biomass is one important ecosystem compartment that retains large amounts of nitrogen.

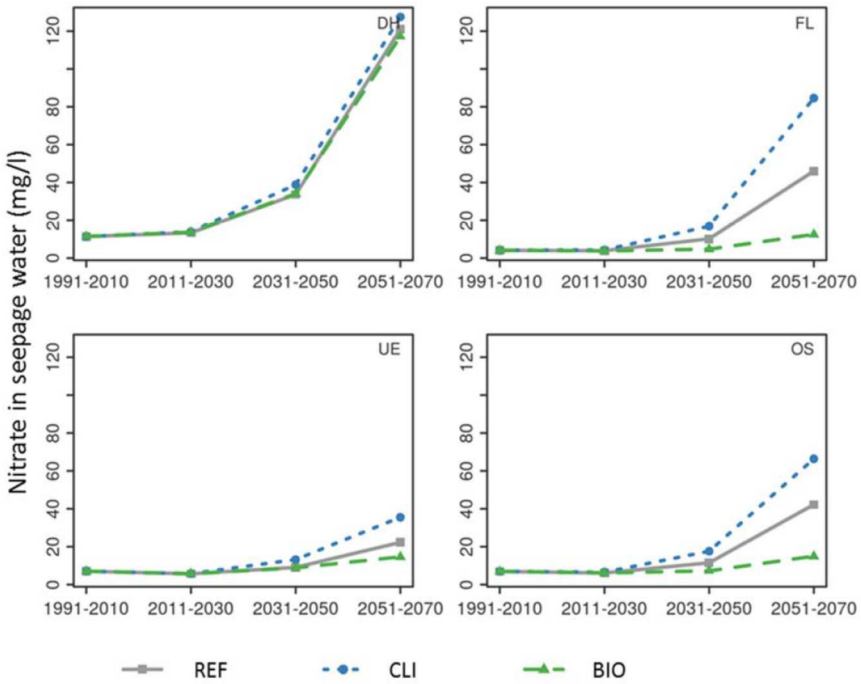


*Fig. 11: Simulated development of nitrate in seepage water in four model regions Diepholz (DH), Uelzen (UE), Fläming (FL) and Oder-Spree (OS) under three silvicultural management scenarios reference (REF), climate protection (CLI) and biodiversity (BIO) applying the median climate scenario for the period 1991 to 2070 (from **publication III**).*

Figure 11 shows how nitrate concentration in seepage water increases with time, presumably due to mineralization of organic bound soil nitrogen under rising temperatures. Distinct differences are apparent for the three silvicultural management strategies in Uelzen, Fläming

and Oder-Spree at the end of the projection period. In Diepholz, however, differences between the management options are less pronounced, because nitrate here is mainly mobilized from the predominant organic soils, where silviculture has only a minor effect on nutrient uptake. The effect of forest management on nitrate concentration in seepage water can be attributed to a large part directly to the uptake of nitrogen from soil to standing biomass. Therefore, the lowest nitrate concentration is projected under the biodiversity strategy which strongly accumulates biomass until 2070. On the other hand, high harvest volumes under the climate protection path result in low standing volume during the projection period and, hence, high nitrate concentration in seepage water. Thus, forest management can actively regulate nitrate leaching.

The primary goal of **publication V** focusing on risk assessment is the vulnerability analysis for drought risk under different management regimes and climate change scenarios. In contrast to **publication III**, it is hypothesized that the silvicultural management strategy only plays a minor role in the assessment of drought risk in comparison to the expectedly strong effect of climate scenarios during the projection period until 2070. In **publication V**, the drought vulnerability analysis relies on the method of drought vulnerability classes based on site water budget formulated by Spellmann et al. (2007) with updated threshold values.

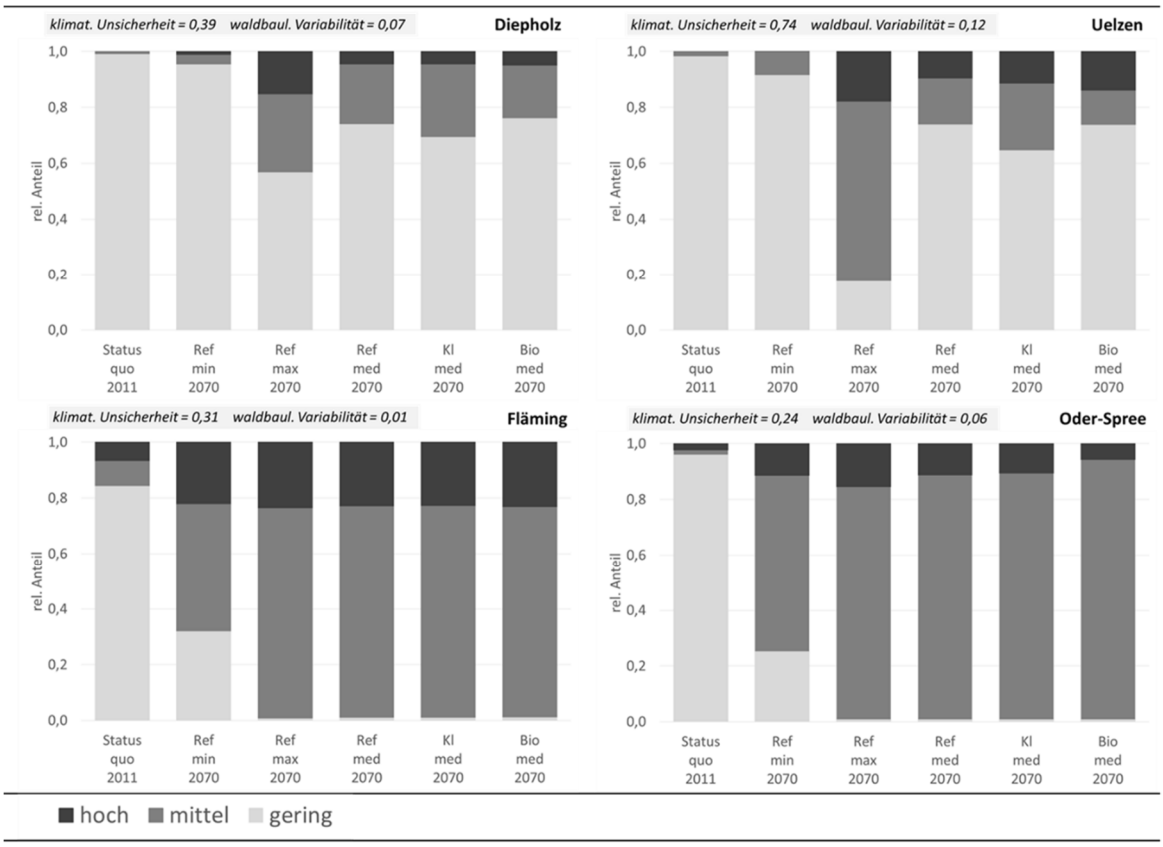


*Fig. 12: Area proportions of all species combined in the drought vulnerability classes low (light gray), medium (gray) and high (dark gray) at status quo and in 2070 under three silvicultural management strategies (reference=Ref, biodiversity=Bio, climate protection=Kl) with Bio and Kl projected under median climate scenario (med) and Ref projected under minimum (min), median (med) and maximum climate scenario (max) (from **publication V**).*

The drought vulnerability assessment shows a drastically increasing risk for all study regions, comparing the conditions for today and in 2070 (Fig. 12). The mean climate uncertainty in area proportions in the drought vulnerability classes between the climate scenarios min, med and max (designated as *klimatische Unsicherheit* in Fig. 12) under the reference management strategy ranges from 0.24 in Oder-Spree to 0.74 in Uelzen[3]. On the other hand, the mean variation between the contrasting management scenarios (designated as *waldbauliche Variabilität* in Fig. 12) varies from 0.01 up to 0.12 depending on region. Thus, the uncertainty in climate change strongly affects the drought vulnerability assessment, while different silvicultural management strategies have a rather minor impact. This is due to the long period of time it takes converting existing stands to stands made up of more drought tolerant species. In the long run, however, the slowly progressing forest conversion could substantially affect the regional drought risk assessment.

The risk assessment in **publication VI** deals with vulnerability to windthrow, depending on different management regimes under climate change. As the windthrow risk in a region is mainly driven by the current species composition and stand heights, it is hypothesized that different silvicultural management strategies and accompanying concepts for species conversion will have a significant effect on mean regional windthrow risk only in the long run. In order to project windthrow risk in the four study regions until 2070, we apply the binary additive regression model with explicit spatial component by Schmidt et al. (2010).

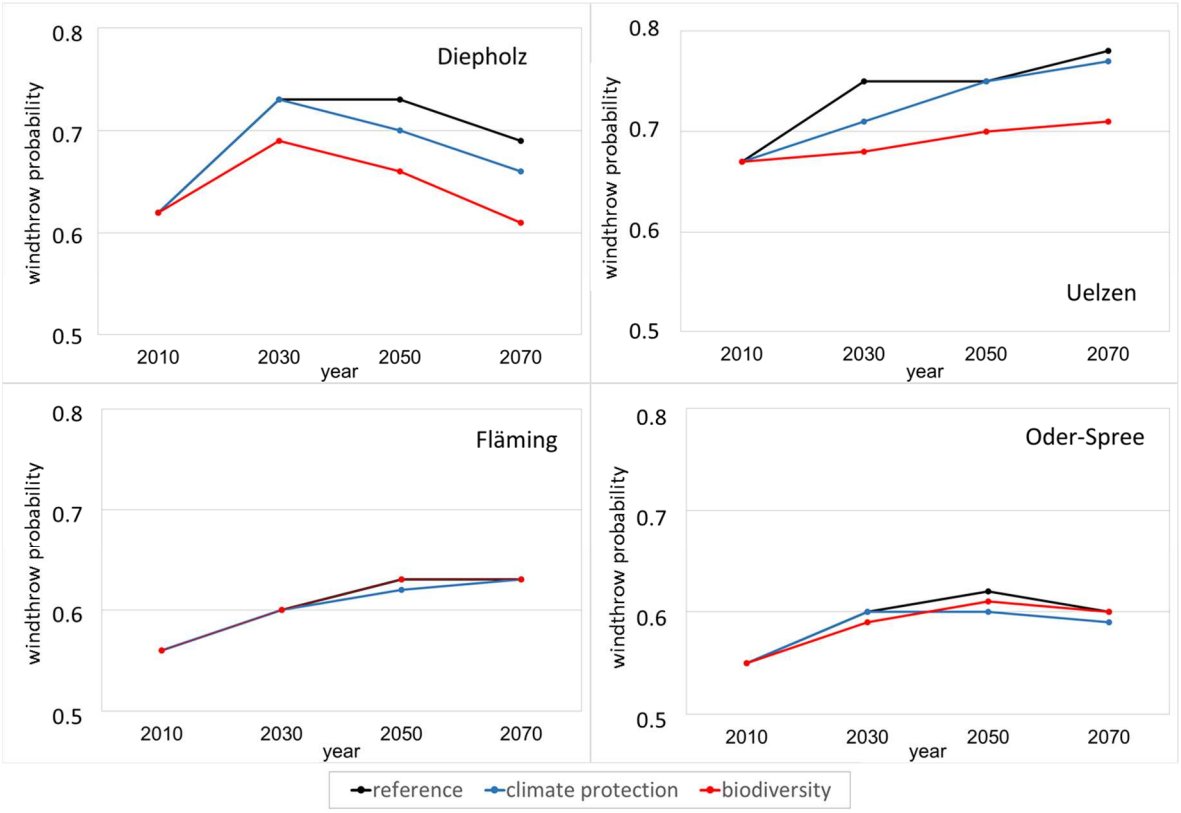


*Fig. 13: Mean volume-weighted windthrow probability over time in four regions under three silvicultural management scenarios (black: reference, blue: climate protection, red: biodiversity) applying the median climate scenario (from **publication VI**).*

[3] For a detailed derivation of the climate uncertainty value and the management variation value please refer to **publication V**.

Figure 13 displays regional differences in mean windthrow probability as well as a temporal trend with different manifestations, depending on region. A considerable differentiation of mean windthrow probability between silvicultural management scenarios is only apparent for Diepholz and Uelzen. The regional differences are best explained by species distribution and age structure. Generally speaking, the level of windthrow probability is much lower in Fläming and Oder-Spree compared to Diepholz and Uelzen since these two regions are dominated by Scots pine which is considered more storm-resistent than Norway spruce or Douglas-fir (e.g. Peltola et al., 1999; Bredemeier et al., 2001; Schmidt et al., 2010). The differences between management scenarios in Diepholz and Uelzen are primarily caused by species conversion, i.e. under the reference strategy the introduction of Douglas-fir and even more under the climate protection path. Further analysis reveals each species' contribution to the overall windthrow probability (cf. **publication VI,** Fig. 7).

An example of an extensive risk analysis involving multiple risk factors such as windthrow, fire, water shortage and insect feeding damage is given in **supplementary publication 2**.

Publications III, V and **VI** attain following key conclusions concerning risk and uncertainty analysis:

(1) In order to provide decision support, simulation studies on forest development have to be unequivocally accompanied by a subsequent analysis of potential risk factors as well as an uncertainty analysis concerning the variability between climate scenarios.

(2) Risk analysis is strongly affected by climatic uncertainty and silvicultural management variability. In the presented impact studies, different management strategies dominate the variability in growth and yield parameters. On the other hand, climatic uncertainty mostly controls the variability in drought risk analysis.

(3) As climatic uncertainty might have a significant impact on different risk factors, forest management needs to plan responsibly and forest conversion must not be in stereotypes but rather incorporate small-scale differences in site. Notably, the simulation results are estimates of mean expectation values based on, for example, aggregated site variables. However, the target variable follows a distribution around the mean. Moreover, small-scale differences like location on slope add to the natural variability in the target variable. This variability needs to be accounted for in operational forest planning.

3.2 Silvicultural Adaptation Strategies

Adaptation to climate change in general embraces all measures in favor of a vulnerable system threatened by current or expected climate effects (Füssel and Klein, 2006). Adaptation strives to reduce the risks or to take advantage of the opportunities. As key characteristics of adaptation, Füssel and Klein (2006) list a relatively short lead time until the measures succeed, the flexible adjustment to local or regional circumstances, and frequent provision of ancillary benefits. However, the accuracy of regional climate projections and the precision of the impact analysis strongly determines the effectiveness of proactive adaptation measures. Furthermore, it is difficult to evaluate the effectiveness because often the standard of comparison, i.e. a reference system without adaptation measures, is missing. Nonetheless, it has to be the purpose of rational adaptation planning to maximize the difference between the impacts under reactive adaptation in answer to climate changes only (or even impacts under no adaptation at all) and impacts through proactive adaptation using all available information (cf. Füssel and Klein, 2006, Fig. 2). Smith (1997) further demands for adaptions measures enough flexibility to significantly diminish the impacts or to empower a system to recover under a wide variety of climate situations. In addition, the anticipated benefits of adaptation measures have to exceed the costs (Yousefpour et al., 2017). In the classification scheme of Yousefpour et al. (2017), reactive adaptation measures are the least cost intensive, followed by proactive adaptation measures and robust adaptation being the most cost intensive. In conclusion on the above points, there is a strong need for proactive or robust adaptation measures, if climate-sensitive risks are urgent, if future impacts are deemed catastrophic or irreversible, or, if the measures require a long preparatory time (e.g. Smith, 1997; Füssel, 2007). On the other hand, decision makers can refrain from immediate adaptation measures, if timely effective response options are always at hand under any climate change scenario, or if anticipated future risks are tolerable.

In the forestry domain, adaptation measures to encounter climate change can be grouped into societal adaptation, adaptation of the forest and adaptation to the forest, according to Spittlehouse (2005). Societal adaptation focusses on people's attitudes and expectations on forest services and adjustments in forest policy on forest management regulations. Adaptation of the forest encompasses all measures to enhance the resistance and resilience of future stockings, e.g. species selection. And in adaptation to the forest, the measures center around empowering the current stocking against climate change impacts, e.g. adjusting the thinning regime to mitigate drought stress (Sohn et al., 2013; 2016). In a different approach, Bolte et al. (2009) classify adaptation measures from the forest management perspective into three strategies, i.e. conservation of forest structures, active adaptation, and passive adaptation. While conservation of forest structures strives to achieve the previously defined management goals, active adaptation applies silvicultural methods to enable current or future forest structures to better cope with climate change even if management goals need to be revised. Passive adaptation deliberately makes use of nature's own reactions to climate change, e.g. natural succession and species migration are incorporated in the management concept. In any case, the right choice of adaptation measures demands a thorough knowledge of the effects of climate on forests (Keenan, 2015). The following key questions need to be answered backed by the understanding of forest

ecosystems' functionalities: (1) Which adaptation measures effectively contain which risks? (2) Are adaptation measures feasible and crucial for the current stocking? (3) Which adaptation measures are needed for future stockings?

Common adaptation measures applied to current stockings include operational actions such as adjustments in silvicultural treatments and harvesting targets, advanced regeneration, and reduction of secondary risk factors, e.g. pest control, wildfire prevention, reduction of excessive hoofed game populations (e.g. Brang et al., 2008; Kätzel and Höppner, 2011; Bolte et al., 2011; **supplementary publications 1, 3, 4, 7,** and **11**). Strategic adaptation measures for future forest generations comprise species selection in combination with adjustments in target growing stock and the applied silvicultural and regeneration system, a comprehensive risk management, soil management, increasing genetic diversity, and enhancing multi land use water management.

3.2.1 Deriving Adaptation Measures for Forest Regions

A set of feasible adaptation measures can be derived based on forest development simulations and accompanying risk and uncertainty analyses (e.g. Clark et al., 2001; Overbeck et al., 2012; Lafond et al., 2014; Yousefpour et al., 2017). Moreover, adaptation measures can be customized based on diverging effects of different silvicultural management strategies. It is important to differentiate between three spatial scales when communicating adaptation measures (cf. Bolte et al., 2009, Fig. 1): (1) The rather general trans-regional recommendations on adaptation measures, e.g. for forest policy and for forest management concepts of state forest enterprises or large private forest companies. (2) The regional adaptation measures taking the specific current stockings and site conditions as well as regional management goals into account. However, conclusions drawn on this spatial scale relate to aggregated information like stand types, species proportions and age class distributions. Thus, on this scale the recommendations need to generalize and are rather strategic than operational, e.g. identifying priorities for adaptation (cf. Overbeck et al. (2012) on risk classes and their corresponding proportion of forest stands within a region). (3) Forest planning on the scale of single stands specifically considers all site and stand characteristics to derive tailored operational adaptation measures integrated into the strategic adaptation planning. Notably, the adaptation measures are interconnected between spatial scales.

Publications I, II, V and **VI** deal with the analysis of climate induced risks and uncertainties and derive adaptation measures on a regional level. As a special case, **publication II**'s topic of species selection as strategic adaptation planning is dealt with in section 3.2.2 below. The unanimous and final goal for **publications I, V** and **VI** is to derive adaptation measures for the study regions Diepholz, Uelzen, Fläming and Oder-Spree in the north German lowlands. Again, it is mandatory to disclose the assumptions and methods used to deduce recommendations (cf. Vanclay, 2014). This is pivotal in order to correctly interpret the results, evaluate their soundness, and finally to achieve acceptability of advised adaptation measures by forest owners, land use managers and the public. Hence, as background information on assumptions, material and methods, it is important to know that all derived adaptation recommendations presented in **publications I, II, V** and **VI** build on forest inventory data which is used to generate model stands. These stands are projected from 2011 to 2070, applying the single-tree site-sensitive growth model in the simulation framework *WaldPlaner*. As climatic forcing we use the climate scenario RCP 8.5 in three versions, designated as minimum, median and maximum climate run[4]. Forest management is simulated utilizing three rule-sets, i.e. business-as-usual forest management, climate protection management and biodiversity management[5]. Based on the results on climate-induced growth and yield changes, drought and windthrow risk assessment and in consideration of inherent climatic uncertainty following general recommendations are given in **publications I, V** and **VI** for the north German lowlands:

[4] For details please refer to section 2.2.

[5] For details please refer to section 2.2 and Table 4.

(1) While the rather generalizing results of the impact studies provide expedient guidelines for adaptation measures in the limits of the simulation settings, other restrictions need to be considered as well, e.g. costs, workload, or even legal issues. Therefore, no impetuous, ill-considered and universalizing actions should be implemented but adaptation measures need to be put into practice with a reasonable sense of proportion in compliance with the simulation results. This differentiated consideration is especially important because of the long production periods and high expenses for active forest conversion.

(2) The most feasible strategic option to counter negative effects of climate change is to distribute potential future risks by promoting climate-adapted species and species mixtures for future forest generations (cf. Ammer, 2018). Moreover, species diversity is a promising perspective to diminish negative impacts of climate change on a regional level.

(3) The presented simulations provide different results conditional on climate scenario and considered risk. Consequently, different adaptation measures are recommended. At best, all results are unidirectional, thus robust decisions on adaptation measures are feasible. In all other cases, the decision maker still has to select the preferred adaptation measures based on simulation output. Thus, implementing adaptation measures to counteract climate induced uncertainty is a matter of individual risk attitude, i.e. preference.

Following specific key recommendations on adaptation are given on a regional scale:

(1) Diepholz: (a) Drought risk is moderate, thus adaptation is no pressing issue. (b) Growth and yield results, however, show potential to enhance other management goals, e.g. to promote species with higher yield expectations to increase CO_2 sequestration, timber supply and income of forest enterprises.

(2) Uelzen: (a) Mixed stands should be promoted consequently. (b) Completed advance planting of European beech should be enriched by natural regeneration of oak, Scots pine and birch or even planting Douglas-fir, Grand fir or red oak. (c) After final harvest, special attention should be given to the selection of climate-adapted species for the next forest generation. If necessary, active forest conversion has to be pursued. (d) The windthrow risk calls for species diversification by converting some pure Scots pine stands into mixed stands with leading Scots pine or Douglas-fir in combination with reduced target diameter harvest. (e) Norway spruce is the most vulnerable species considering both drought risk and windthrow probability. Thus, conversion to different species or mixed stands with Norway spruce as admixture species seems advisable if the specific site does not fully comply with Norway spruce suitability.

(3) Fläming/Oder-Spree: (a) Drought risk is a critical issue, however, adaptation measures seem limited as the most drought-tolerant species, Scots pine, already dominates species distribution with 74 % in Fläming and 81 % in Oder-Spree today. (b) Nevertheless, mixed forests with leading Scots pine or Douglas-fir in mixture with European beech or oak should be promoted.

In summary, **publications I, V** and **VI** yield following core conclusions concerning the derivation of adaptation measures:

(1) Drought risk calls for adaptation measures, above all forest conversion in the long-term.

(2) Windthrow probability is no serious overall threat in the north German lowlands, above all due to the absence of large areas of old Norway spruce or Douglas-fir stands, thus being under high risk. However, if stands are identified as susceptible, adequate counter-measures should be taken.

(3) The selected silvicultural management system strongly determines the scope and the measures of adaptation.

(4) Scots pine will persist as an important and economically meaningful species especially in the northeastern German lowlands.

(5) Growth rates for beech and oak tend to decrease, while growth of Scots pine shows both positive and negative reactions to climate change depending on site and location.

(6) As other risk factors such as biotic hazards or wildfire are not included in the analysis in **publications I, V** and **VI**, a comprehensive and local risk assessment is inevitable before the here proposed adaptation measures are put into practice.

3.2.2 Species Selection under Climate Change

Species selection under changing climatic conditions is especially crucial because of the long-term commitment of this strategic forest planning decision. Forest conversion is seen as an effective adaptation measure to counter or at least diminish the negative effects of climate change (e.g. Brang et al., 2008; Schelhaas et al., 2015). In order to anticipate changing climatic conditions in species selection, especially the dynamics in site water budget, it is essential to evaluate species' site-suitability, taking future drought vulnerabilities into account (e.g. **supplementary publication 7**; Spathelf et al., 2014).

Publication II presents an approach for species selection suitable for area-wide forest planning encompassing climate projections, their uncertainty, stand-type planning rule-sets and drought risk assessment. It is the major goal of **publication II** to uncover the interaction of different silvicultural management regimes and climate uncertainty on species selection. The extent of adaptive planning respecting future drought vulnerabilities is of paramount importance for forest planning. In **publication II**, species are first selected considering current stocking and site-suitability under current climate but neglecting any future drought restrictions. Afterwards, species selection is conducted, explicitly taking future drought vulnerabilities into account (Fig. 14). As a simplifying assumption[6] in order to emphasize the climatic effect and the inherent uncertainty on species selection, we assign new stand types to each site in the year 2070 regardless of the current stands' age. However, the forest management system in central Europe with long production periods is very inert. Thus, actual species conversion to diminish the increasing drought risk will extend over a much longer period along with an increased area of forest at risk (Schelhaas et al., 2015).

[6] For further assumptions and methods applied please refer to section 3.2.1.

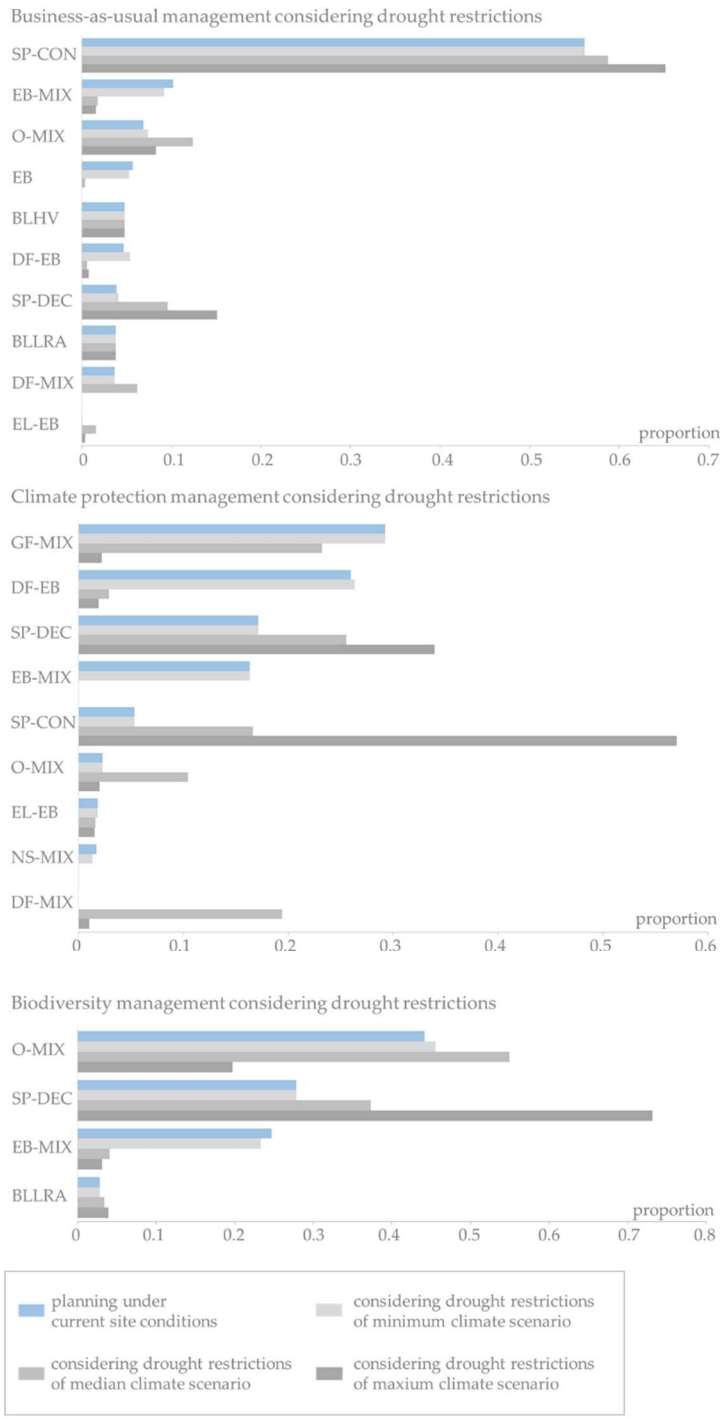


*Fig. 14: Frequency distribution of succeeding stand type area under constant site conditions in 2070 (light blue) and adaptive planning considering drought restrictions under minimum (light gray), median (gray) and maximum (dark gray) climate scenarios under three silvicultural management strategies in the study region Uelzen (from **publication II**)*[7].

Figure 14 depicts the impact of climate change on species selection conditional to the underlying silvicultural management strategy. Obviously, the more extreme the climate scenario, the higher the need for adaptive planning. But also the choice of forest management goals, i.e. the respective management strategy with corresponding species' preferences, has

[7] For an explanation of the abbreviations for stands types please refer to **publication II**, Tab. 4.

a considerable influence on the amount of adaptive planning necessary. The adaptation effort score (AES)[8] summarizes the extent of adaptive planning for an entire region. The AES compares the frequency distributions of succeeding stand type area under constant site conditions and under adaptive planning considering drought restrictions under three climate scenarios and three silvicultural management strategies (Tab. 5).

*Tab. 5: Adaptation effort score (AES) under the forest management strategies business-as-usual (BAU), climate protection (CP) and biodiversity management (BIO) applying the climate scenarios of minimum, median and maximum run in the study regions Uelzen and Fläming. The uncertainty range is the difference between the AES values of the maximum and minimum climate run (from **publication II**).*

		Climate Scenario			Uncertainty
		Minimum	Median	Maximum	Range
Uelzen	BAU	2.0	17.9	21.8	19.8
	CP	0.3	31.5	54.8	54.5
	BIO	3.2	48.5	74.1	70.9
Fläming	BAU	12.2	14.9	15.1	2.9
	CP	28.2	40.4	40.6	12.4
	BIO	50.5	56.1	56.2	5.7

The AES quantifies that in Uelzen the proportion of adaptive planning under the biodiversity management strategy is highest, followed by the climate protection regime and the business-as-usual path (Tab. 5). Also, the uncertainty range due to the three climate scenarios shows the same ranking. In the study region Fläming, the need for adaptive planning is significantly higher under minimum and median climate scenario than in Uelzen. In Fläming, the ranking of the adaptation effort score looking at management regimes is the same as in Uelzen. However, the uncertainty ranges are generally much lower and the climate protection strategy displays the highest variability.

From the methods and results in **publication II** following core conclusions are drawn:

(1) Successful adaptation planning indispensably requires the decision-makers' awareness of the interactive nature of management goals and limitations imposed by changing climatic conditions and their intrinsic uncertainty (cf. Yousefpour et al., 2012; Yousefpour and Hanewinkel, 2016).

(2) The presented approach to quantify the extent of imperative adaptation planning enables specific recommendations on silvicultural management options and species selection for the next generation of forests based on current stockings on defined sites under climate change. Thus, the information generated is well suited to be used in decision support in strategic regional forest planning.

(3) This method for regional forest planning which builds on easily and ubiquitously available data complements large-scale approaches which clarify tendencies and draw more

[8] The AES has a natural range of values between 0 (no adaptation is necessary at all) and 100 (absolutely no realizability of planned species). Thus, the AES can be interpreted as the species proportion that needs adaptation to meet the drought restrictions. For a detailed derivation of the AES please refer to **publication II**, chapter 2.5.

general conclusions (e.g. Bolte et al., 2009; Yousefpour and Hanewinkel, 2009; Schelhaas et al., 2015; Yousefpour et al., 2017).

3.3 Decision Making: The 3D-ecogram – A novel Decision Support Tool

The next step in the process to assist forest management and planning is the actual decision process after generating information on possible forest developments (**publications IV, VII** and **VIII**; cf. chapter 2.2), subsequently assessing risks and uncertainties (**publications I, II, III, V** and **VI**; cf. chapter 3.1) and deriving potential adaptation measures (**publications I, II, V** and **VI**; cf. chapter 3.2). As it is not possible to eliminate much of the uncertainty and risks associated with managing forest ecosystems, the influence of uncertainty and risk on decision making needs to be accounted for (Kangas and Kangas, 2004; Borchers, 2005). Moreover, Pe'er et al. (2014) endorse the attitude to deal with uncertainty as being found. Furthermore, they add another component to the context of uncertainty and decision making. They point to an additional source of uncertainty when data and knowledge have to be processed in order to be used in the decision process, designated by Pe'er et al. (2014) as uncertainty of the "societal sphere" as opposed to uncertainty of the "knowledge sphere". Ascough et al. (2008) as well as Eyvindson and Kangas (2018) further emphasize that uncertainties associated with all aspects of the decision making process need to be explicitly considered. Likewise, impacts of risks substantially affecting the decision making process need to be contemplated sufficiently.

As multiple hazards threaten forest ecosystems at different ages or development stages, it is not reasonable to develop one universal risk model to be used in decision making. Instead, different tailored approaches to incorporate specific risks and uncertainties in forest management decision making are used (cf. Hanewinkel et al., 2011). These approaches comprise methods to primarily assess natural hazards and to eventually deal with economic aspects of these risks. Hanewinkel et al. (2011) propose four steps to incorporate risk into forest management decision making under climate change: (a) the analysis of the underlying framework conditions such as climate change scenarios, (b) the prediction of probabilities for hazards, (c) the calculation of costs with and without taking risk into account, and (d) the actual decision making, i.e. choice of action under cost-benefit analysis.

Ultimately, risk can be interpreted as economic losses (Möllmann and Möhring, 2017). An intriguingly effective way to account for risk in an economic analysis is presented by Staupendahl and Möhring (2011), who derive annuities under risk by applying an age-dependent survival function. The annual risk costs are then calculated as the difference between annuities with and without considering risk. Moreover, the survival function's parameters can be easily modified to adjust to different risk types and levels and still annual risk costs are readily available. This is an advantage over iterative approaches, e.g. by means of Monte Carlo simulation (Dieter, 2001), or numerical methods, e.g. applying linear programming (e.g. Nuutinen et al., 2006; Buongiorno and Zhou, 2015). Möllmann and Möhring (2017) further extend the application of the age-dependent survival function by calculating expected loss in terms of land rent with and without considering risk. The authors conclude that the approach is appropriate to include risk in the decision making process as the expected loss can be used as an indicator for the optimal harvesting age and the profitability of a species. However, it does not include all risk aspects and does not account

for the decision-maker's risk attitude. Pukkala and Kangas (1996), however, present a heuristic method for integrating risk as well as the decision-maker's attitude towards risk into the forest planning process.

From a more hierarchical point of view, the economic evaluation of risks is the last step preceded by an assessment of single risk factors, an analysis of survival time and presumably the consideration of risk effects on forest growth (NW-FVA, 2018).

Looking back at a large number of decision support systems (DSS) which aid in forest management and planning since the early 1980s, the following two key lessons could be learnt according to Muys et al. (2010): (1) Most crucial is to clearly focus on the decision making process and on the specific decision maker. It is most important to keep the DSS as simple as possible. If the DSS is too universal regarding the output and recipients of the information, it is likely to be too complex for practical application. Moreover, Yousefpour et al. (2012) pronounce the necessity to overcome the gap between comprehensive ecological models and rather generalizing economic models by providing appropriate modelling tools to aid forest managers in the complex decision process. (2) There exists a justified request for complete transparency of the DSS and especially for a thorough disclosure of the formal reasoning mode of the DSS. Without comprehensive transparency, the DSSs' recommendations are burdened with distrust and practical implementation seems unlikely.

Publication VII (see also **supplementary publications 7** and **9**) introduces the novel three-dimensional (3D) ecogram as a tool to support species planning under climate change. The 3D-ecogram meets the above mentioned requests for DSS, i.e. a precise focus on one decision problem as it solely evaluates species suitability depending on site-productivity and drought risk, and a transparent presentation of the underlying statistical model including the assumptions and limitations. The 3D-ecogram features a statistical growth model part and expert rules, i.e. drought limits to classify a species' suitability for cultivation. However, the 3D-ecogram does not qualify as a complete classical DSS in the strict sense but rather as a tool in a DSS framework, because it especially lacks the stakeholder preferences (cf. Reynolds, 2005; Muys et al., 2010).

The problem definition in **publication VII** covers the development of a decision support tool to assist in evaluating species suitability for cultivation considering growth potential and drought risk under climate change. It is hypothesized that in most cases a standard regression model rendering average expectation values on site index, as for example the site-productivity models in **publication VII** and **VIII**, is inadequate to fully assess the yield aspect of species' suitability for cultivation. As a research assignment it is formulated to estimate the 20% quantile of site index, to classify species' drought vulnerability and to combine both criteria, i.e. species productivity and drought risk, to suitability classes for cultivation.

We apply the method of LMS-quantile regression by Cole and Green (1992) to develop quantile regression models to estimate the site index distribution with functions for the expectation value μ, the skewness λ and the coefficient of variation σ. We use soil and climate parameters as predictors to achieve site-sensitive estimates of the 20% quantile of site index for five species (Tab. 6).

*Tab. 6: Quantile regression model formulations to estimate the 20% quantile of site index for five species (from **publication VII**).*

Europ. beech	$\mu_i = \alpha_1 + Nähr_i^T \beta_1 + f_1(WH_i) + f_2(Temp_i) + f_3(Ndep_i) + \alpha_2 \cdot LP_{1_i} + ... + \alpha_{k+3} \cdot LP_{k_i}$ $\log(\sigma_i) = \alpha_1 + Nähr_i^T \beta_1 + f_1(WH_i) + f_2(Ndep_i)$ $\lambda_i = \alpha_1 + f_1(WH_i) + \alpha_2 \cdot Ndep_i$
Pedunc. and Sessile oak	$\mu_i = \alpha_1 + Nähr_i^T \beta_1 + f_1(WH_i) + f_2(Temp_i) + f_3(Ndep_i) + \alpha_2 \cdot LP_{1_i} + ... + \alpha_{k+3} \cdot LP_{k_i}$ $\log(\sigma_i) = \alpha_1 + Nähr_i^T \beta_1 + f_1(WH_i) + f_2(Ndep_i)$ $\lambda_i = \alpha_1 + Nähr_i^T \beta_1$
Norway spruce	$\mu_i = \alpha_1 + Nähr_i^T \beta_1 + f_1(WH_i) + f_2(Temp_i) + f_3(Ndep_i) + \alpha_2 \cdot LP_{1_i} + ... + \alpha_{k+3} \cdot LP_{k_i}$ $\log(\sigma_i) = \alpha_1 + Nähr_i^T \beta_1 + \alpha_2 \cdot Ndep_i + \alpha_3 \cdot LP_{1_i} + ... + \alpha_{k+3} \cdot LP_{k_i}$ $\lambda_i = \alpha_1 + Nähr_i^T \beta_1 + \alpha_2 \cdot Temp_i + f_1(Ndep_i)$
Scots pine	$\mu_i = \alpha_1 + Nähr_i^T \beta_1 + f_1(WH_i) + \alpha_2 \cdot Temp_i + f_2(Ndep_i) + \alpha_3 \cdot LP_{1_i} + ... + \alpha_{k+3} \cdot LP_{k_i}$ $\log(\sigma_i) = \alpha_1 + Nähr_i^T \beta_1 + \alpha_2 \cdot WH_i + f_1(Temp_i) + f_2(Ndep_i)$ $\lambda_i = \alpha_1 + Nähr_i^T \beta_1 + f_1(Ndep_i)$
Douglas-fir	$\mu_i = \alpha_1 + f_1(WH_i) + \alpha_2 \cdot Temp_i + f_2(Ndep_i) + \alpha_3 \cdot LP_{1_i} + ... + \alpha_{k+3} \cdot LP_{k_i}$ $\log(\sigma_i) = \alpha_1 + f_1(Ndep_i)$ $\lambda_i = \alpha_1 + f_1(Ndep_i)$

with Nähr: indicator vector for soil nutrient classes; WH: soil water as the sum of climatic water balance in growing season (GS) and available soil moisture [mm]; Temp: temperature sum in GS [°C]; Ndep: mean annual nitrogen deposition [eq/ha/a]; LP_1 … LP_k: spline bases of two-dimensional smoothing spline from a mean value regression model; β_1: parameter vector on soil nutrient classes; α_1 … α_k: regression coefficients; f_1, f_2, f_3: one-dimensional smoothing splines; k: base dimension of the two-dimensional spline in the mean value regression model.

The parameter selection for the functions in Table 6 demonstrates that the expectation value μ, the skewness λ and the coefficient of variation σ all depend on various soil and climate characteristics. Using these 20% quantile regression models in combination with the expert formulation of threshold values for species' productivity and drought stress, suitability classes for cultivation are derived. Finally, a location- and species-specific 3D-ecogram is available as a decision support tool for species selection (Fig. 15).

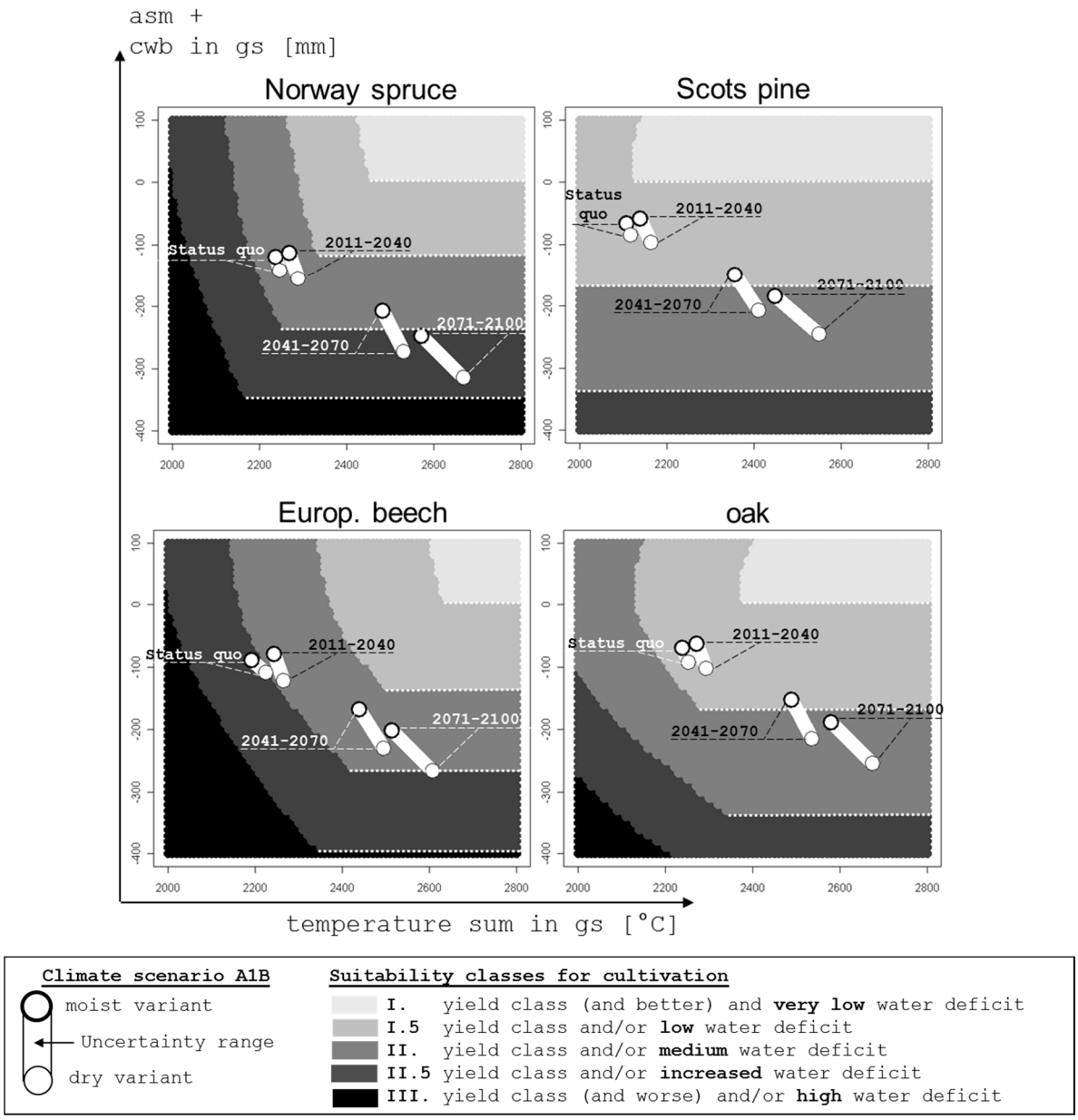


*Fig. 15: 3D-ecograms for Norway spruce, Scots pine, European beech and oak at a specific forest location in Lower Saxony. The different shades of gray indicate the five suitability classes for cultivation. The dotted white lines mark thresholds, where the water deficit criterion replaces the site-productivity criterion to determine the suitability classes for cultivation (from **publication VII**).*

The area according to the range of the sum of available soil moisture (asm) and climatic water balance (cwb) in the growing season (gs) and the range of the temperature sum in gs is species-specifically divided into suitability classes for cultivation (Fig. 15). Important to note is the placement of the location-specific site characteristics on the 3D-ecogram under status quo conditions[9] and the temporal shift for three projection periods 2011 to 2040, 2041 to 2070 and 2071-2100. Equally substantial is the identified uncertainty range arising from the here applied two variants of climate scenario A1B.

[9] For consistency, the climate values for status quo conditions are also predicted using the regional climate model WETTREG (Spekat et al., 2006), thus, rendering also two states under status quo conditions.

Publication VII in combination with **supplementary publications 7** and **9** yields following key conclusions regarding the 3D-ecogram:

(1) The 3D-ecogram provides information on species' suitability for cultivation at the forest stand level. Thus, it is a decision support tool designed for the needs of forest management at the operational level.

(2) The 3D-ecogram assists in the species selection process by incorporating site-productivity and its change under climate change, drought vulnerability as one important risk factor for species site suitability and climate uncertainty applying two climate projections (in the examples of **publication VII**).

(3) The 3D-ecogram is a decision support tool capable to take multiple soil and climate characteristics into account when estimating the 20% quantile of site index. Thus, it is one step further than, for example, the climate envelopes, promoted by Kölling (2007), which provide decision support for species suitability based only on two factors, mean annual temperature and annual precipitation, without considering species' productivity. However, efforts are initiated to complement insights from species distribution models with information on species productivity in order to assess species site-suitability (cf. Falk et al., 2012; Walentowski et al., 2017).

(4) The 3D-ecogram as an example of a decision support tool evinces a predicament prevailing especially in complex decision processes dominating in forest ecosystem management and planning. When designing a decision support tool it has to be weighed whether to include expert knowledge, e.g. in the form of defined threshold values on site-productivity and on drought vulnerability, or to utilize the decision makers' perception to define the threshold values. However, the more complex the planning problem the more useful it seems to integrate expert knowledge (cf. Kangas et al., 2000).

4. Conclusions and Outlook

To come full circle, the question needs to be answered if the three major goals formulated at the beginning of the habilitation thesis could be achieved.

The first goal covers modelling the site-productivity relationship climate-sensitively and to project forest development under climate change for forest planning issues in general. Regarding the first goal following final conclusions are drawn:

(1) Site-productivity models are built using various soil and climate variables as predictors (**publication VII** and **VIII**). By applying the GAM methodology, potentially non-linear effects of predictor variables on site index can be identified. The site-productivity models are parameterized for European beech, Pedunculate and sessile oak, Norway spruce, Scots pine and Douglas-fir. The validity range covers Germany as a whole. The models show biologically feasible performance and react sensitively conditional on changes of single predictors under climate change scenarios.

(2) By applying the developed site-productivity models, it is possible to simulate forest development under climate change conditions (**publication IV**). Alternatively, projecting shifts in longitudinal height-diameter curves site-sensitively (cf. Schmidt, 2010; Burggraef et al., 2017) within a forest growth simulator yields targeted predictions of forest development under climate change as well (**publications I, III, V** and **VI**). The extent of the models' climate sensitivity facilitates scenario analyses applying different climate projections.

(3) Forest planning requires the most accurate information available on future forest development for setting up successful and goal-oriented forest management plans. In order to generate pertinent information, basically two simulation approaches seem feasible. First, impact studies as performed in **publications II, III, V** and **VI** identify key levers in forest management and planning which are important to justify recommendations on adaptation measures and to warrant transparency in the decision process. One disadvantage of impact studies in this context is that the simulation framework refrains from feedback effects due to tree or forest losses. Thus, a retrospective vulnerability analysis is indispensable. Nevertheless, forest growth projections with retrospective vulnerability analyses are very well suitable to derive adaptation recommendations (**publications II, III, V** and **VI**). The second possible approach comprises a full model prediction, i.e. projections of forest development explicitly taking feedback effects into account. This methodological proceeding, which unfortunately is not yet accessible, potentially depicts forest development more precisely. However, the driving causes are concealed within the simulation results. Any justifications for recommendations and decisions taken only become available after a disintegration of the simulation results into single effects afterwards.

The second goal specifically encompasses the detailed analysis of changes in stand productivity and a comprehensive risk assessment, explicitly incorporating climate

uncertainty and variability in silvicultural management strategies. Of course, this is performed by applying the growth models of **publications VII** and **VIII**, among others, in scenario simulations. Regarding the second goal, the following final conclusions are drawn:

(1) In general, impact assessments focus on analyzing the effect of changes in a single factor or content-related key determinants on a system, e.g. the effect of changing climatic conditions on forest growth or how different silvicultural management regimes control forest development. In **publication I**, the impact of persistent dryer climates on forest growth is evaluated under different climate projections. The results clearly point out that forest productivity decreases depending on species and region. Additionally, in **publication VI**, the effect of climate uncertainty and silvicultural management variability on forest dynamics and selected risks is demonstrated. Thus, the methods applied and analyses performed quantify the effects of climate uncertainty and silvicultural management regimes on forest development including a comprehensive evaluation of potential risks.

(2) Forest management significantly controls forest development. Thus, the variability in silvicultural management strategies is crucial and the effects on growth and yield need to be communicated (**publications V** and **VI**). Furthermore, different management strategies may directly alter the risk profile of forests or forest regions which also needs to be considered (e.g. **publication II**).

(3) Climate uncertainty dominates the magnitude of risks, especially shown for the drought vulnerability assessment (**publications I, II, V** and **VI**).

The third goal focusses on deriving recommendations for adaptive forest planning. Regarding the third goal, the following final conclusions are drawn:

(1) Simulations of forest development and accompanying risk assessments are essential cornerstones in order to generate information for decision support (cf. Muys et al., 2010; **publications I** to **VI**). Quantitative assessments of future forest development complement empirical knowledge and information from forest inventories in decision making.

(2) Adaptive forest management and especially forest conversion must incorporate small-scale differences in site. Above all, this precise distinction in site characteristics is important against the background of high climate uncertainty and taking into account the potential to actively steer forest development by applying the appropriate silvicultural management strategy (**publications II, V** and **VI**).

(3) Implementing adaptation measures to counteract negative impacts of climate change is a matter of individual risk attitude. This becomes apparent looking at climate uncertainty. If all simulation results are unidirectional in the effects of climate change on growth and risks, at least a robust decision is warranted. Nevertheless, the decision maker needs to select one potential scenario deemed most probable in order to implement the specific adaptation measures necessary (**publications I** and **II**).

(4) The novel 3D-ecogram provides information on species' site-suitability considering species' future productivity and drought vulnerability including the effects of climate

uncertainty at the site unit level. Thus, it is perfectly fit to support forest management in species selection at the operational level (**publication VII**).

In summary, the major goals of the covered research questions are achieved. Nonetheless, considerable improvements on the models are possible, especially considering the fast improving data base. Additionally, a vast set of pursuing research questions with regard to forest growth under climate change and decision support for forest planning issues remains unanswered.

Hereafter, I will elaborate on selected possible improvements and new fields of research which are nested as follows: (1) potential improvements of growth models form the inner circle contributing to (2) advancements in forest development projections which ultimately lead to (3) refining the information base for decision support (Fig. 16).

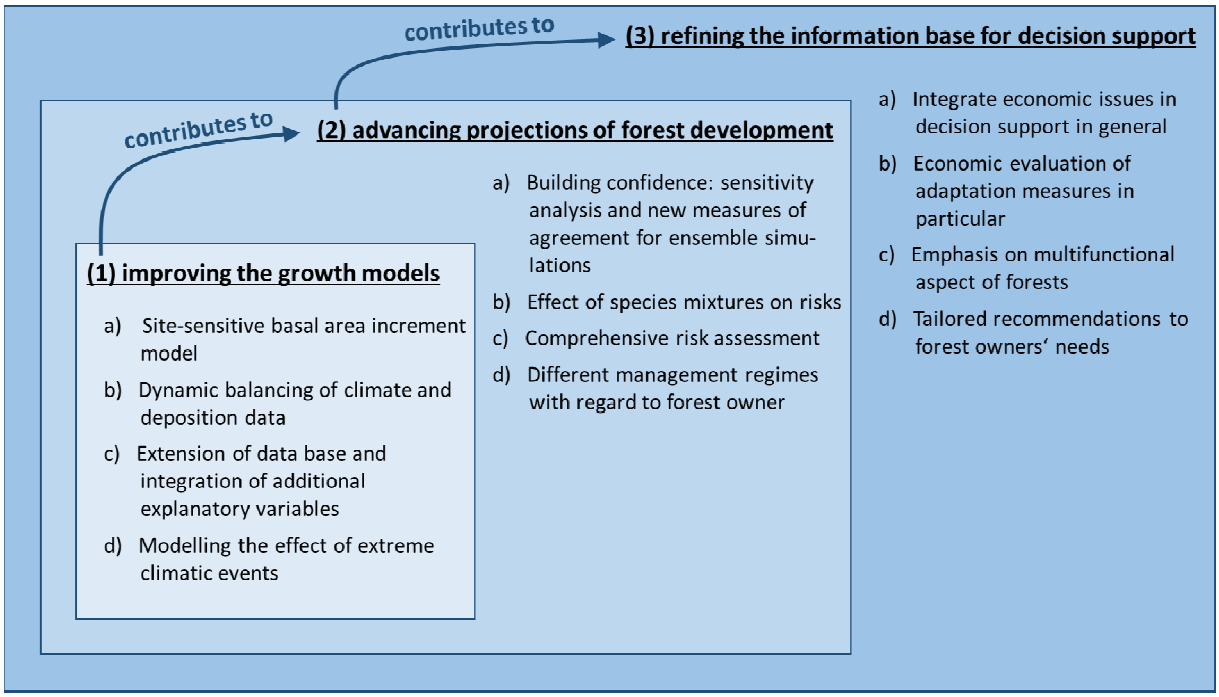


Fig. 16: Three nested groups of selected future research needs.

In the context of future improvements concerning forest growth, climate change and forest planning, further development of forest growth models lies at the core. Relating to the simulation framework *WaldPlaner* which is applied in **publications I, III, IV, V** and **VI**, the most obvious improvement is to incorporate a site-sensitive basal area increment model (issue 1a in Fig. 16). A first approach is undertaken in **supplementary publication 6**. It is expected that the explicit incorporation of climate and soil effects in basal area prediction will improve growth predictions under climate change overall (Rohner et al., 2017).

A methodological improvement is addressed under issue 1b (Fig. 16). During the development of the site-productivity models presented in **publications VII** and **VIII**, retrospective climate and deposition data was only available for the reference period 1961 to 1990. Furthermore, the annual climate values were derived from a retrospective run of the regional climate model WETTREG (Spekat et al., 2006). The use of this data base for model parameterization was a necessary simplification. However, in the meantime recorded climate

data by the German Weather Service (DWD) is available on an annual basis going back well beyond the climate reference period. Thus, model parameterization should, first, be based on measured climate data and, second, balancing climate sums or means need to consider the stand's actual lifespan instead of the 30-year reference period. For height-diameter models, these improvements are demonstrated by, e.g., Burggraef et al. (2017) and Schmidt (2018).

It is often argued that extending the data base will improve the respective model (issue 1c in Fig. 16). In the case of statistical climate-sensitive growth modelling, however, it is especially crucial to cover extreme situations to possibly avoid predictions in the far extrapolation range. In this context, Mahony et al. (2018) show that extrapolations into novel climates, i.e. beyond the range of current observations, tend to underestimate the magnitude of climate change and modeling uncertainty. Therefore, a selective sampling of forest sites in rather extreme climates, which are rare and, thus, seldomly captured by systematic inventories, seems promising to enlarge the range in the parameterization data. Moreover, in the course of model parameterization, it is desirable to include additional explanatory variables such as CO_2-concentration (cf. Körner et al., 2005; Kahle et al., 2008; Lindner et al., 2014; Lasch-Born et al., 2015) or sulphur deposition (cf. Nellemann and Thomsen, 2001; Savva and Berninger, 2010). Also, interaction effects such as between nitrogen deposition or CO_2-concentration and soil nutrients should be incorporated in the model, if possible (cf. Kirschbaum et al., 1998; Egli et al., 1998). In a first approach, the interaction term of soil nutrient class and nitrogen deposition proved highly significant in the site index model for Norway spruce (**publication VIII**).

Among others, Lindner et al. (1996), Muys et al. (2010) as well as Vitali et al. (2017) call for the inclusion of the effects of extreme climate events when analyzing or modelling forest growth (issue 1d in Fig. 16). The impact of severe droughts, for example, was confirmed in numerous studies (e.g. Orwig and Abrams, 1997; Klos et al., 2009; Michelot et al., 2012; Weber et al., 2013). Considering the impact of singular extreme climatic events could substantially refine modelling of forest development, i.e. forest growth as well as mortality caused by disturbances. Consequently, climate change impact studies would further improve through incorporating both long-term changes, as presented in **publication I** on persistent dryer climates, and short-term disruptions of climate means. Disregarding the influence of extreme climate events on forest growth might explain many of the discrepancies between observed growth trends and growth projections according to Lindner et al. (2014).

Intentionally disregarded in the field of improving models to predict forest development are all risk models in this outlook. While considerable enhancements in modelling risks are possible and certainly necessary (cf. Hanewinkel et al., 2011), a thorough analysis of shortcomings and potential improvements would be too far-reaching and beyond the scope of this outlook.

All growth model improvements (issues 1a to 1d of Fig. 16) will be of benefit to the projection of forest development. Additionally, substantial advances are achievable in the field of projecting forest development focusing on the process of generating and analyzing scenarios in its own right. Foremost, building confidence in the projection results is imperative in decision support (issue 2a in Fig. 16). Two starting points provide an excellent opportunity to enhance the reliability and trustworthiness of simulation results in forest growth projection under climate change, i.e. to account for uncertainties and errors in the data base and in

prediction models as well as to evaluate the deep uncertainty of the applied climate change scenarios. Next to classical model validation approaches and error estimation, sensitivity analysis may provide conclusive information on the reliability of the simulation results (cf. Vanclay and Skovsgaard, 1997). Muys et al. (2010) argue that sensitivity analysis concerning input data and model formulation strives to quantify all components of output uncertainty. While this is a legitimate claim to improve forest growth projections, the inherent uncertainty in climate change scenarios persists. Thus, in a first approach it is desirable to at least quantify climatic uncertainty within an ensemble approach (cf. **publications I, II, V** and **VI**). However, an important issue of future research is to derive measures to evaluate the agreement in ensemble simulations (cf. Mahony et al., 2017 and 2018). From the decision maker's point of view, a high level of agreement in ensemble simulations increases the trustworthiness in the simulations overall. Likewise, the concept of robust decision making serves to adequately consider climate uncertainties, rendering satisfying recommendations in the decision process (Radke et al., 2017). Mahony et al. (2017; 2018) raise another issue, as already stated above, i.e. the extrapolation into novel climates significantly affecting the reliability of forest projections. The authors define novelty as the climatic distance between the projected climate and its closest historical analog within a certain spatial scale, e.g. at landscape or continental scale. Regional susceptibility, topographic position and magnitude of projected climate change determine the occurrence of novel climates. Thus, detecting extrapolation into novel climates is crucial when evaluating the effects of climate change on forest development. In conclusion, future research has to focus on measures of agreement for ensemble simulations as well as identifying extrapolations into novel climates.

The issue of risk assessment offers a variety of measures for advancing projections of forest development. First of all, the effect of species mixtures on potential hazards needs to be emphasized (issue 2b in Fig. 16). While many methods and models assess the occurrence and magnitude of future risks regarding pure stands or single species (e.g. Peltola et al., 1999; Staupendahl and Möhring, 2011), the particularities and especially tree species interactions in mixed stands on hazards are not sufficiently understood, yet (cf. Bredemeier et al., 2001; Forrester et al., 2013; Pretzsch et al., 2017; Ammer et al., 2018). Some studies exemplarily examine how species mixtures affect drought risk (e.g. Pretzsch et al., 2013; Thurm et al., 2016) or if species mixtures reduce the risk of windthrow (e.g. von Lüpke and Spellmann, 1997; Griess et al., 2012). The model by Overbeck and Schmidt (2012) to predict bark beetle infestation risk of Norway spruce serves as an example to acknowledge the effect of species mixtures by prominently containing spruce proportion as an explanatory variable. However, results remain fragmentary. On the other hand, a wide-ranging risk assessment needs a sound and complete knowledge base.

The request for more substantial knowledge of potential risks on forests directs to the implementation of this knowledge in a comprehensive risk assessment (issue 2c in Fig. 16). In forest growth projections used for decision support, the effects of risks must not remain exemplarily but rather include every important aspect, be it via feedback or in a subsequent analysis. The analysis of survival probability is one possible approach to integrate several risk factors into one measure (cf. Staupendahl and Möhring, 2011; NW-FVA, 2018). A different comprehensive risk assessment method is introduced in **supplementary publication 2**. Here, risk diagrams are constructed for relevant risk factors which can be applied in a retrospective risk evaluation. Whichever approach is chosen for this purpose, it is also necessary to assess the interaction of individual risk factors, e.g. bark beetle outbreaks after storm damage (e.g.

Hanewinkel et al., 2008; Stadelmann et al., 2014). As with the effect of species mixtures on risks, the knowledge on the interaction of individual risk factors is far from being satisfactory (cf. Hanewinkel et al., 2011).

Finally, projections of forest development on a regional or larger scale could benefit from discriminating the applied silvicultural management regime according to the forest owner (issue 2d in Fig. 16). While it is important in climate impact studies to keep the variation in scenario settings to a minimum in order to identify the driving factors of change (cf. **publication I** to **VI**), a realistic prediction of forest development needs to account for differing management practices according to the forest owner. Thus, to provide decision support more specifically, the settings for silvicultural management regimes need to be stratified to implement the different forest owners' goals.

Deliberately omitted in this outlook on future research needs are all aspects regarding the use of different model approaches to predict forest development, e.g. forest landscape models (cf. Shifley et al., 2017) or process-based models (cf. Weiskittel et al., 2011, p.227 ff).

The selection of potential improvements in projections of forest development (issues 2a to 2d in Fig. 16) will aid in the refinement of the decision making process. Of course, the field of decision making itself offers various additional options for advancement (issues 3a to 3d in Fig. 16). To begin with, strengthening the economic aspects in decision support would add valuable information beyond the analyses presented so far in **publications I, II, V** and **VI** (issue 3a in Fig. 16). This task is straightforward as multiple economic parameters and methods to economically evaluate different scenarios exist (cf. Möhring, 1994; Möhring et al., 2017).

More specifically, a current problem deals with the economic evaluation of forest management actions under climate change, i.e. the economic advantageousness of adaptation measures, including species conversion strategies, in particular (issue 3b in Fig. 16). Adaptation measures are always adjustments in forest planning to diminish future risks or to profit from expected changes. Concerning risks, or more explicitly losses of parts of or even entire forest stands, different approaches exist to quantify survival, e.g. Monte-Carlo simulation (cf. Dieter, 2001) or a straightforward application of survival functions (cf. Staupendahl and Möhring, 2011). However, no unambiguous consensus exists on the practical implementation of these approaches into the decision making process (Möhring et al., 2011). Thus, further work seems necessary, e.g. the advancement of survival functions to express cash flow of forest production and its present value as a function of risk (Möhring et al., 2011).

Many adaptation measures are put into practice over a medium- to long-term planning horizon. Knoke et al. (2017a) argue that under long planning periods, time declining discount rates may offer a superior alternative to conventional discounting. This is especially important as discounting quite often leads to forest management recommendations which diverge from forest management regimes applied in practice (Möhring, 2001). Thus, the concept of declining discount rates seem to be a promising approach for an economic evaluation of adaptation measures (cf. Knoke et al., 2017a).

By reviewing the historical evolution of forest growth modeling, Shifley et al. (2017) expose the ever increasing importance of multifunctional forestry which has to be considered in forest planning and decision making (issue 3c in Fig. 16). In order to offer a comprehensive

information base for decision support, it is indispensable to focus future work on providing the necessary indicator values by further shaping growth simulators towards useful output (cf. Muys et al., 2010; see also **supplementary publication 1**). Concerning the processing of information within the decision making procedure, Knoke et al. (2017b) discuss shortcomings of classical approaches and ask for improved methods. They deduce that a risk-averse attitude in the decision process of forest planning will lead to economic diversification. This will foster enhanced biodiversity and higher levels of multiple ecosystem services. However, classical economic optimization methods to provide decision support fall short of optimizing all ecosystem services equally. Thus, Knoke et al. (2017b) call for new portfolio-based methods to integrate multiple services including their uncertainties into the optimization process. Moreover, Matthies et al. (2019) stress that future research has to address the question how modern portfolio theory, as one of such new approaches among others, can best assess the diversification and trade-off dynamics triggered by, e.g., climate change.

Finally, Muys et al. (2010) demand that recommendations for adaptation measures should be tailored to different forest owners' needs (issue 3d in Fig. 16). As a prerequisite for tailored recommendations, knowledge of forest owner's goals and preferences is required, i.e. to integrate the owners' input into the decision process (cf. Mattsson et al., 2018). Above all, it is essential to tackle the problem to transpose theoretical frameworks for decision support in forest planning into practical applications. Mattsson et al. (2018) clearly address this shortcoming and propose a multimetric index of quantitative decision support to improve the implementation of decision support in practice.

Again, certain fields of future research and extensions in decision support are deliberately omitted as they go well beyond the scope of this habilitation thesis, e.g. the advancement of decision support towards comparative risk assessment (cf. Linkov and Ramadan, 2004) and, furthermore, towards multi-criteria decision making (cf. Keeney and Raiffa, 1993; Kiker et al., 2005; **supplementary publications 13** and **14**).

5. Summary

The key messages of each **publication I** to **VIII** highlight the most important novel and innovative results:

- **Publication I**: The first methodological approach is presented to quantify the effect of persistent dryer climates on forest growth which is suitable at forest management level. The presented method complements the commonly in practical forestry in northwestern Germany applied qualitative drought stress assessment for tree species selection.

- **Publication II**: The comprehensive analysis of the effects of climate uncertainty for tree species selection subject to drought limitations reveals that intense interactions between forest management goals, regional natural conditions and climate scenarios exist. The newly developed adaptation effort score summarizes the extent of adaptive planning for an entire region. In conclusion, in most cases adaptive species planning has to be a compromise between management goals and projected site suitability, according to the underlying climate scenario the decision maker deems most probable. This paper emphasizes the strategic long-term aspect of species conversion.

- **Publication III**: The future risk of high nitrate concentration in seepage water can be evaluated using climate-sensitive forest growth predictions. The importance and the considerable influence of selected silvicultural management strategies on nitrate concentration is demonstrated.

- **Publication IV**: A novel complex dynamic simulation model system is introduced. It is capable to project forest development and to assess the impact of climate change for the first time anywhere in Germany. The model system comprises of a climate-sensitive growth model and several abiotic and biotic risk models utilizing high-resolution climate data and soil parameters.

- **Publication V**: The multidimensional consequences of climate uncertainty for forest management and planning are demonstrated for four regions in northern Germany. Regional natural conditions and silvicultural management strategies may alter the impact of climate change on forest development considerably and affect adaptation measures. This paper emphasizes the short- to medium-term aspects of adaptation measures.

- **Publication VI**: The effects of different climate projections in combination with three silvicultural management alternatives on potential risks are evaluated. The vulnerability analysis uses drought stress and windthrow as examples in order to highlight the importance to account for climate uncertainty in forest planning.

- **Publication VII**: The first Germany-wide applicable climate-sensitive site-productivity model for European beech, Pedunculate and Sessile oak, Norway spruce, Scots pine and Douglas-fir is presented. Additionally, three-dimensional ecograms as a novel decision support tool to aid forest planning in tree species selection are introduced.

- **Publication VIII**: The theoretical background of the novel climate-sensitive site-productivity model (cf. publ. VII) is described. It is a preliminary model stage parameterized with a data subset from Lower Saxony for European beech and Norway spruce.

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7. Scientific Contributions

7.1 Own Contribution on Publications used for the Habilitation Thesis

I ALBERT, M., NAGEL, R.-V., SUTMÖLLER, J. AND SCHMIDT, M.: 2018
Quantifying the effect of persistent dryer climates on forest productivity and implications for forest planning: a case study in northern Germany
Forest Ecosystems {2.426}[10]

Idea and methodological concept for analysis of the growth effects, prediction of forest growth, data analysis and computation of results, processing of results and interpretation, writing of manuscript for the most part and finalization, conception and preparation of all figures, except figure 1, and tables 1, S1 and S2

II ALBERT, M., NAGEL, R.-V., NUSKE, R.S., SUTMÖLLER, J. AND SPELLMANN, H.: 2017
Tree Species Selection in the Face of Drought Risk – Uncertainty in Forest Planning
Forests {1.956}

Idea and methodological concept for assessment of the interaction of management regime and climate uncertainty on species selection, data analysis and computation of results, processing of results and interpretation, development of adaptation effort score, writing of manuscript for the most part and finalization, conception and preparation of all figures, except fig. 2 and 4, and all tables, except table 3

III FLECK, S., AHRENDS, B., SUTMÖLLER, J., ALBERT, M., EVERS, J. AND MEESENBURG, H.: 2017
Is Biomass Accumulation in Forests an Option to Prevent Climate Change Induced Increases in Nitrate Concentrations in the North German Lowland?
Forests {1.956}

Projection of forest growth, computation of growth and yield results, participation in the interpretation of results concerning the effect of silvicultural management regimes on groundwater recharge, nitrogen budget and nitrate in seepage water, conception and preparation of table 2, participation in writing the manuscript

[10] **Journal Impact Factor** from the *2018 Journal Citation Reports* (based on 2017 data) by Clarivate Analytics.

IV THIELE, J.C., NUSKE, R.S., AHRENDS, B., PANFEROV, O., ALBERT, M., STAUPENDAHL, K., JUNGHANS, U., JANSEN, M. AND SABOROWSKI, J.: 2017
Climate change impact assessment – A simulation experiment with Norway spruce for a forest district in Central Europe
Ecological Modelling {2.507}

Development of the site-sensitive site index model used in the growth projection, participation in the interpretation of results especially concerning forest growth, participation in writing the manuscript

V ALBERT, M., LEEFKEN, G., NUSKE, R.S., AHRENDS, B., SUTMÖLLER, J. AND SPELLMANN, H.: 2016
Auswirkungen von klimatischer Unsicherheit auf die Forstplanung am Beispiel von vier Regionen im norddeutschen Tiefland
Allg. Forst- u. J.-Ztg. {0.342}

Idea and methodological concept for assessment of climate uncertainty and variability of silvicultural management regimes on indicators for forest management and planning, processing of forest data, projection of forest development, participation in formulation of silvicultural management regimes, technical implementation of silvicultural management regimes in *WaldPlaner*, data analysis and computation of results, processing of results and interpretation, writing of manuscript for the most part and finalization, conception and preparation of all figures and all tables, except table 3 and 4

VI ALBERT, M., HANSEN, J., NAGEL, J. SCHMIDT, M. AND SPELLMANN, H.: 2015
Assessing risks and uncertainties in forest dynamics under different management scenarios and climate change
Forest Ecosystems {2.426}

Idea and methodological concept for risk assessment under climate change, processing of forest data, projection of forest development, participation in formulation of silvicultural management regimes, technical implementation of silvicultural management regimes in *WaldPlaner*, data analysis and computation of results, processing of results and interpretation, writing of manuscript for the most part and finalization, conception and preparation of all figures, except figure 1, and all tables, except table 4 and 5

VII ALBERT, M. AND SCHMIDT, M.: 2012
Standort-Leistungs-Modelle für die Entwicklung von waldbaulichen Anpassungsstrategien unter Klimawandel
Archiv f. Forstwesen u. Landsch.ökol. {-}

Development of site-sensitive site index models and quantile regression models for the 20% quantile of site index, construction of 3D-ecogram, data processing, data analysis and computation of results, processing of results and interpretation, writing of manuscript for the most part and finalization, conception and preparation of all figures and all tables, except table 5

VIII ALBERT, M. AND SCHMIDT, M.: 2010
Climate-sensitive modelling of site-productivity relationships for Norway spruce (*Picea abies* (L.) Karst.) and common beech (*Fagus sylvatica* L.)
Forest Ecol. Manage. {3.166}

Development of site-sensitive site index models, data processing, data analysis and computation of results, processing of results and interpretation, writing of manuscript for the most part and finalization, conception and preparation of all figures and all tables

7.2 List of Supplementary Publications to the Habilitation Thesis

1 Spellmann, H., Ahrends, B., **Albert, M.**, Andert, S., Barkmann, T., Böcher, M., Breckling, B., Christen, O., Dvorak, J., Eggers, M., Fleck, S., Fohrer, N., Gauly, M., Gerowitt, B., Gieseke, D., Grocholl, J., Hakes, W., Hammes, V., Hartje, V., Haunert, G., Hoffmann, M., Hufnagel, J., Isselstein, J., Kätzel, R., Kayser, M., Kehr, I., Knauer, H., Krott, M., Lambertz, C., Lange, A., Langer, G., Leefken, G., Löffler, S., Meesenburg, H., Meißner, R., Messal, H., Meyer, P., Möhring, B., Möller, K., Nagel, J., Nuske, R.S., Oetzmann, A., Ohrmann, S., Redwitz, C.v., Riediger, J., Schmidt, M., Schröder, J., Schröder, W., Siebert, R., Spindelndreher, D., Stahlmann, H., Stöck, L., Sutmöller, J., Svoboda, N., Tänzer, D., Tiedemann, A.v., Ulber, B., Wegner, K., Werner, P.C., Winter, M., Wüstemann, H., Zander, P, and Ziesche, T. (2017). *Nachhaltiges Landmanagement im Norddeutschen Tiefland*. Göttingen: Beiträge aus der NW-FVA, Band 18. 432 S. doi:10.17875/gup2018-1073

2 Kätzel, R., Fleck, S., and **Albert, M.** (2016). Die Wälder des norddeutschen Tieflandes unter dem Einfluss aktueller und zukünftiger Risikofaktoren – Beispiele für eine Gefährdungsanalyse. *Eberswalder Forstliche Schriftenreihe*, *64*, 45–53.

3 Spellmann, H., Meesenburg, H., Schmidt, M., Nagel, R.-V., Sutmöller, J., and **Albert, M.** (2015). Klimaanpassung ist Vorsorge für den Wald. Strategien zur Stabilisierung der Wälder - ohne Aktionismus. *proWald - Magazin des Dt. Forstvereins*, (11), 4–10.

4 Fleck, S., **Albert, M.**, Plasil, P., Nagel, R.-V., Sutmöller, J., Ahrends, B., Schmidt, M., Evers, J., Hansen, J., Overbeck, M., Schmidt, W., Spellmann, H., and Meesenburg, H. (2015). *Pilotstudie zu den lokalen Auswirkungen des Klimawandels auf die Forstwirtschaft in ausgewählten Regionen Sachsen-Anhalts*. Göttingen: Universitätsverlag Göttingen. 221 S.

5 **Albert, M.**, Schmidt, M., and Hansen, J. (2014). Auswirkungen von Klimaszenarien und Nutzungsstrategien in Waldentwicklungsprojektionen. In *Tagungsband Sektion Ertragskunde des DVFFA*.

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8. Reprints of Publications of this Habilitation Thesis

I ALBERT, M., NAGEL, R.-V., SUTMÖLLER, J. AND SCHMIDT, M.: 2018
Quantifying the effect of persistent dryer climates on forest productivity and implications for forest planning: a case study in northern Germany
Forest Ecosystems

II ALBERT, M., NAGEL, R.-V., NUSKE, R.S., SUTMÖLLER, J. AND SPELLMANN, H.: 2017
Tree Species Selection in the Face of Drought Risk – Uncertainty in Forest Planning
Forests

III FLECK, S., AHRENDS, B., SUTMÖLLER, J., ALBERT, M., EVERS, J. AND MEESENBURG, H.: 2017
Is Biomass Accumulation in Forests an Option to Prevent Climate Change Induced Increases in Nitrate Concentrations in the North German Lowland?
Forests

IV THIELE, J.C., NUSKE, R.S., AHRENDS, B., PANFEROV, O., ALBERT, M., STAUPENDAHL, K., JUNGHANS, U., JANSEN, M. AND SABOROWSKI, J.: 2017
Climate change impact assessment – A simulation experiment with Norway spruce for a forest district in Central Europe
Ecological Modelling

V ALBERT, M., LEEFKEN, G., NUSKE, R.S., AHRENDS, B., SUTMÖLLER, J. AND SPELLMANN, H.: 2016
Auswirkungen von klimatischer Unsicherheit auf die Forstplanung am Beispiel von vier Regionen im norddeutschen Tiefland
Allg. Forst- u. J.-Ztg.

VI ALBERT, M., HANSEN, J., NAGEL, J. SCHMIDT, M. AND SPELLMANN, H.: 2015
Assessing risks and uncertainties in forest dynamics under different management scenarios and climate change
Forest Ecosystems

VII ALBERT, M. AND SCHMIDT, M.: 2012
Standort-Leistungs-Modelle für die Entwicklung von waldbaulichen Anpassungsstrategien unter Klimawandel
Archiv f. Forstwesen u. Landsch.ökol.

VIII ALBERT, M. AND SCHMIDT, M.: 2010
Climate-sensitive modelling of site-productivity relationships for Norway spruce (*Picea abies* (L.) Karst.) and common beech (*Fagus sylvatica* L.)
Forest Ecol. Manage.

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Forest Ecosystems

RESEARCH Open Access

Quantifying the effect of persistent dryer climates on forest productivity and implications for forest planning: a case study in northern Germany

Matthias Albert[1*], Ralf-Volker Nagel[1], Johannes Sutmöller[2] and Matthias Schmidt[1]

Abstract

Background: Forest management decisions are based on expectations of future developments. For sound decisions it is essential to accurately predict the expected values in future developments and to account for their inherent uncertainty, for example the impact of climate change on forests. Changing climatic conditions affect forest productivity and alter the risk profile of forests and forest enterprises. Intensifying drought stress is seen as one major risk factor threatening forest management in the north German lowlands. Drought stress reduces tree growth and vitality and might even trigger mortality. But so far, it is not possible to quantify effects of a persistent dryer climate on forest productivity at a level suitable for forest management.

Methods: We apply a well-established single-tree forest growth simulator to quantify the effect of persistent dryer climates on future forest productivity. We analyse the growth of Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.) and oak (*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.) in two forest regions in the north German lowlands for a time interval of 60 years until 2070. The growth response under three different climate projections is compared to a baseline scenario.

Results: The results show clear differences in volume increment to persistent dryer climates between tree species. The findings exhibit regional differences and temporal trends. While mean annual increment at biological rotation age of Scots pine and oak predominantly benefits from the projected climate conditions until 2070, beech might suffer losses of up to 3 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ depending on climate scenario and region. However, in the projection period 2051 to 2070 the uncertainty ranges comprise positive as well as negative climatic effects for all species.

Conclusions: The projected changes in forest growth serve as quantitative contributions to provide decision support in the evaluation of, for example, species future site suitability and timber supply assessments. The analysis of productivity changes under persistent dryer climate complements the drought vulnerability assessment which is applied in practical forestry in northwestern Germany today. The projected species' productivity has strong implications for forest management and the inherent uncertainty needs to be accounted for.

Keywords: Climate change, Forest growth, Forest productivity, Persistent dryer climate, Simulation study, Uncertainty

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Background

A more and more aggravating climate change shakes one of the key features of forest planning, i.e. to assign species for cultivation according to site suitability (Brang et al. 2008). Formerly, species selection depended on static parameters, e.g. soil nutrients, site water budget and silviculture region as a substitute for regional climatic conditions. In the meantime, the rapidly changing climate affects the primary growing conditions well below a classical rotation period (e.g. Boisvenue and Running 2006; Pretzsch et al. 2014; Kohnle et al. 2014; Aertsen et al. 2014). Thus, forest planning has to account for dynamic site conditions and management decisions are based on expectations of future site developments. Besides projections of site conditions species selection for future forests depends on species resilience, its productivity and ecological conduciveness to name but a few. For sound decisions it is essential to accurately predict the expected values in future developments and to account for their inherent uncertainty, for example the impact of different climate change scenarios on forests.

Spittlehouse (2005) categorizes forest management actions to encounter climate change into societal adaptation, adaptation of the forest and adaptation to the forest. Societal adaptation covers adjusting people's expectations on forest services and changes in forest policy on management and conservation. Adaptation of the forest includes, for example, species selection. And adaptation to the forest comprises amongst others applying the adequate silvicultural regime, harvesting and utilization of more salvage wood and modifications in wood processing. All these measures can be proactive approaches to reduce vulnerability and enhance recovery in advance or reactive responses to diminish the impact afterwards (Ogden and Innes 2007).

According to Spittlehouse and Stewart (2003) determination of vulnerabilities and critical thresholds is an integral part of forest management adaptation to climate change. One of the core issues for forest management in the north German lowlands is the vulnerability of forests to projected changes in precipitation pattern. The most likely reduced rainfall in the growing season and increasing evapotranspiration due to rising temperatures will result in persistent dryer conditions or even drought stress on many forest sites. This will most likely affect forest productivity and alter the risk profile of forests and forest enterprises (Lindner et al. 2010, 2014).

As drought stress reduces tree growth and vitality and might even trigger tree mortality (Hanson and Weltzin 2000; Allen et al. 2010), adaptation measures should account for the effects of persistent dryer climate conditions on forests (Hogg and Bernier 2005). Two main future drought types can be distinguished. First, intense and more frequent dry spells in the growing season will occur in central Europe (IPCC 2013; Lindner et al. 2014). Second, the decrease of mean precipitation in the growing season along with increasing mean temperatures will result in long-term persistent dryer conditions. Many studies quantify growth reactions after short-term extreme drought events (e.g. Orwig and Abrams 1997; Klos et al. 2009; Michelot et al. 2012; Weber et al. 2013). These exemplary studies confirm the obviously negative effect of extreme drought events on tree growth while evincing differences according to for example species, sites, forest layers or distribution range. While these growth declines after singular short-term drought events are mostly reversible on many sites (Bigler et al. 2006; Zingg and Bürgi 2008; Sutmöller et al. 2017), still with increasing frequency of drought events the short-term growth reductions might aggregate to considerable losses in the long run.

Other case studies investigate the long-term effect of persistent dryer conditions on forest productivity. Kint et al. (2012) observed a drought-induced growth decline for beech in Belgium since the 1960s. Piovesan et al. (2008) related the reduction in stand basal area increment observed for beech forests in the central Appennines, Italy, since the last three to four decades to dryer conditions. Furthermore, they found evidence for a stronger effect of temperature increase to drought than reduction of precipitation. They conclude that for beech persistent drought stress will overcompensate the positive influence of an earlier beginning of the growing season. Barber et al. (2000) assume drought stress as one possible explanation for the lessening of the positive effect of temperature increase on radial growth of white spruce in interior Alaska. Based on observed radial growth data from Scots pine, European beech and Pedunculate oak in northern Germany Bauwe et al. (2015) developed regression models and projected growth until 2100 using the emission scenario A1B for future climate conditions. Their simulation results show growth reductions for beech and oak with increasingly dryer conditions while Scots pine did not display a clear trend.

These case studies give evidence for long-term growth trends which correspond to persistent drought stress. But so far, it is not possible to satisfactorily quantify effects of persistent dryer climates on a level suitable for forest management (e.g. Adams et al. 2009; Choat et al. 2012; Anderegg et al. 2013). Until now, in Germany forest planning relies on drought vulnerability thresholds which are based on expert knowledge and/or singular observations on monitoring plots or experimental sites or current presence/absence observations in relation to various environmental factors (e.g. Spellmann et al. 2011, 2015; Kölling et al. 2009; Falk et al. 2013; Hanewinkel et al. 2014). To enhance the understanding of

interactions between persistent dryer climates and forest productivity and to harness quantitative drought assessment information for forest planning we pursue three goals in the presented research: (1) We quantify the effect of persistent dryer climates on forest productivity in two north German forest regions until 2070. This is pivotal as we want to complement the currently qualitative drought vulnerability assessment by quantitative effects of climate change on forest growth. For this purpose we apply a single-tree growth simulator which already serves as a prediction tool for practical forest planning in northern Germany. For our analysis we present and employ an extended site-sensitive model version. (2) We quantify the uncertainty inherent in climate change by applying three different climate projections. (3) Finally, we point out how forest growth simulations of actual current forests in a specified region and for a defined projection period might add information to support forest planning decisions. This analysis serves as a first step towards a quantitative drought vulnerability assessment to be considered in forest management on a regional basis, for example for silvicultural management strategies, species selection decisions or long-term timber supply studies.

Methods

This study is based on projections of forest development applying the site-sensitive version of the single-tree growth simulator *WaldPlaner 2.1* (Hansen and Nagel 2014). Site-sensitivity comprises, among others, effects of climatic conditions on tree growth, i.e. the impact of precipitation and temperature. In the simulation design we vary the climatic conditions according to three climate scenarios while all other factors are held constant. Thereby, differences in forest growth in the simulation results are traced back solely to variations in climate.

Study area

In this study we use forest inventory data from two regions *Uelzen* and *Fläming* in the north German lowlands (Fig. 1).

The two regions feature different current climatic and site conditions with favourable water supply in *Uelzen* and already today problematic precipitation and available water capacity in the lower parts of the *Fläming* region at least for less tolerant tree species (Table 1). Climate change is believed to increase water shortage in the future. Standard forest management surveys (cf. Böckmann et al. 1998) provide information on forest stands at 999 locations in *Uelzen* and 1008 locations in *Fläming*.

Model description

Figure 2 displays the individual components of the *WaldPlaner 2.1* simulation framework to project forest development (for equations and parameters refer to Hansen and Nagel 2014). Single growth functions and a previous version of the model system have been extensively validated (Schmidt and Hansen 2007; Vospernik et al. 2010, 2015; Nagel 2013; Sprauer and Nagel 2015). One growth projection step commonly covers a 5-year period. The single tree data base stores individual tree parameters as described in the initialization data section below. An ingrowth routine adds trees to the data set and the density-dependent mortality model predicts single tree mortality. The competition

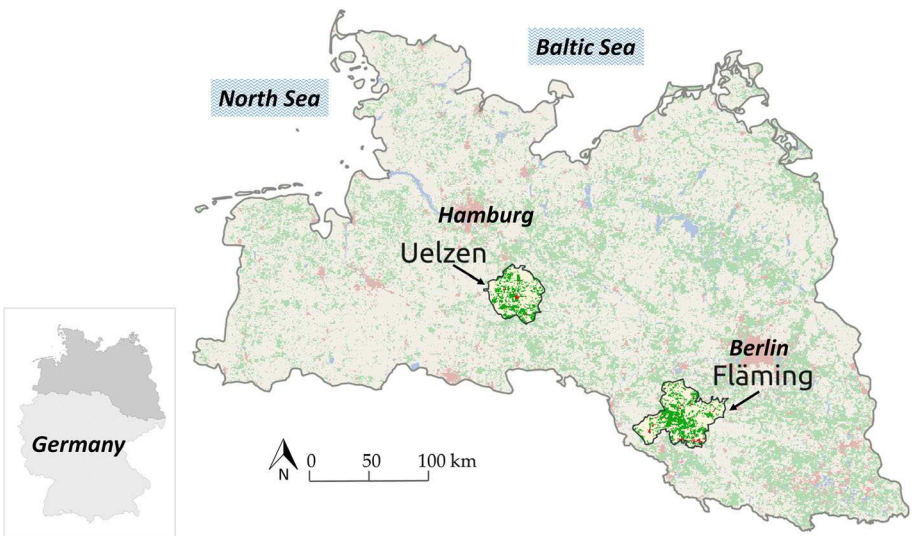


Fig. 1 The two study regions *Uelzen* and *Fläming* in the north German lowlands near the cities of Hamburg and Berlin (land cover data in the overview map © ESA / ESA GlobCorine Project, led by Université Catholique de Louvain)

Table 1 Characteristics of *Uelzen* and *Fläming* (climate values as averages in the period 1991 to 2010; cwb_{gs}: climatic water balance (=precipitation-evapotranspiration for grass) in growing season; awc: available water capacity)

	Species area proportion (%)			Annual mean temp. (°C)	Annual prec. (mm)	cwb_{gs} (mm)	Mean awc (mm)
	pine	beech	oak				
Uelzen	61.3	4.8	6.1	9.2	727	-65	110
Fläming	73.5	12.8	5.9	9.8	572	-216	123

index (c66) and the change in the competition index (c66c) due to tree removal and mortality are calculated afterwards. Basal area increment (bai) is a function of the tree parameters age, crown surface area (csa), the competition index and its change. The updated diameter at breast height (dbh) is then used to derive an updated tree height applying the site-sensitive longitudinal height-diameter model by Schmidt (2010) which utilizes climate and soil data. When applying climate scenarios in impact studies it is recommended to use average values of 30-year periods (IPCC 2013, p. 1450). Therefore, for each 5-year growth prediction the values of mean annual temperature sum in the growing season and aridity index are calculated for a 30-year period centered around the respective projection period and applied to the height-diameter model. Furthermore, development of crown surface area (csa) depends on crown width and crown length which, in turn, are functions of tree diameter and tree height. Thus, as tree height development is predicted site-sensitively soil and climate parameters also affect diameter increment. Finally, thinning and harvesting rules can be applied.

The height-diameter model by Schmidt (2010) constitutes the site-sensitive core of the single-tree growth model. It builds on a height-diameter model by Lappi (1997) which is a modified version of the Korf function (Eq. 1).

$$\ln\left(H_{kti}\right) = A - Bx_{kti} + \epsilon_{kti} \tag{1}$$

with

$$x_{kti} = \frac{\left(dbh_{kti}+\lambda\right)^{-C} - \left(30+\lambda\right)^{-C}}{\left(10+\lambda\right)^{-C} - \left(30+\lambda\right)^{-C}} \tag{1.1}$$

and

H_{kti}: tree height value [m] for tree i in stand k at time t with $\epsilon_{kti} \sim N(0,\sigma^2)$;

dbh_{kti}: dbh of tree i [cm] in stand k at time t;

A, B, C, λ: parameters of the height-diameter model.

The parameter values of C and λ in Eq. 1.1 are optimized to yield minimum quadratic deviation of the model. Further on, these values are fixed and Lappi's model becomes linear. As convenient properties Lappi's

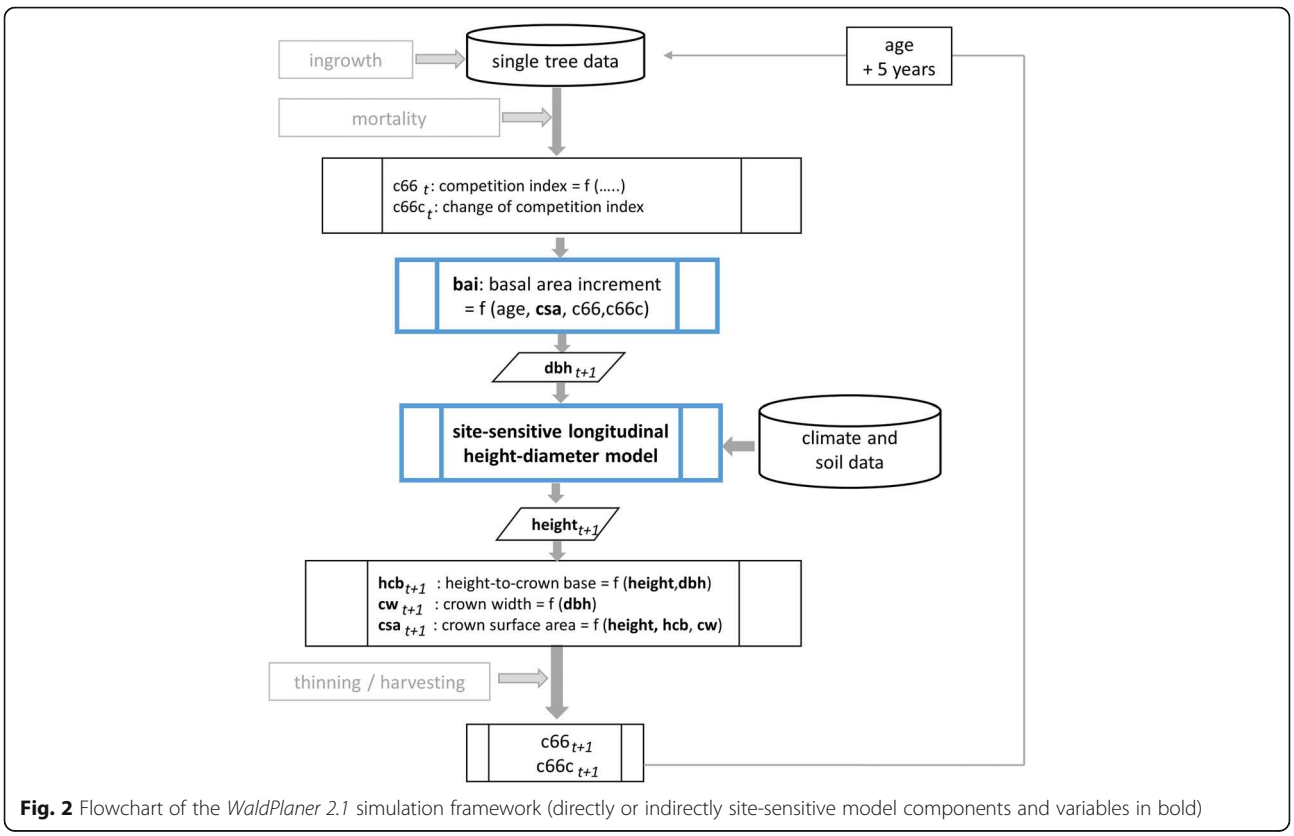


Fig. 2 Flowchart of the *WaldPlaner 2.1* simulation framework (directly or indirectly site-sensitive model components and variables in bold)

model formulation is biologically interpretable with A being the level and B the slope of the height-diameter curve on logarithmic scale and the two parameters show low collinearity.

The longitudinal height-diameter model (Eq. 2) by Schmidt (2010) is formulated as a generalized additive model.

$$\begin{aligned}\ln\{E(H_{kti})\} = \widehat{p_{1a}} + p_{2a}\left(1-e^{-\widehat{p_{3a}}age_{kti}}\right)^{\widehat{p_{4a}}} + f_{2a}(rd_{kti}) \\ + f_{3a}(yg_{ki}) + f_{4a}(tsum_k) + f_{5a}(ari_k) \\ + f_{6a}(lon_k, lat_k) - p_{0b}x_{kti} - p_{1b}age_{kti}x_{kti} - p_{2b}elev_k x_{kti}\end{aligned} \quad (2)$$

with

$E(H_{kti})$: expected value of tree height [m] for tree i in stand k at time t with $H_{kti} \sim N(\exp(\eta_{kti}), \sigma^2)$;

age_{kti}: age [years] of tree i in stand k at time t;

rd_{kti}: relative diameter [cm] as the ratio of dbh of tree i in stand k at time t and the respective quadratic mean diameter;

yg_{ki}: year of germination of tree i in stand k;

$tsum_k$: average temperature sum in the growing season [°C] in stand k in the climatic reference period 1961 to 1990;

ari_k: average aridity index value by De Martonne (1926) in stand k in the climatic reference period 1961 to 1990;

lon_k, lat_k: Gauss-Krueger coordinates of stand k's centroid;

$elev_k$: elevation [m] above sea level of stand k's centroid;

$\widehat{p_{xa}}$: parameter constants (with x = 1,3 and 4, respectively) of Chapman-Richards function used to approximate the age trend of the original parameter A (see formula 1);

p_{2a}: parameter of Chapman-Richards function used to approximate the age trend of the original parameter A (see formula 1);

f_{xa}: one-dimensional smoothing regression term (with x = 2, 3, 4 and 5, respectively) to describe non-linear effects of independent variables on the original parameter A (see formula 1);

f_{6a}: two-dimensional smoothing regression spline to account for large scale spatial autocorrelation of the original parameter A (see formula 1);

p_{xb}: parameter of linear effects (with x = 0, 1 and 2, respectively) on the original parameter B (see formula 1).

In a first step the expected tree height value is estimated using, among others, the climate variables temperature sum in the growing season (*tsum*) and De Martonne's (1926) aridity index (*ari*) as described in the climate data section below. The model is parameterized based on data of the first two German National Forest Inventories, the forest enterprise inventory of Lower Saxony and experimental plots for Pedunculate and Sessile oak, European beech, Norway spruce, Douglas-fir and Scots pine in Germany (Eq. 2).

The second stage of the height-diameter model (Eq. 3) uses the predictors available water capacity (*awc*), soil nutrients (*nut*) and ground water class (*gw*) to further enhance site sensitivity (cf. Fleck et al. 2015, p. 47). A separate second stage is necessary as the soil parameters were not available throughout Germany during model development but only for Lower Saxony.

$$\begin{aligned}\ln\{E(H_{kti})\} = \ln\left\{E(\widehat{H_{kti}})\right\} + f_{1a}(awc_k)Z_k \\ + gw_k^T\beta_1 + nut_k^T\beta_2 \\ + f_{2a}(lon_k, lat_k)\end{aligned} \quad (3)$$

with

$E(H_{kti})$: expected tree height value [m] for tree i in stand k at time t with $H_{kti} \sim N(\exp(\eta_{kti}), \sigma^2)$;

$E(\widehat{H_{kti}})$: estimated expected tree height value [m] for tree i in stand k at time t using Eq. 2;

awc_k: available water capacity in stand k [mm];

Z_k: indicator variable to define ground water impact in stand k with categories "ground water impact" and "no ground water impact";

gw_k: vector of the categorical variable to define ground water impact with categories "no ground water impact (ground water table > 2.5 m)", "low to medium ground water impact (ground water table 0.95 to 2.5 m)" and "medium to strong ground water impact (ground water table < 0.95 m)";

nut_k: vector of the categorical variable to define soil nutrient supply in stand k (1 = very poor, 2 = poor, 3 = medium, 4 = good, 5 = rich; including further differentiation using + and – variants);

lon_k, lat_k: Gauss-Krueger coordinates of stand k's centroid;

f_{1a}: one-dimensional smoothing regression spline to describe the non-linear effect of awc;

f_{2a}: two-dimensional smoothing regression spline to account for large scale spatial autocorrelation;

β_1, β_2: coefficient vectors.

The estimated expected tree height values calculated with Eq. 2 are used as an offset in the second model stage (Eq. 3).

Both stages of the site-sensitive height-diameter model are implemented in the forest simulation framework *WaldPlaner*. Various studies already proved the climate-sensitivity and biological plausibility of the model (Schmidt 2010; Albert et al. 2015, 2016; Fleck et al. 2015). In a comparative analysis bias and precision of the model proved satisfying (Albrecht et al. 2017).

Soil data

The height-diameter model requires among others soil data as predictors. For each of the 2007 locations in *Uelzen* and *Fläming* information on soil nutrients, available water capacity and a classification of groundwater availability is provided. Details are given in Albert et al. (2015, 2016). In this analysis, however, soil data is of lower interest as the comparison of tree growth focusses on the climate aspect. Nevertheless, due to the interaction between climate and soil parameters the effect of soil properties may differ among the simulation runs.

Climate data

The 5th IPCC report introduces a new generation of climate scenarios to depict the future concentration of global warming gases in the atmosphere (IPCC 2013). Four scenarios, denominated representative concentration pathways (RCP), are selected in the report. The scenarios differ in the underlying pathways, i.e. under RCP 8.5 rising CO_2-equivalents after 2100 (>1,370 ppm in 2100), two pathways stabilizing the CO_2-equivalents on different levels in 2100 (~850 ppm under RCP 6.0 and ~650 ppm under RCP 4.5), and a peak and decline pathway with a maximum of ~490 ppm before 2100 under RCP 2.6.

Based on the climate scenario *RCP 8.5* (Moss et al. 2010; van Vuuren et al. 2011) three climate projections from 2011 to 2070 specify the range of potential climate change in this study. The three projections are calculated using the global circulation models *INM-CM4* (Volodin et al. 2010), *ECHAM6* (Stevens et al. 2013) and *ACCESS1.0* (Bi et al. 2013).

The regional climate model *STARS* (Orlowsky et al. 2008) further downscales the realisations of the global circulation models to Germany. In the period 2051 to 2070 the projected temperature based on *INM-CM4* shows a 1.1°C deviation from today's (1991 to 2010) mean annual temperature for the north German lowlands. *ECHAM6* exhibits a 1.6°C deviation and *ACCESS1.0* 2.7°C. Subsequently, these three climate scenarios are labelled minimum, median and maximum climate run. Furthermore, a retrospective climate scenario from 1951 to 2010 is projected using *STARS* based on daily weather records from 1218 climate stations run by the *German Weather Service*. Thus, a consistent time series from 1951 to 2070 is provided for each climate station.

The site-sensitive height-diameter model applies the climate parameters temperature sum in the growing season and aridity index as predictors. The beginning of the growing season is defined using the model *LNVAR* by Menzel (1997, p. 52 ff). The end is calculated according to suggestions by Walther and Linderholm (2006) and Frich et al. (2002) using either the temperature criterion or the short day criterion, whichever is met first. The temperature criterion applies, if the moving average of mean temperature in a 7-day period between July and October falls below 5°C. We follow von Wilpert (1990) and fix the short day criterion, defined as the day length needed for xylem growth, to October 5. De Martonne (1926) defines the aridity index as the ratio of annual precipitation sum [mm] and mean annual temperature [°C] +10. We calculate the aridity index based on annual values as the soil functions as a water storage. Finally, the temperature sum in the growing season and the aridity index is provided for all 2007 locations in *Uelzen* and *Fläming* in yearly resolution from 1951 to 2070 by interpolating the projected values of all climate stations within a 20 km distance from the respective location. The interpolation is done using *WaSiM-ETH*'s (Schulla 2015; Schulla and Jasper 2007) distance-weighted regression model.

Figure 3 illustrates how the temperature sum in the growing season and aridity index develop differently in *Uelzen* and *Fläming* over time. The linear trend lines clearly display an increase in temperature over time (Fig. 3a and b). For the aridity index, with lower values indicating dryer conditions, the findings show increasing dryer conditions with time (Fig. 3c and d). The temperature trend in *Uelzen* is on a slightly lower level than in *Fläming*. However, the aridity index states much dryer conditions in *Fläming*.

The baseline climate scenario is used as a reference in this study. It requires to avoid any temporal changes in temperature sum and aridity index looking at 20-year averages. Annual fluctuations, however, are necessary to display short-term climate variability. Therefore, the annual climate values of the reference period 1991 to 2010 are randomly mixed to create new sequences for each of the three projection periods 2011 to 2030, 2031 to 2050, and 2051 to 2070. This procedure returns identical means and variances for the three future periods.

Initialization data

Using the forest simulation framework *WaldPlaner 2.1* (Hansen and Nagel 2014) 2007 forest stands with individual trees are generated based on the provided stand information, i.e. for every species and for each layer values on age, quadratic mean diameter, and volume per hectare as well as species proportions and stocking degree. Single tree heights are estimated site-sensitively applying the height-diameter model. These initial tree heights are further updated in each 5-year prediction period with newly predicted values from the height-diameter model. As the survey data has different inventory dates all stands are projected to 2010 as a uniform starting year for the growth projections.

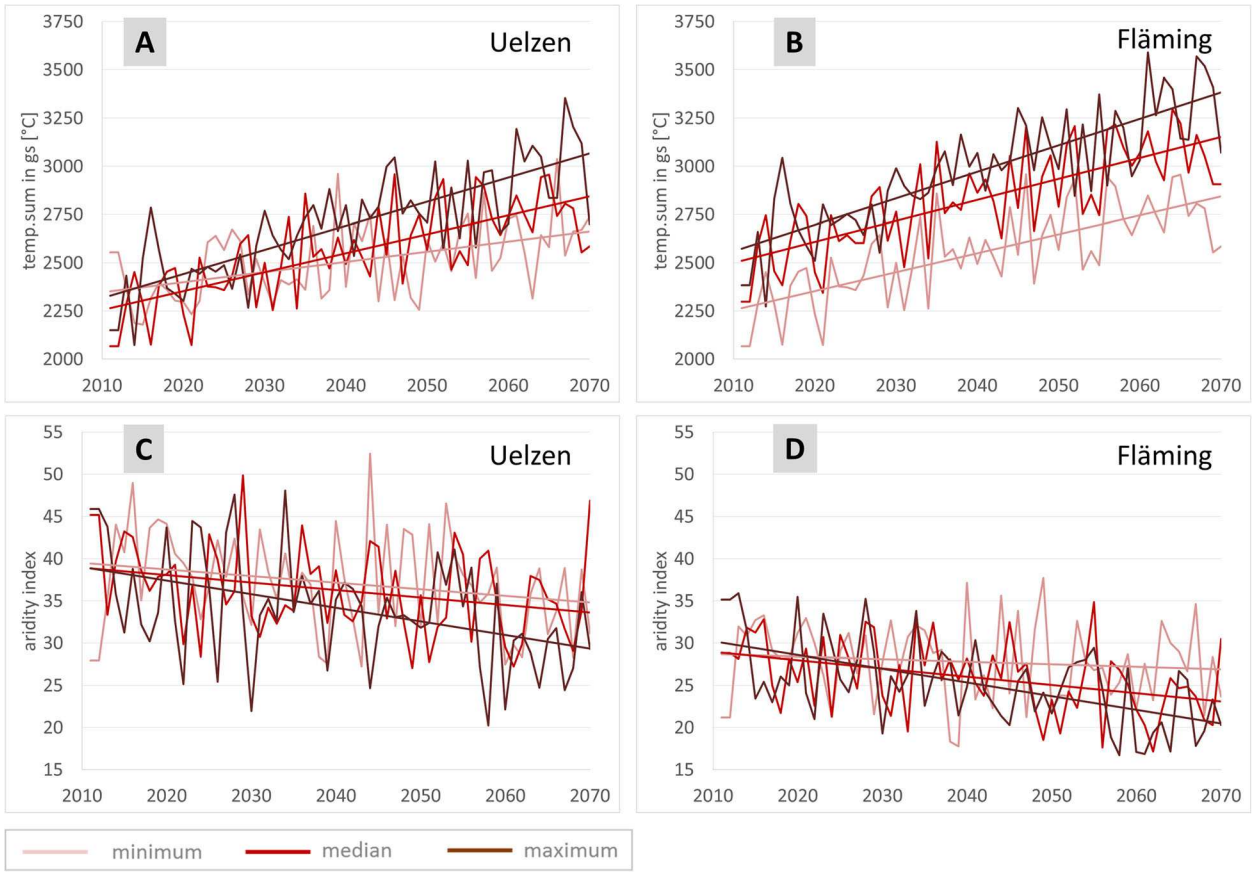


Fig. 3 Climate parameters over time for the simulation period 2011 to 2070 projected with STARS using RCP 8.5 (**a** average temperature sum in the growing season in *Uelzen* under the minimum, median and maximum climate run, **b** corresponding figure for *Fläming*, **c** average aridity index value in *Uelzen* under the minimum, median and maximum climate run, **d** corresponding figure for *Fläming*)

The effect of different climatic conditions on single-tree volume increment, periodic volume increment at stand level and mean annual increment at biological rotation age of the three most abundant tree species in *Uelzen* and *Fläming*, i.e. Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.) and Pedunculate and Sessile oak (*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.), is analysed comparing the simulation results under three different climate projections to a baseline scenario with constant climate until 2070. For the analysis we distinguish three 20-year projection periods, i.e. the first period from 2011 to 2030, the second from 2031 to 2050 and the third from 2051 to 2070. In the course of the simulations more and more individual trees are removed by the thinning and harvesting algorithm or due to mortality and new trees are introduced by the ingrowth algorithm. Ingrowth, on the other hand, is not identical on a single tree basis among the four simulation runs. Thus, although starting with quite a number of individuals in 2011 in later periods the data base for tree-wise comparison becomes too small especially in younger age classes. Therefore, tree collectives are selected for comparison (cf. Additional file 1: Tables S1 and S2). Under each scenario all trees of one species, i.e. pine, beech or oak, being alive at the end of the respective 20-year projection period or being cut or dying because of density induced mortality during the period form one collective. As a result 9 collectives under the baseline scenario (3 periods × 3 species) are compared to 27 collectives under climate change (3 periods × 3 species × 3 climate scenarios). For each tree within the collectives the mean annual volume increment is predicted.

The collectives to be compared, i.e. per species and within one period, consist of roughly the same number of individuals, most of them being identical, and have a very similar age span. The tree dimensions vary as projected tree growth depends on the assumed climate conditions. The establishment of new stands and possible species conversions, influence the age structure of all collectives as well. Under each simulation run the same settings for the business-as-usual silvicultural treatment scenario and the same rule-sets for regeneration and forest conversion apply (cf. Albert et al. 2015).

Deriving the climatic effect on volume increment

Based on the tree collectives described above the climate effect on mean single tree volume increment [$m^3 \cdot yr^{-1}$] over initial volume classes is calculated separately for tree species and projection period as the deviation between the respective climate scenario and the baseline scenario:

$$\Delta \bar{iv}_{jx} = \frac{\sum_{i=1}^{n_{j_x}} iv_{ij_x}}{n_{j_x}} - \frac{\sum_{i=1}^{n_{j_b}} iv_{ij_b}}{n_{j_b}} \quad (4)$$

with

iv_{ijx}, iv_{ijb}: volume increment of tree i in initial volume class j under climate scenario x and under baseline b [$m^3 \cdot yr^{-1}$];

x: climate scenario (minimum, median, maximum);

n_{jx}, n_{jb}: number of trees in initial volume class j under climate scenario x and under baseline b.

Periodic volume increment is also calculated based on the tree collectives, however, only trees of the dominant stand are taken into account as it is common in forest planning to differentiate between layers. The deviation in periodic volume increment [$m^3 \cdot ha^{-1} \cdot yr^{-1}$] between the respective climate scenario and the baseline scenario is derived separately for each of the three species and for each of the three projection periods as follows:

$$\Delta i\bar{V}_x = \frac{\sum_{j=1}^{m_x}\left[\left(\sum_{i=1}^{n_{kj_x}} iv_{ij_x}\right)/ba_{j_x}\right]}{m_x} - \frac{\sum_{j=1}^{m_b}\left[\left(\sum_{i=1}^{n_{kj_b}} iv_{ij_b}\right)/ba_{j_b}\right]}{m_b} \quad (5)$$

with

iv_{ijx}, iv_{ijb}: volume increment of tree i in stand j under climate scenario x and under baseline b [$m^3 \cdot yr^{-1}$];

ba_{jx}, ba_{jb}: proportion of respective species basal area in stand j under climate scenario x and under baseline b;

x: climate scenario (minimum, median, maximum);

n_{kjx}, n_{kjb}: number of trees of species k in stand j under climate scenario x and under baseline b;

m_x, m_b: number of stands under climate scenario x and under baseline b.

The climate effect on mean annual increment at biological rotation age (MAI_{max}) is derived only for stands which are or soon will be close to rotation age, i.e. European beech and Scots pine stands aged 81 and older and oak stands aged 121 and older at the end of the respective projection period. The rationale of this restriction is that we derive MAI_{max} based on the simulated stand's top height using static site index assessment refraining from the dynamic influence of changing site conditions which is a permissible approximation in this case. In order to obtain MAI_{max}-values for younger stands taking climate change into consideration we would need to project forest growth climate-sensitively for younger stands beyond 2070. However, for this study no data on climate projections beyond 2070 is available. Therefore, only stands close to rotation age warrant a meaningful interpretation of MAI_{max}-values under climate change conditions.

The site index at age 100 (SI) is estimated using the yield tables by Nagel (2017) based on the simulated top height and age of beech, oak and pine occurrence in each stand i at the end of the respective projection period. The SI-values are further transformed into MAI_{max}-values applying following functions:

$$\text{European beech}: MAI_{max_i} = 0.0139 \times SI_i^2 - 0.187 \times SI_i + 1.5186 \quad (6a)$$

$$\text{Sessile and pedunculate oak}: MAI_{max_i} = 0.0046 \times SI_i^2 + 0.1855 \times SI_i \quad (6b)$$

$$\text{Scots pine}: MAI_{max_i} = 0.003 \times SI_i^2 + 0.3702 \times SI_i - 2.6784 \quad (6c)$$

Finally, the climate effect on MAI_{max} [$m^3 \cdot ha^{-1} \cdot yr^{-1}$] is calculated separately for tree species and projection period as follows:

$$\Delta \bar{MAI}_{max_x} = \frac{\sum_{i=1}^{n} MAI_{max_{ix}}}{m_x} - \frac{\sum_{i=1}^{m} MAI_{max_{ib}}}{m_b} \quad (7)$$

with

$MAI_{max_{ix}}$, $MAI_{max_{ib}}$: mean annual increment at biological rotation age in stand i under climate scenario x and under baseline b [$m^3 \cdot ha^{-1} \cdot yr^{-1}$];

x: climate scenario (minimum, median, maximum);

m_x, m_b: number of stands under climate scenario x and under baseline b.

Results

It is the primary objective of this simulation study to quantify the effect of long-term persistent dryer climates on forest productivity and to derive tangible recommendations for regional forest planning. Thus, we first compare volume increment under climate change to volume increment under constant current climate. The analysis based on mean values from single trees provides deeper insights into individual growth reactions to climate change. The innate age trend on volume increment is eliminated by looking at deviations. However, the absolute value of volume increment depends on initial tree dimension (c.f. Berrill and O'Hara 2014). Consequently, the larger the initial volume the more likely a large

deviation between volume increment under climate change and constant climate will occur.

Five general findings are apparent when analyzing the climatic effects on mean single-tree volume increment over initial volume classes (Figs. 4 and 5). (1) The expected trend of larger deviations in absolute terms in larger initital volume classes is obvious for all species in both regions except for Scots pine in *Uelzen*. Accompanying, the uncertainty range prominently increases over initial volume classes, i.e. the differences in volume increment deviation among the three climate scenarios are relatively minor for small trees but increase to a significant extent for larger trees. (2) Climate change has a positive effect throughout initial volume classes in most cases in the first period. This effect diminishes or even reverses over time. (3) While the uncertainty range includes only positive deviations in most cases in the first period, the uncertainty range indicates positive as well as negative climate impacts on volume increment throughout initial volume classes in most cases in the second and third period. This is especially apparent for Scots pine in the third period and for European beech as well as oak in the second and third period in both regions. (4) Scots pine is the least sensitive species regarding the climatic effect on volume increment followed by oak and beech being affected the strongest (please observe the dashed lines in Figs. 4 and 5 indicating different scales of the vertical axes). (5) Furthermore, the climatic effect is stronger in *Fläming* than in *Uelzen*.

Deviations in mean single-tree volume increment over initial volume classes help to analyze climate effects on tree growth on the scale of biological productivity. However, the climatic effect on volume increment at the forest stand level might differ. Thus, it is also necessary to report results of deviations in periodic volume increment. On the scale of area productivity using periodic

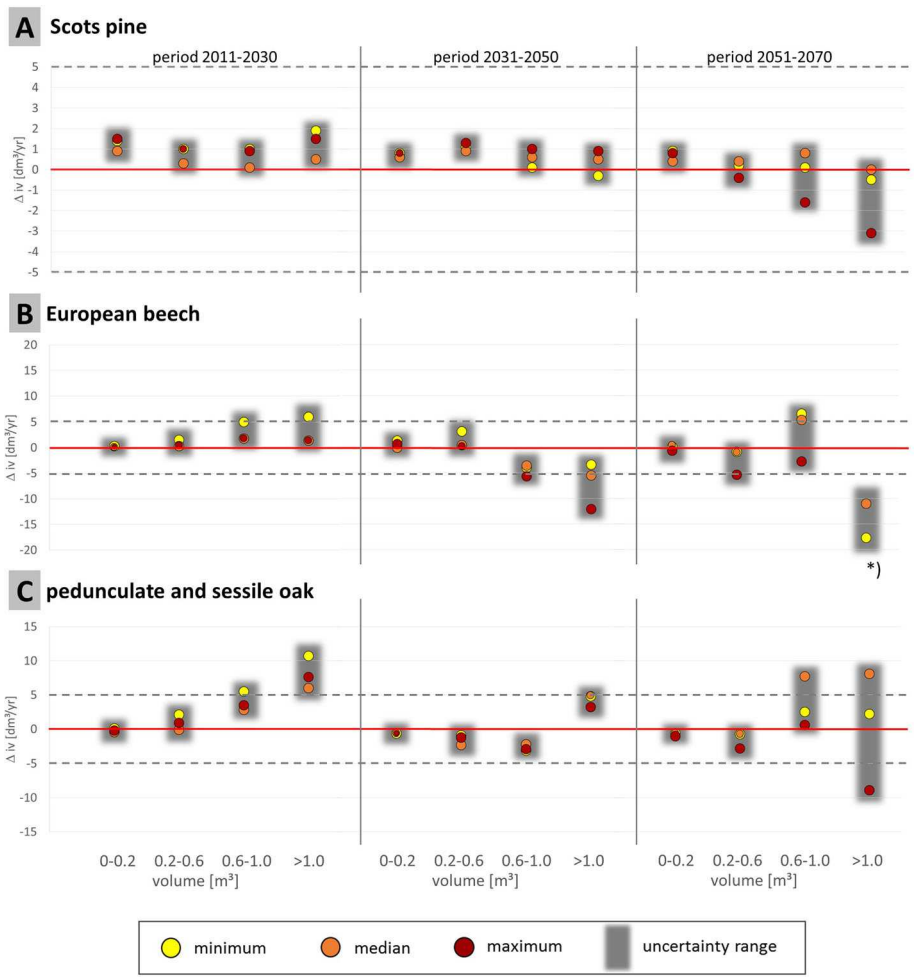


Fig. 4 Deviation in mean single-tree volume increment for different classes of initial single-tree volume between the respective climate scenario (minimum (yellow), median (orange) and maximum (dark red)) and the base line scenario for Scots pine (**a**), European beech (**b**) and Pedunculate and sessile oak (**c**) in *Uelzen* (blurred gray area indicates the uncertainty range; *) no observations under maximum climate scenario; dashed lines emphasize the –5 $dm^3 \cdot yr^{-1}$ to 5 $dm^3 \cdot yr^{-1}$ range for better comparison due to unequal scaling of the vertical axes)

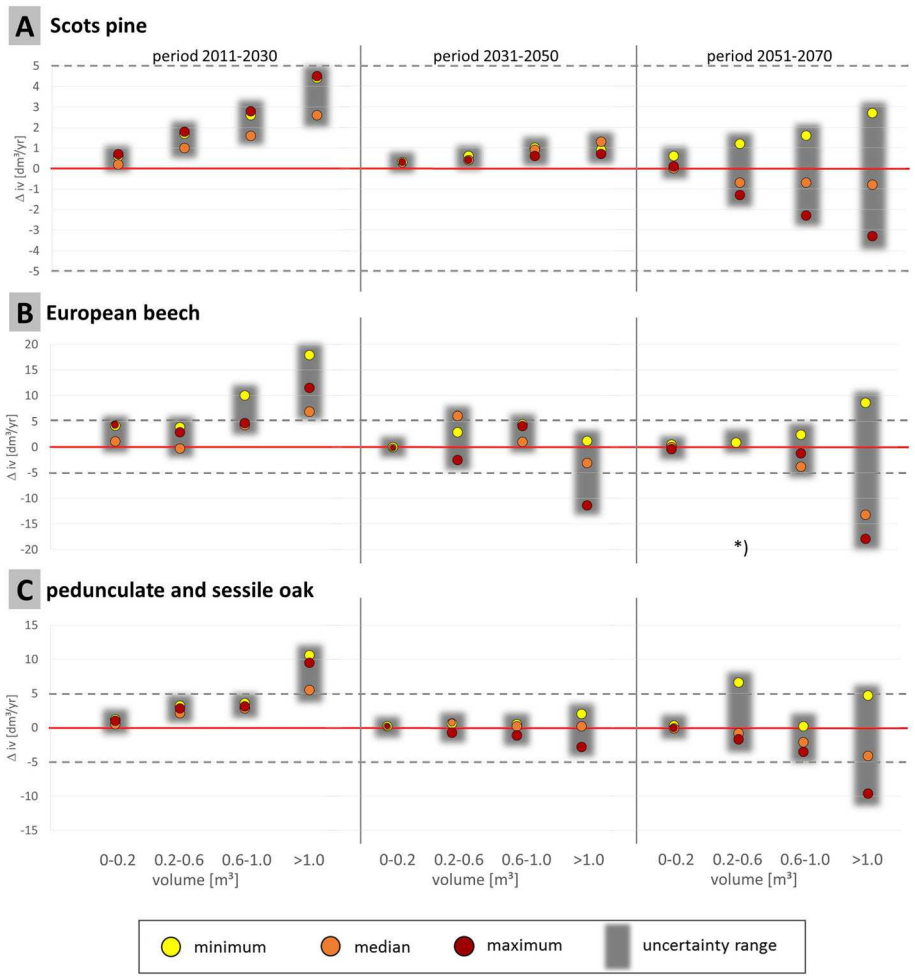


Fig. 5 Deviation in mean single-tree volume increment for different classes of initial single-tree volume between the respective climate scenario (minimum (yellow), median (orange) and maximum (dark red)) and the base line scenario for Scots pine (**a**), European beech (**b**) and Pedunculate and sessile oak (**c**) in *Flaeming* (blurred gray area indicates the uncertainty range; *) no observations under median and maximum climate scenario; dashed lines emphasize the –5 $dm^3 \cdot yr^{-1}$ to 5 $dm^3 \cdot yr^{-1}$ range for better comparison due to unequal scaling of the vertical axes)

volume increment more general tendencies of climatic effects on forest productivity can be identified (Fig. 6). As a reference we provide distributions on absolute values of periodic volume increment in the supplement (Additional file 2: Figures S1–S6).

The overall deviations in periodic volume increment displayed in Fig. 6 point out five general tendencies. (1) In accordance with the findings on mean single-tree volume increment periodic volume increment of all species benefits from climate change in the first projection period in both regions except for European beech and oak in *Uelzen* under the median and maximum scenario. (2) The uncertainty range widens over time and in most cases encompasses positive as well as negative deviations. Especially European beech strongly reacts on climate scenarios with positive deviations up to 2 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ as well as negative values down to –3 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in the third period. (3) Basically, the positive effect of climate change in the first period diminishes over time and even turns negative in many cases. While the deviation in periodic volume increment of Scots pine shows only a few small negative values in the third period, periodic volume increment of oak is negatively affected by climate change in *Uelzen* entirely but not so much in *Fläming*. The climate effect on periodic volume increment of European beech shows a disparate picture over time with positive tendencies under minimum and median climate scenario in *Uelzen* and a clearly negative trend under median and maximum climate scenario in *Fläming*. (4) Scots pine is the least sensitive species, both positive and negative. Climate change has the strongest impact on European beech with the most positive deviations in *Fläming* in the first period and the most negative deviations in *Uelzen* and *Fläming* in the third period. Oak takes on an intermediate position looking at the deviations in periodic volume increment. (5) Comparing both regions a stronger climate effect is

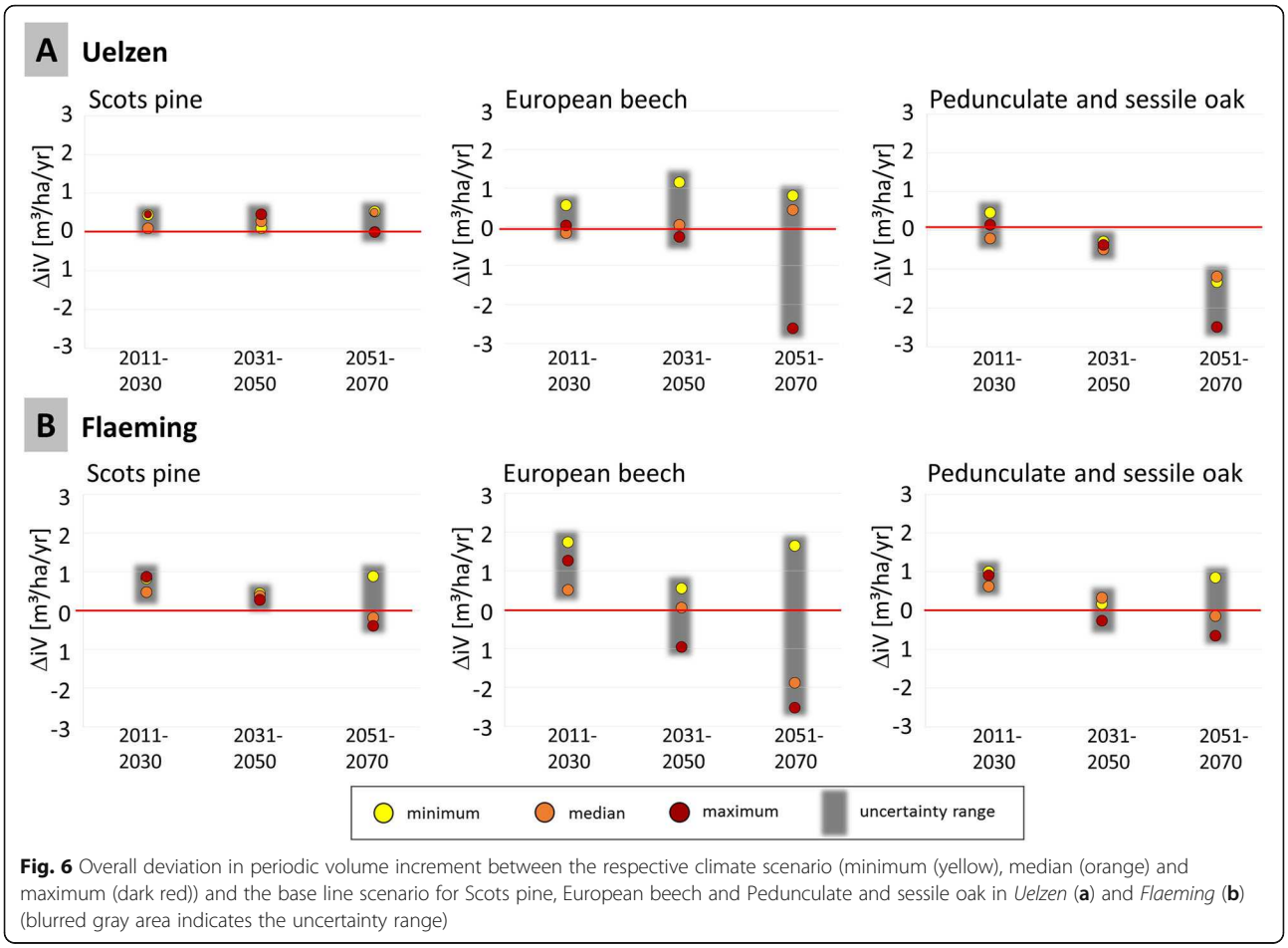


Fig. 6 Overall deviation in periodic volume increment between the respective climate scenario (minimum (yellow), median (orange) and maximum (dark red)) and the base line scenario for Scots pine, European beech and Pedunculate and sessile oak in *Uelzen* (**a**) and *Flaeming* (**b**) (blurred gray area indicates the uncertainty range)

noticeable in *Fläming* looking at Scots pine and European beech. In *Fläming* the periodic volume increment of both species shows more positive reactions in the first period and under median and maximum scenario significant negative deviations in the third period. Periodic volume increment of pedunculate and sessile oak, however, is affected more heavily by climate change in *Uelzen*.

While the results displayed in Figs. 4, 5 and 6 emphasize the immediate short-term climatic effect on volume increment during the 20-year projection periods, the analysis of mean annual increment at biological rotation age (MAI_{max}) detects the cumulative long-term consequences of climate change on forest productivity. The differences in MAI_{max} indicate how the gradual divergences in volume growth between the baseline and the three climate scenarios accumulate to economically meaningful additional or fewer productivity, respectively (for absolute values on MAI_{max} please refer to Additional file 2: Figures S1–S6).

In *Uelzen* Scots pine and oak both benefit with additional MAI_{max} of up to 0.4 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ depending on climate scenario and projection period (Fig. 7a). The projection only indicates a marginal loss for oak under maximum climate scenario in the third period. In *Fläming* the deviation in MAI_{max} shows similar patterns for pine and oak, however with slightly larger uncertainty ranges comprising larger positive values up to 0.6 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ for pine (0.25 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ for oak) and negative values down to −0.2 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ for both species in the third period (Fig. 7b). While the uncertainty range increases significantly for both species in both regions over time, there is no obvious trend in productivity with increasing dyrer conditions until 2070. Contrary for European beech, the losses in MAI_{max} clearly increase over time. While beech productivity benefits from climate change in the first period in most cases with deviations in MAI_{max} up to 0.7 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in *Uelzen* and *Fläming*, there is a strong negative effect in *Uelzen* of down to −1 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in the second and even down to −3 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in the third projection period. In *Fläming* a similar trend for beech is observed with negative values down to −0.8 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in the second and down to −2 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in the third period. However, in *Fläming* under minimum climate scenario positive

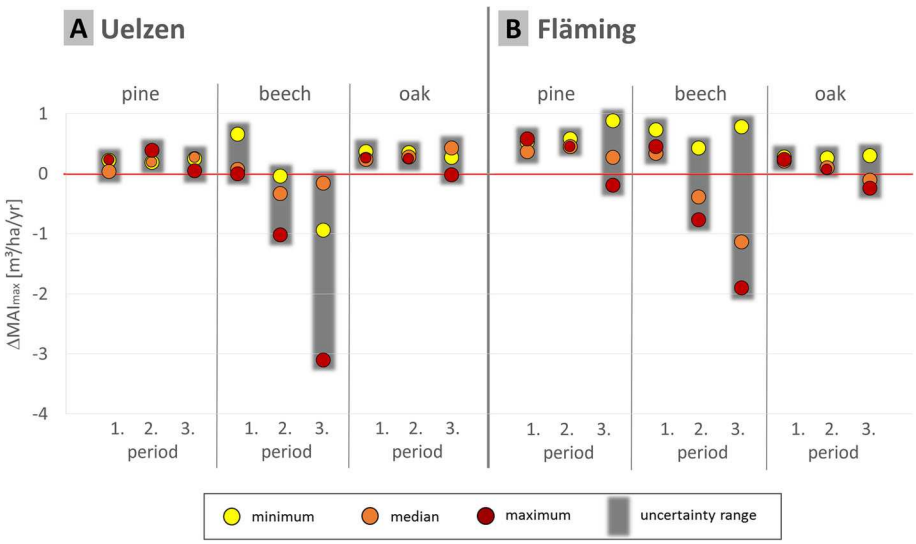


Fig. 7 Deviation in mean annual increment at biological rotation age (MAI_{max}) between three climate scenarios and the baseline scenario for Scots pine, European beech and oak for ages 81 and older in *Uelzen* (**a**) and *Fläming* (**b**) in the first (2011–2030), second (2030–2051) and third (2051–2070) projection period

deviations in MAI_{max} of 0.4 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in the second period and even of 0.8 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in the third period are projected.

Discussion

Generally, simulation studies serve to evaluate future developments in the light of differing framework conditions (Clark et al. 2001). The main objective of simulation studies is to provide information beyond measurements and observations for forest planning and to support decision making. In contrast, resource assessments, field experiments and observational studies collect data and record forest conditions in the first place (Zhao et al. 2014). The measured data and the results and conclusions derived thereof are used for policy making, forest planning and resource allocation, hypothesis testing and modelling. Therefore, simulation studies on possible future developments and measurement data from different sources with a retrospective view may complement each other especially for forest planning issues under uncertainty.

The presented simulation study relies on current forest survey data which is then projected to assess forest development under climate change until 2070. The analysis of persistent dryer climate on forest growth and forest productivity reveals insights on three major issues.

(1) As a prerequisite for any decision support the effect of climate change on forest growth has to be quantified. Recommendations for adaptation measures cannot be derived before potential deviations between the current growth level and the projected growth level under climate change are assessed. Furthermore, it is crucial for reliable forest planning to take the uncertainty in projections into account. In view of the practical application of this simulation study the deviation in volume increment between constant climate and three climate scenarios for three species, Scots pine, European beech and Pedunculate and Sessile oak, is evaluated in two forest regions. Thus, the results show variations due to the variability in the initial forest and site conditions as well as the variability in the climate projections. The immediate, short-term effect of climate change on volume increment gives evidence of the growth model's sensitivity to the opposing climate factors, i.e. the positive influence of rising temperatures on growth and the inhibitory effect of reduced precipitation. In the near future of the first projection period the positive effect of rising temperatures ensures higher periodic volume increments of up to 2 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ depending on species, region and climate scenario (cf. Fig. 6). However, in the projection period 2051 to 2070 the effect of persistent dryer conditions finally overcompensates the positive effect of higher temperatures in most cases in *Uelzen* and *Fläming* with losses up to –3 $m^3 \cdot ha^{-1} \cdot yr^{-1}$. This quantitative comparison of periodic volume increment under constant and climate change conditions allows to evaluate species' productivity and future site-suitability beyond a risk assessment alone. Specifically, in *Uelzen* beech will most likely suffer significant decreases in volume increment. Thus,

persistent dryer conditions will strongly affect managing beech as a leading species on many sites. In the *Fläming* region, however, where beech predominantly serves as an admixed species already today (Albert et al. 2017), projected decreases in volume increment will be tolerable. On the other hand, Scots pine in pure and mixed stands dominates in both regions with proportions of almost 70% of the entire forest area in *Uelzen* and even 90% in *Fläming*. Therefore, even small decreases in volume increment will amount to considerable losses in the regions. Similar to beech, oak only plays a minor role in both regions looking at the current proportions of 5% in *Uelzen* and 4% in *Fläming*. However, even small potential decreases in volume increment might have a considerable impact on oak management in both regions as the economic value per cubic meter oak wood is high. While the analysis of single-tree and periodic volume increment in the three projection periods reveals the immediate impact of changing climatic conditions on forest growth, the evaluation of changes in MAI_{max} aims at the long-term, aggregating climatic effect on forest productivity. Basically, the results on periodic volume increment and MAI_{max} are in accordance. On average the productivity of all pine stands close to rotation age will profit from climate change until 2070, with the exception of the MAI_{max}-value under maximum climate scenario in *Fläming* in the third projection period. Consequently, looking at overall productivity climate change does not negatively affect the management of Scots pine stands being harvested in *Uelzen* and *Fläming* until 2070. Contrary, persistent dryer climates heavily affect beech management with MAI_{max} losses up to -3 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in *Uelzen* and -2 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in *Fläming*. Especially in stands with beech as the leading species it might be necessary to adapt the management goals, e.g. to reduce the target diameter in order not to unduly extend rotation age. As a summary, the effect of climate change on the growth of Scots pine and European beech is quite similar looking at periodic volume increment and MAI_{max}. However, small distinctions are obvious for oak. The reported losses in volume increment for oak in the second and third period in both regions are not as pronounced looking at MAI_{max}. Especially in comparison to beech MAI_{max}-values for oak indicate only minor losses (Fig. 7) while the negative deviations in periodic volume increment in the third period especially in *Uelzen* and under maximum climate scenario in *Fläming* seem considerable (Fig. 6). In the case of *Uelzen*, we explain this discrepancy with the cultivation effort of oak even on less favourable sites in the beginning of the 1970s. These oak stands seem to suffer under dryer conditions, thus, the deviations in periodic volume increment are negative. However, these stands are not included in the data used for MAI_{max} assessment because of the age restriction. On the other hand, the older oak stands mainly stock on sites which are not so much affected by dryer conditions, thus, deviations in MAI_{max} are positive.

(2) The second major issue of the presented analysis is to improve drought stress assessments with quantitative data on forest productivity. One common method to account for potential drought stress limitations when evaluating species for natural or artificial regeneration in northwestern Germany is a species-specific vulnerability assessment based on site water budget according to Grier and Running (1977), i.e. the sum of climatic water balance in the growing season (difference of precipitation and potential evapotranspiration for grass reference (Allen et al. 1998)) and the available water capacity (Spellmann et al. 2007, Spellmann et al. 2015). Generally, vulnerability is defined as the extent to which a system is susceptible to disturbances, or in our case how a forest ecosystem is affected by climate change (Füssel and Klein 2006). Specifically, drought vulnerability is related to exposition, i.e. duration and severity of water shortage, species' resilience against fluctuations in water availability and species' ability to adapt to climate-induced drought. Spellmann et al. (2007, Spellmann et al. 2015) assess drought stress by transferring ranges of site water budget into species-specific vulnerability classes (Table 2). The reasoning behind this method is that different tree species need a specific amount of water supply to achieve an economically advisable cultivation and management. And forest management is only economically promising, if the tree species show

Table 2 Definition of drought vulnerability classes for five major tree species (* Pedunculate and sessile oak) according to Spellmann et al. (2007, Spellmann et al. 2015)

Drought Vulnerability	Site water budget in growing season (mm)			
	Norway spruce	European beech	oak* / Douglas-fir	Scots pine
Low	> 0	> −25	> −150	> −180
Medium	0 to −80	−25 to −100	−150 to −400	−180 to −450
High	< −80	< −100	< −400	< −450

sufficient growth potential and potential risks do not exceed a certain level.
The values in Table 2 were derived from observations on species distribution ranges in combination with a qualitative assessment of cultivation risks. The cultivation risks comprise effects on growth, vitality and mortality. The values classify mean site conditions, i.e. not accounting for influencing factors such as topographic site exposition. The values indicate Norway spruce as most prone to drought vulnerability, followed by European beech, oak and Douglas-fir and Scots pine as most resistant.
An example illustrates how results from a drought vulnerability assessment following the method proposed by Spellmann et al. (2007, Spellmann et al. 2015) can valuably be amended by quantitative information on future species productivity. In a former study, we evaluated the necessity of adapting tree species selection in *Uelzen* and *Fläming* taking drought restrictions into account (Albert et al. 2017). For *Uelzen* we concluded that the number of Scots pine dominated stands will increase from 60% refraining from drought limitations to 69% under medium climate scenario and even 80% under maximum climate scenario until 2070 (under minimum climate scenario the proportion is estimated to be constant). This strong preference of Scots pine in future tree species selection based simply on drought vulnerability limits is in line with the current analysis that no severe losses neither for periodic volume increment (Fig. 6) nor for MAI_{max} (Fig. 7) are to be expected. For oak, however, a recommended slight increase from 7% under the assumption of sufficient water supply to 8% under maximum climate scenario might be challenged looking at the projected future productivity. If the productivity goal is rated high in the decision process, potential losses in periodic volume increment of up to −2.5 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ might influence the decision process on species selection towards more productive species under climate change although oak qualifies as a species to be cultivated under the drought vulnerability limits.
Evaluating European beech requires a different line of reasoning. In our species selection study we expected the proportion of beech dominated stands in *Uelzen* to drop from 16% with no assumed drought limitations to 14% under minimum, and an insignificant 2% under median and maximum climate scenario. While these recommendations are based solely on the intrinsic and fuzzy approach transferring expert-knowledge of species' productivity and risks into drought vulnerability classes we complement and confirm these results with sound information on projected substantial losses for beech looking at periodic volume increment and MAI_{max} under climate change in *Uelzen*.
In summary, as forest growth is projected as a function of several climatic and soil properties the derived results of the presented study complement the drought vulnerability assessment of Table 2 beyond evaluating the site water budget alone. The quantitative statement on potential productivity losses, including an uncertainty range which depends on the assumed climate projections and the time horizon, enriches the information basis for forest planning decisions in the light of persistent dryer climates.

(3) It is another objective to evaluate the approach's potential to derive conclusions for forest management and to formulate adaptation strategies using the two regions *Uelzen* and *Fläming* as an example. First of all, our results correspond to the perception by Kätzel and Höppner (2011) who conclude that Scots pine will persist as an important and economically meaningful species for forest management in the northeastern German lowlands and that oak and beech will show different reactions to climate change depending on other environmental factors. Our results also confirm findings by Bauwe et al. (2015) who predicted the radial growth response to climate change of Scots pine, European beech and Pedunculate oak along a precipitation gradient in northeastern Germany. As in our analysis growth rates for beech and oak were projected to decrease under the A1B climate scenario until 2100 while Scots pine showed slight growth increase as well as decrease depending on site and location (as a reference, A1B is best comparable to RCP 6.0). A broad study on sustainable land use management by Spellmann et al. (2017) specifically recommends to promote climate-adapted tree species and species mixtures for future forest generations in order to lower and distribute potential future risks in *Uelzen*.
Furthermore, the already completed advance planting of beech should be enriched with natural regeneration of more drought tolerant species such as oak, Scots pine and birch or even by planting Douglas-fir, Grand fir or red oak in beech gaps. Our analysis clearly supports the recommendations by Spellmann et al. to promote Scots pine and critically question the future role of beech in *Uelzen*.
However, our results on potential productivity losses in the case of oak at least relativize its

importance for forest management in *Uelzen*. In any case, it is crucial in forest planning to implement tree species selection for future stands as a case-by-case decision. In the same study, Spellmann et al. conclude for the *Fläming* region that the increasingly dryer conditions will also negatively affect Scots pine. Our results on periodic volume increment seem to support this assessment. However, the silvicultural scope in tree species selection is limited in *Fläming*, thus, it is most advisable to promote mixed forests, i.e. mainly leading Scots pine or Douglas-fir with admixtures of beech or oak.

Assumptions and model limitations

In this study the interaction between the site-sensitive longitudinal height-diameter model and the basal area increment model as well as other functionalities, e.g. mortality and ingrowth, within the framework of the growth simulator *WaldPlaner* plays a major role. The interpretation of our simulation results is subject to various assumptions and model limitations.

(1) First of all, the results are only valid for conditions specified by the applied growth functions, i.e. the model functionalities and the parameterization basis, and in the range of the assumed climate projections. The site-sensitive height-diameter model is parameterized for the entire area of Germany. The other growth functions of the *WaldPlaner* framework are parameterized for northwestern Germany. Thus, the spatial scope in this study is well covered. Furthermore, the height-diameter model is a statistical model fit on past observations. This implies two possible pitfalls. First, under climate change the parameter values might well be in the extrapolation range with unsuspected model behavior. However, biologically feasible results were obtained in various sensitivity studies on the model (Schmidt 2010; Albert and Schmidt 2014). Second, the model philosophy assumes that the significance of the selected model parameters has the same explanatory power under future climatic conditions. However, under more extreme climate conditions other factors could strongly influence forest growth. For example, Michelot et al. (2012) compared growth reactions of European beech, sessile oak and Scots pine to climatic variations and soil water deficits in France. Their findings clearly show that growth of beech and Scots pine will be determined by mainly summer maximum temperatures and precipitation in the growing season also under future climate conditions, whereas oak growth will be strongly affected by autumn droughts due to tree carbohydrate storage depletion. In this case, with increasing autumn drought stress and a higher frequency of extreme drought events during that season in the future a new parameter, e.g. autumn water deficit, would presumably be significant in modelling growth. These possible shifts on parameter significance and interactions under climate change are beyond the capabilities of statistical model approaches. But we assume that the broad range of observed climate values and especially different combinations on temperature and aridity index in the past throughout Germany covers or is close to projected future conditions for the large part.
The simulation results strongly rely on the climate projections, which in turn depend on the applied regional climate model STARS (Orlowsky et al. 2008). Independent from the three climate scenarios resulting from three different global circulation models (GCM), STARS always projects climate patterns with dryer summers and wetter winters in Germany under any scenario. These climate patterns stimulate the presented impact analysis. These uniform climate patterns originate from a specific temperature-driven resampling algorithm (TCR) being used for climate projections by the statistical model STARS. The GCMs define the temperature forcing as a periodic trend. TCR generates a new sequence of annual climate values according to the temperature forcing in a first step. In a second step 12-day-weather sequences are newly arranged. Wechsung and Wechsung (2014, 2015) criticized the underlying assumption by Gerstengarbe et al. (2013) to validate STARS based on mean statistical estimates during the period 1951 to 1975 in comparison to a new period with newly arranged values using TCR. Moreover, Wechsung and Wechsung (2014, 2015) prove a negative bias in STARS' projections of precipitation of 5% per 1°C temperature increase. Nevertheless, accepting the model limitations and regarding the type of climate change projection Wechsung and Wechsung (2014) recommend STARS to be used in climate impact studies. Therefore, we employ STARS' climate projections in the presented impact study in lack of alternative available data, knowing about potential pitfalls.

(2) Conclusions on the results are only permitted under the assumption that the scope of future

climate conditions is within the quantified uncertainty range of the climate projections. The knowledge on the likelihood of a certain climatic development is low. Therefore, probabilities cannot be assigned whether or not certain climate conditions will be realized (Foley 2010). As a consequence scenario analysis employing climate ensembles is utilized to quantify a range of possible outcomes. This range defines the uncertainty in climate modelling. However, this approach falls short to cover the uncertainty in its entirety as beyond scenario analysis which assumes certain boundary conditions there is a considerable amount of uncertainty left due to the lack of any knowledge that originates from the long time scales and complexity, termed deep uncertainty (Walker et al. 2003; Kandlikar et al. 2005). Knutti and Sedláček 2012 reported on the robustness and uncertainties in the *Coupled Model Intercomparison Project Phase 5* (CMIP5) by the *World Climate Research Programme*. They conclude that in spite of tremendous improvements of the climate models and higher spatial resolutions the projection uncertainties did not decrease compared to successive IPCC reports. Hence, Knutti and Sedláček (2012) advise to account for the uncertainties when deriving decision support from climate impact analysis. Our reported analysis reflects climate projection uncertainties by applying three climate scenarios which is a compromise between adequate computational workload and sufficient consideration of possible projection uncertainties. Informed recommendations for forest planning thus are possible, however, any conclusion derived from impact analysis must remain highly conditional on the underlying ranges of climate projections. But at best, conclusions drawn are robust, e.g. in *Uelzen* under each of the three applied climate scenarios the deviation in MAI_{max} indicates a consistent positive climate effect for Scots pine and, contrary for European beech, a consistent negative effect in the third period (Fig. 7). Therefore, any decision in favor of Scots pine management will result in higher productivity. And the other way around, any decision to the disadvantage of beech management, e.g. turning away from the currently common practice of converting Scots pine stands into stand types with leading beech or even an earlier conversion of current beech stands to more productive species, are justified by losses in MAI_{max}.

(3) The dynamics in climate parameters are accounted for in the height development, although the height-diameter model is strictly speaking static. The climate effect on basal area growth, however, is indirect as the predictor crown surface area is estimated based on tree height. As analyzed in this study, the growth model is capable to reproduce effects of persistent dryer climate conditions on forest productivity in a long-term perspective. One shortcoming of the growth model is that disturbances such as extreme short-term drought events are neglected. The impact of severe dry spells on tree growth was confirmed in numerous studies (e.g. Orwig and Abrams 1997; Klos et al. 2009; Michelot et al. 2012; Weber et al. 2013). In summary, both the growth reactions to long-term trends and the consequences of disturbances are important factors to adequately project forest development. Lindner et al. (2014) stated in this context that not accounting for extreme events might explain the deviations between observed growth trends and growth projections in many cases. Nevertheless, decision support for forest planning and specifically in the assessment of species suitability can be granted based on projections of species productivity as shown in the impact study in combination with a sound vulnerability analysis accounting for possible disturbances, for instance an increasing frequency of extreme drought events.
Ecophysiological processes such as interactions between competition, species mixture, pathogens, nitrogen deposition or elevated CO_2 levels with drought stress are also not accounted for in the applied growth model. Evidence for these interactions are provided by several studies. For example, Giuggiola et al. (2013) reported for Scots pine on xeric sites in Switzerland that a strong reduction in basal area of 40% to 60% of the regular management regime mitigated drought effects. On the issue of species mixture Arthur and Dech (2016) contributed further findings that species mixtures have a significant influence on the effects of drought on forest growth. The hypothesis that species composition can mitigate drought effects was also supported by Pretzsch et al. (2013). On the other hand, Thurm et al. (2016) showed for Douglas-fir and European beech mixed stands that not all species equally profit from mixtures looking at drought stress release. In their study Thurm et al. (2016) provided evidence that in mixture Douglas-fir is positively affected while beech shows a higher sensitivity to climate impacts.
Besides the direct interaction of tree or stand properties on drought stress also external factors

may alter the impact of drought on forest growth. A strong interaction between drought and pathogens and, eventually, with tree vitality, growth and even mortality exists (e.g. Desprez-Loustau et al. 2006; Overbeck and Schmidt 2012; Schoneberg 2017). There is still a great uncertainty about the direction and the magnitude in the response of insects and fungi to drought (Jactel et al. 2011). But as drought causes physiological changes in tree defenses it will alter the patterns and effects of biotic disturbances (Ayres and Lombardero 2000). Consequently, the interaction of drought and pathogens will affect tree growth and tree vitality (Dobbertin 2005).

Increased nitrogen deposition has a fertilizing effect on forest growth (Hyvönen et al. 2007; Kahle et al. 2008a). Then again, the positive effect of nitrogen does not apply to all sites equally (e.g. Näsholm et al. 2000). Furthermore, some studies suggest that nitrogen fertilization might have a negative effect on root growth and might increase root mortality, thus reducing tree vitality (Clemensson-Lindell and Persson 1995a, 1995b; Persson and Ahlström 2002). Moreover, it is speculated if higher nitrogen availability causes higher drought risks (e.g. Näsholm et al. 2000; Dziedek et al. 2016).

A similar line of reasoning applies to the issue of elevated CO_2-concentration. Several studies analyzed the effect of elevated CO_2-concentration on forest growth, unfortunately with no consistent findings (e.g. Hättenschwiler et al. 1997; Körner 2006; Handa et al. 2006; Kahle et al. 2008b). Recently, simulation studies indicated the high sensitivity of forest growth to assumed future CO_2 increase (Reyer et al. 2014; Lindner et al. 2014; Schelhaas et al. 2015). The assessment of interactions between elevated CO_2-concentration and drought is even more sophisticated. Hättenschwiler et al. (1997), Ellsworth (1999) and Körner (2006) reported a possibly beneficial impact of elevated CO_2 on tree growth under drought conditions. Some studies indicated a higher water-use efficiency of trees as the main reason for a positive effect of higher CO_2 under drought stress (e.g. Battipaglia et al. 2013; Keenan et al. 2013). Contrary, Tognetti et al. (2000) found no evidence for growth response to increasing CO_2 during drought stress for five Mediterranean forest tree species.

All the above mentioned interactions could alter tree growth under extreme drought events and even under a persistent dryer climate. More research is needed to include these effects in growth models to improve informed decision support for forest management. Ciais et al. (2005) clarified the extent of the implications as they assumed that extreme drought events and persistent dryer conditions might significantly alter the long-term carbon balances and reverse forests from sinks to sources in Europe.

Conclusions

This study illustrates a method to assess the long-term effects of persistent dryer climate conditions on forest growth and productivity by comparing mean single-tree volume increment, periodic volume increment and mean annual increment at biological rotation age (MAI_{max}) under constant climate conditions and under three climate projections until 2070. The projected changes in forest growth within a specified uncertainty range serve as quantitative contributions to provide decision support in forest planning, e.g. adapting silvicultural management strategies, evaluating species future site suitability and assessing the impact on timber supply. The quantitative analysis of possible productivity changes under persistent dryer climate complements the expert-knowledge based drought vulnerability assessment which is applied in northwestern Germany today (cf. Table 2). The drought vulnerability assessment as a synoptic approach qualitatively aggregates the effects of drought on tree growth, vitality and mortality based on thresholds for site water budget. The reported projection of productivity changes quantifies effects of persistent dryer climates on forest growth separately. In addition, the effects of drought on vitality and mortality still needs to be quantified on a level suitable for forest management.

In particular, on the grounds of the specific simulation results following conclusions for forest planning in the two regions can be drawn: (1) Although the uncertainty range in the third period (2051 to 2070) encompasses positive as well as negative effects on volume increment in many cases for European beech, pedunculated and sessile oak and Scots pine in both regions decisions on species suitability have to be made. In this case, differences in site conditions need to be taken into account and furthermore the decision also is a question of risk attitude. The results presented are average values for all sites considered. Thus, favourable site conditions, e.g. sufficient available water capacity, might well compensate the negative effect of persistent dryer climates and different recommendations for these sites apply. (2) Scots pine is rated as the least sensitive species to dryer climate conditions. MAI_{max} of Scots pine even increases in the time period and regions under consideration. Thus, from the growth and yield point of view Scots pine will be well suited for forest management in the future. The same but not quite as pronounced applies to the management of oak in the *Fläming* region while being doubtful in *Uelzen*. (3) European beech faces the

most severe growth reductions. In stands with beech as the leading species the negative impact of climate change might call for silvicultural adaptation measures and a change in species in the next forest generation. On sites, where a vulnerability analysis does not exclude beech from cultivation, forest management with beech as an admixture species is still advisable at the cost of lower productivity. (4) The clear temporal trend in magnitude and direction of the effect of persistent dryer climates on forest growth and productivity has to be considered.

Additional files

Additional file 1: Table S1. Characteristic numbers for the collectives under baseline (base) and minimum (min), median (med) and maximum (max) climate scenario for *Uelzen* at the end of the respective period (for age, dbh and height 1st quantile, median (med) and 3rd quantile values are given). **Table S2.** Characteristic numbers for the collectives under baseline (base) and minimum (min), median (med) and maximum (max) climate scenario for *Fläming* at the end of the respective period (for age, dbh and height 1st quantile, median (med) and 3rd quantile values are given). (DOCX 28 kb)

Additional file 2: Figure S1. Boxplots of periodic volume increment (upper row) and mean annual increment at biological rotation age (lower row) under baseline (gray), minimum (yellow), median (orange) and maximum (red) climate scenario for **European beech** in *Uelzen* (included are only stands with beech as a leading species). **Figure S2.** Boxplots of periodic volume increment (upper row) and mean annual increment at biological rotation age (lower row) under baseline (gray), minimum (yellow), median (orange) and maximum (red) climate scenario for **Pedunculate and sessile oak** in *Uelzen* (included are only stands with oak as a leading species). **Figure S3.** Boxplots of periodic volume increment (upper row) and mean annual increment at biological rotation age (lower row) under baseline (gray), minimum (yellow), median (orange) and maximum (red) climate scenario for **Scots pine** in *Uelzen* (included are only stands with Scots pine as a leading species). **Figure S4.** Boxplots of periodic volume increment (upper row) and mean annual increment at biological rotation age (lower row) under baseline (gray), minimum (yellow), median (orange) and maximum (red) climate scenario for **European beech** in *Fläming* (included are only stands with beech as a leading species). **Figure S5.** Boxplots of periodic volume increment (upper row) and mean annual increment at biological rotation age (lower row) under baseline (gray), minimum (yellow), median (orange) and maximum (red) climate scenario for **Pedunculate and sessile oak** in *Fläming* (included are only stands with oak as a leading species). **Figure S6.** Boxplots of periodic volume increment (upper row) and mean annual increment at biological rotation age (lower row) under baseline (gray), minimum (yellow), median (orange) and maximum (red) climate scenario for **Scots pine** in *Fläming* (included are only stands with Scots pine as a leading species). (ZIP 1002 kb)

Abbreviations

ari: Aridity index; awc: Available water capacity; bai: Basal area increment; c66: Competition index at 66% of tree height from top; c66c: Change in competition index c66; csa: Crown surface area; cwb: Climatic water balance; dbh: Diameter at breast height; GCM: Global circulation model; gs: Growing season; gw: Groundwater class; iV: Periodic volume increment; iv: Volume increment of single tree; MAI_{max}: Mean annual increment at biological rotation age; nut: Soil nutrient class; RCP: Representative concentration pathway; SI: Site index at reference age 100; TCR: Temperature-driven resampling algorithm; tsum: Temperature sum

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Authors' contributions

The first author (MA) conducted the data analysis and wrote the first draft. RN was mainly involved in interpreting the simulation results and deriving silvicultural conclusions as well as recommendations for forest management. MS provided the site-sensitive height-diameter model and contributed to the methods and data analysis significantly. JS substantially contributed to the method to assess drought stress. All authors jointly discussed the results, drew conclusions and finalized the manuscript. All authors read and approved the final manuscript.

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Ethics approval and consent to participate

Not applicable

Consent for publication

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Competing interests

The authors declare that they have no competing interests.

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Tree Species Selection in the Face of Drought Risk—Uncertainty in Forest Planning

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Abstract: Rapid climate change leads to significant shifts in the site-productivity relationship of tree species and alters abiotic and biotic risks well beyond classical rotation ages on many forest sites worldwide. Forest conversion may be an adequate measure to counter possible negative effects of climate change. Unfortunately, climate-driven changes in abiotic and biotic risks bear a significant source of intrinsic uncertainty inherent in climate projections. It is our goal to appraise uncertainty in species selection under drought stress, one of the most important risk factors for many forests. We derive a method to assess drought restrictions and demonstrate the uncertainty in the process of species selection by applying three climate scenarios. Furthermore, we interpret the consequences of climate uncertainty in the light of different management goals, i.e., a business-as-usual silviculture, a climate protection strategy favoring CO_2 sequestration and a biodiversity strategy increasing diversity. The methods are applied to two representative regions in the North German Plain. The results clearly show the strong need for adaptive planning when drought restrictions are considered. However, different silvicultural management objectives may alter the extent of adaptive planning. The uncertainty in the planning process arising from different underlying climate projections strongly depends on the regional site characteristics and on forest management strategy. In conclusion, it is most important in forest planning to clearly state the management goals and to carefully explore if the goals can be met under climate change and if the uncertainty due to climate projections significantly affects the results of species selection.

Keywords: forest conversion; species selection; drought risk; climate change; uncertainty; forest management

1. Introduction

Strategic forest planning decisions such as species selection in regeneration are strongly impaired by changing climate conditions because of their long-term commitment. Climate change alters the growing conditions of forests well beyond a stand's lifespan [1]. In central Europe, projected rising temperatures, the most likely seasonal shift in precipitation and an accumulation of extreme weather events such as droughts, torrential rain and storms [2–4] will change tree growth and will have a considerable impact on survival rate (e.g., [5–8]). Ultimately, stand productivity and thus forest enterprise economics will be affected (e.g., [9–12]).

Forest conversion is seen as one adaptive measure to counter or at least diminish the negative effects of climate change (e.g., [13,14]). Formerly, good forestry practice based species selection on constant site characteristics, i.e., soil nutrients and site water budget. Under climate change, site water budget is no longer constant but varies according to altered climatic water balances, i.e., the difference

between precipitation and evapotranspiration. Consequently, forest planning now has to consider the dynamics in site water budget. This, in fact, poses a new challenge. While forest planning always had to decide on a basis of incomplete information, projections of climate change bear an intrinsic uncertainty, where climate scenarios cannot be assigned any probability of occurrence [15], thus termed 'deep uncertainty'. The uncertainty in climate projections when used in forest planning raises two concerns, i.e., to build confidence in the projections [16,17] and to communicate the degree of uncertainty for proposed recommendations [18]. Several studies point out methods of how to account for deep uncertainty (e.g., [19,20]). In order to successfully adapt forest ecosystems and forest management practices to climate change uncertainties, robust decision making approaches are promoted [21]. Furthermore, sensitivity analysis should be applied to examine how robust a decision is to adapt to climate change [22]. Our approach to deal with climate uncertainty in this study is straightforward as we use a set of three climate projections to set up a range of potential climate developments to assess their impact on planning decisions.

This study on tree species selection under climate change considering drought risk puts the above-mentioned methods and procedures into practice for two forest regions in the North German Plain. Most importantly, we present an approach suitable for area-wide forest planning encompassing climate projections, their uncertainty, stand type planning rule-sets and drought risk assessment. Risk in general is defined as the probability of expected loss or damage due to a particular hazard for a given area and reference period [23]. Drought risk, in particular, is the reduction in forest productivity, loss of vitality and eventually even mortality induced by temporal shifts towards dryer site conditions (e.g., [24–27]). Already nowadays and even more under future climate conditions, water availability limits species selection on many sites in the North German Plain [28,29]. Generally, the direct effect of drought on trees is hard to quantify (e.g., [30,31]). Thus, we account for drought vulnerability, i.e., the degree to which forests are susceptible to negative impacts of drought [32], rather than quantifying actual risk, when assessing future species' site suitability.

This study pursues three goals: (1) to illustrate the options in stand type planning based on site characteristics and implemented silvicultural management strategy and to point out the alternatives in adaptive planning under drought restrictions; (2) to quantify the uncertainty in the planning process arising from different climate projections; and (3) to demonstrate the consequences of climate uncertainty for forest planning based on the findings in two typical regions, representative for larger growth zones in the North German Plain, i.e., whether the choice of one particular climate scenario is necessary as it strongly affects the stand type planning or if the differences between stand type planning under the different climate scenarios are acceptably small to desist from considering climate uncertainty.

As the results are based on forest inventory data, with three underlying management strategies and three climate projections in two representative regions, this study allows for detailed analysis and specific conclusions. We draw conclusions on the interaction between management scenario and climate projection and its consequence for forest planning under uncertainty. This fosters the learning process and aids forest managers to cope with uncertainty.

2. Materials and Methods

This study investigates how different climate scenarios and silvicultural management strategies influence species selection in forest planning. Therefore, the combinations of species occurrence and site characteristics in two representative regions are identified. The site-specific foundations, i.e., soil and climate properties, are presented and the rule-set for species selection considering drought restrictions in regard to different management strategies is introduced.

2.1. Forest Data

The primary research question, to account for uncertainty in forest planning, is examined based on forest stand data in two regions, Uelzen with a total of 48,682 ha of forests (33.5% forest cover)

and Fläming with 90,903 ha of forests (42.3% forest cover), in the North German Plain (Figure 1). Both regions are representative in regard to site characteristics and forest structure for larger growth zones in the North German Plain.

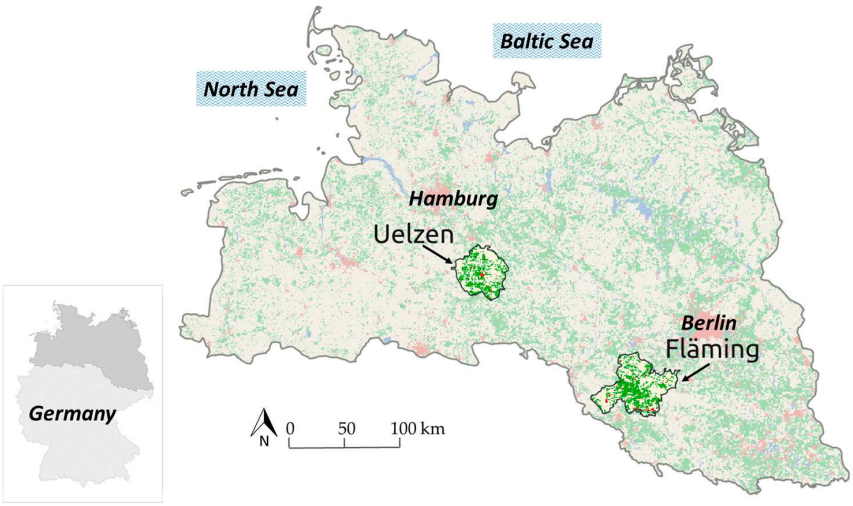


Figure 1. The two study regions Uelzen and Fläming in the North German Plain near the cities of Hamburg and Berlin (land cover data in the overview map © ESA/ESA GlobCorine Project, led by Université Catholique de Louvain).

In each region a representative number of stands was sampled from all forest stands with available inventory data (n = 999 in Uelzen and n = 1008 in Fläming). These two study regions were selected, because they comprise different starting conditions concerning species occurrence (Table 1), regional climate and soil conditions (Table 2).

Table 1. Proportions of species area [%] in Uelzen and Fläming in 2011 according to available inventory data (BLHV = broadleaves of high value; BLLRA = broadleaves of low rotation age).

	European Beech	Oak	BLHV	BLLRA	Norway Spruce	Scots Pine	Douglas-Fir	European Larch	Grand Fir
Uelzen	4.8	6.1	0.7	8.0	13.3	61.3	3.9	1.9	-
Fläming	12.8	5.9	1.0	3.3	1.8	73.5	0.4	1.0	0.2

Table 2. Site characteristics in Uelzen and Fläming (climate values as averages in the period 1991 to 2010; asm: available soil moisture calculated for 1 m soil depth, annual temp.: annual mean temperature; annual prec.: total annual precipitation; cwb_{gs}: climatic water balance (=precipitation − evapotranspiration for grass) in growing season).

	Asm [mm]	Annual Temp. [°C]	Annual Prec. [mm]	cwb_{gs} [mm]
Uelzen	110	9.2	727	−65
Fläming	123	9.8	572	−216

In both regions Scots pine is the dominant species but the spectrum in Uelzen is much more diverse with considerable proportions of Norway spruce, other broadleaves, pedunculate and sessile oak, European beech and Douglas-fir. In Fläming only beech, oak and other broadleaves contribute considerably.

The climate values indicate slightly warmer and much dryer conditions in Fläming compared to Uelzen. Especially in the growing season the water deficit, expressed by the climatic water balance, is obvious in Fläming although the mean available soil moisture is marginally larger than in Uelzen.

2.2. Climate Scenarios

We characterize the range of potential future climate from 2011 to 2070 using three climate projections all based on the emission scenario RCP 8.5 [33,34]. The Potsdam Institute for Climate Impact Research created three regional scale climate projections using the regional climate model STARS (Statistical Analogue Resampling Scheme) [35] by downscaling the global circulation models INM-CM4 [36], ECHAM6 [37] and ACCESS1.0 [38]. Although under debate [39,40] the climate model STARS is still recommended for climate impact assessments (e.g., [41]). Climate parameters for all 1218 weather stations of the German Weather Service from 2011 to 2070 were obtained in a daily resolution. The basic climate parameters used in this research are precipitation sum in the growing season and mean temperature in the growing season. Regarding the projected annual mean temperature, the projections predict a 1.1 °C increase for the North German Plain comparing current values (mean in period 1991 to 2010) with values in period 2051 to 2070 under the INM-CM4 run while ECHAM6 projects a 1.6 °C increase and ACCESS1.0 even a 2.7 °C increase. With regard to the pre-industrial age an additional increase of 0.8 °C until 2010 needs to be added resulting in an overall increase of approx. 1.9 °C to 3.5 °C. Throughout this study these three climate projections are labelled minimum, median and maximum climate run.

The projected daily mean temperature and precipitation sum of all climate stations within a 20-km distance of the respective location are interpolated to obtain climate values for each selected stand using WaSiM-ETH's distance-weighted regression model [42,43].

The key climate variable in the process of selecting species in forest planning is site water budget. Site water budget is defined according to [44], i.e., the sum of climatic water balance in the growing season (difference of precipitation and potential evapotranspiration for grass reference [45]) and the available soil moisture as defined by [46]. The start of the growing season is defined according to the model LNVAR by [47] (p. 52) and the ending is determined applying suggestions by [48–50], i.e., either the temperature or the short day criterion, whichever is met first.

Figure 2 displays the development as mean values of all selected sites in Uelzen and Fläming under minimum, median and maximum climate run.

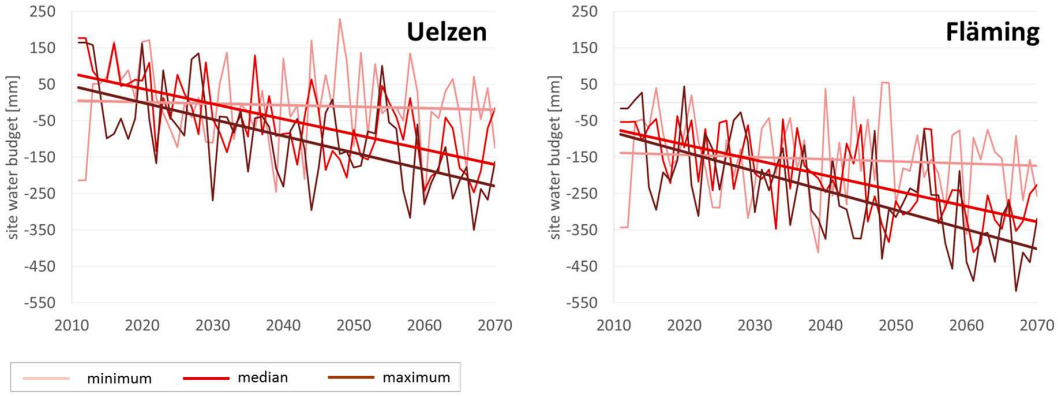


Figure 2. Site water budget over time projected with STARS using RCP 8.5 under minimum, median and maximum climate scenarios in Uelzen (**left**) and Fläming (**right**). The values are means of all individual sites.

Obviously, in Uelzen throughout time and across climate scenarios, site water budget values are on a higher level than in Fläming. Annual fluctuations are generally higher than trends over time. Both in Uelzen and Fläming under the minimum run the trend line indicates hardly any deviation from the current situation. The median run clearly shows a negative trend to much dryer conditions in both regions at the end of the projection period. Even worse is the decrease in site water budget under

the maximum climate scenario, which projects values as low as approximately −250 mm in Uelzen and −400 mm in Fläming in 2070.

2.3. Soil Data

Decisions on site suitability of species in this context rely, first of all, on soil nutrients and site water budget. For each selected stand the necessary variables, soil nutrients and available soil moisture (asm) calculated for 1 m soil depth, are assessed using the soil map of scale 1:1 Mio [51]. Soil nutrients are organized in five classes according to the information of the soil map and model functions by [52].

A heatmap gives a summary of the proportions of sites according to soil nutrients and site water budget (Figure 3).

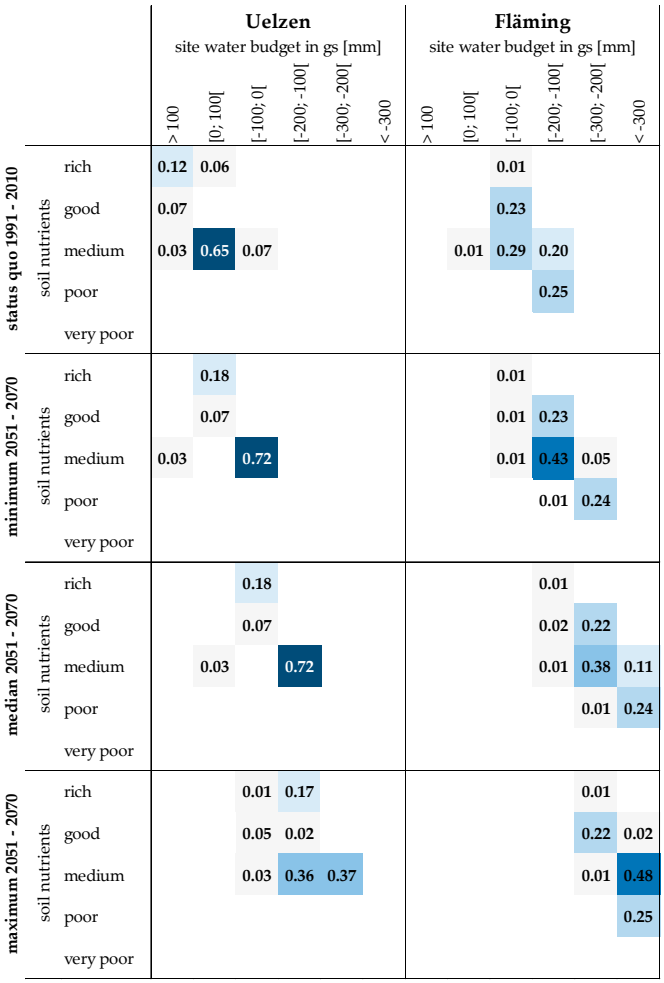


Figure 3. Proportion of sites according to soil nutrient classes and site water budget in growing season classes in Uelzen and Fläming (top heatmaps for the period 1991 to 2010; three rows of heatmaps below for site water budget conditions in the period 2051 to 2070 under three climate scenarios of minimum, median and maximum; only classes with proportions greater than 1% are listed).

Currently, the majority of sites in Uelzen (65%) exhibit a medium soil nutrient status and a positive site water budget up to 100 mm (Figure 3, top heatmaps). A considerable proportion of sites (12%) are rich in nutrients and well water supplied with more than 100 mm. In Fläming soil nutrients and site water budget are generally much lower under status quo conditions. Almost all sites are characterized by a negative site water budget in the growing season. In the category −100 to 0 mm 23% show a good soil nutrient status and another 29% are classified in the medium soil nutrient category. A combined

amount of 45% are represented by the site water budget class of −200 to −100 mm, divided into 20% medium and 25% poor soil nutrient supply. The lower three rows of heatmaps display the distributions of sites according to site water budget conditions in the period 2051 to 2070 applying three climate scenarios of minimum, median and maximum. Obviously, the sites in Uelzen and Fläming face dryer conditions in the future. The shift of site proportions towards more negative site water budget classes is intensified the more extreme the underlying climate scenario. While under minimum climate scenario still 28% of all sites in Uelzen exhibit a positive site water budget in the period 2051 to 2070, almost the entire area suffers negative balances under median and maximum climate scenarios. In Fläming the shift is even more severe as large proportions of sites are categorized into the site water budget class −100 to −200 mm (67% under minimum climate scenario), into the class −200 to −300 mm (61% under median and 24% under maximum climate scenario) or even below −300 mm (35% under median and 75% under maximum climate scenario).

2.4. Rule-Set for Stand Type Planning

As a starting point in our stand type planning analysis we assume that all sampled stands in the two regions are final harvested in 2011 and a new forest generation is planned on these sites. The climatic conditions of the period 2051 to 2070 under the climate scenarios of minimum, median and maximum specify drought restrictions considered in the planning process. Other than simulating a progressive harvesting and planning over time taking actual stand development into account, this approach bears the advantage that all forest stands will be 50 years old in mid-period 2051–2070. This is crucial as the rejection of species in the planning process because of drought restrictions needs to be oriented towards future climate conditions. With 50 years into stand development this should be sufficient to warrant at least stand survival refraining from other risk factors. Furthermore, this approach enhances the comparability between the different forest management concepts as it only applies the different species preferences in the course of stand type planning and ignores the different rotation ages. We justify this theoretical construct—to ignore the actual stand ages and instead assume immediate planning of new forest generations on all sites in 2011—because the sampled forest data from the two regions is representative for large growth zones. Therefore, we assume that in the growth zones a sufficient number of stands having the same site and species entities as in the analyzed sample are close to rotation age and are pending for final harvest in 2011. Consequently, the results derived from the study areas in Uelzen and Fläming are valid for their respective growth zones.

Forest management concepts predetermine decisions on species selection for the next forest generation. In order to evaluate the interaction between species selection priorities, changing climatic conditions and drought restrictions, we implement three contrasting forest management concepts: (1) a business-as-usual strategy which mimics currently-applied silvicultural practices on public forest land in Germany; (2) a climate protection strategy which aims to maximize CO_2 sequestration in standing volume as well as wood products; and (3) a biodiversity strategy which focusses on increasing the area of potential natural vegetation (for more information see [53]). The selection of future tree species always has to be in line with species site-suitability for all management strategies. The business-as-usual strategy prefers deciduous species and mixed stand types as defined by the principles of close-to-nature silviculture. In the climate protection strategy a high CO_2 sequestration can best be realized by fast-growing conifer species. The biodiversity strategy consequently selects tree species of potential natural vegetation.

In the first stage of the planning process for each forest site the next generation of species is selected according to common methodology based on a matrix of soil nutrients and current site water budget (Figure 4) [54].

The ecogram concept illustrated in Figure 4 is further refined to meet forest management goals and adjusted to the regional climate conditions of growth zones. Thus, we obtain one matrix for each applied management strategy and study region (cf. Tables S1–S6 in the supplement). Stand types are assigned based on 7 soil nutrient classes and 14 site water budget classes as is customary in forest

planning in the state forests of Lower Saxony [54]. In many cases several stand types are site-suitable. Therefore, following rules are applied to determine the final decision. Under the business-as-usual strategy, the stand type among the recommended is selected which is closest to the current stocking, i.e., planning the same stand type or including the leading or mixed species if possible. In case none of the current species is among the suggested stand types, a completely different stand type is planned. The reasoning behind this approach is to keep the costs of forest conversion as low as possible, i.e., to utilize natural regeneration instead of planting. The concept of the climate protection strategy as well as the biodiversity strategy is to reverse the current management practices and to stress the new objectives. Thus, regardless of the current stocking, under climate protection and biodiversity strategy a stand type is randomly selected from the recommended according to predefined probabilities in any case (probabilities are given in Table S7 in the supplement).

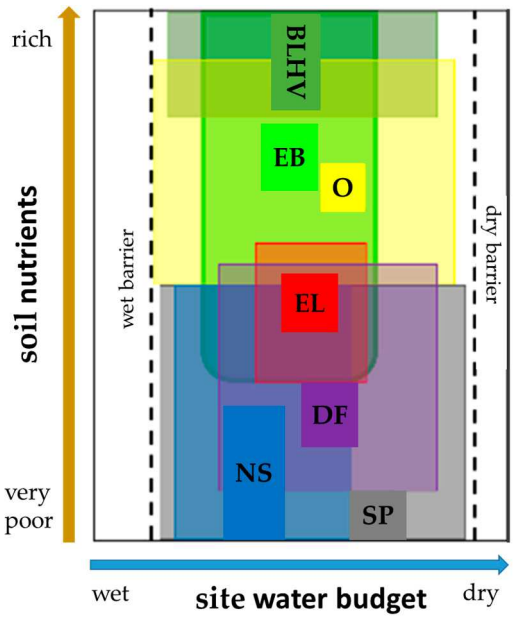


Figure 4. Simplified ecogram to assign species based on a matrix of soil nutrients and site water budget in the North German Plain (BLHV: broadleaves of high value; EB: European beech; O: oak species; EL: European larch; DF: Douglas-fir; NS: Norway spruce; SP: Scots pine).

Although current regional climate conditions are considered in this planning approach as site water budget is a function of precipitation and temperature, explicit changes of the climate conditions are not taken into account. Thus, in this study we refer to the first stage as planning under current (constant) site conditions. The species assignment is motivated mainly by silvicultural management decisions always respecting site suitability.

Climate projections strongly suggest a significant shift in site water budget within a time horizon well less than rotation ages. Therefore, in a second planning stage we account for climate change by assessing the potential future site water budget under different climate scenarios. This second stage is termed planning under future site conditions or adaptive species planning. Specifically, at each site the suggested species of the first stage is further checked for drought restrictions. Thus, species assignment is motivated by silvicultural management decisions respecting current site suitability and future drought restrictions.

In forest planning the decision on species' site-suitability has to rely on certain thresholds which evaluate drought vulnerability. Ecosystem vulnerability in the context of climate change is commonly defined as the impact of adverse climatic effects on ecosystem services [55]. Considering the available data, which needs to be at hand or could easily be generated for each forest site in the planning process, we propose to use site water budget during growing season, i.e., the sum of the climatic water balance

in the growing season plus the available soil moisture, as an indicator in the drought vulnerability assessment [28,56]. The continuous parameter site water budget is converted into vulnerability classes following the threshold theory according to [44]. For five major tree species Table 3 presents the applied vulnerability classes and their interpretation in the planning process.

Table 3. Definition of drought vulnerability classes for five major tree species and corresponding planning measures according to [28,53].

Drought Vulnerability	Site Water Budget in Growing Season [mm]				Planning Measures
	Norway Spruce	European Beech	Oak/Douglas-Fir	Scots Pine	
low	>0	>−25	>−150	>−180	primary species
medium	0 to −80	−25 to −100	−150 to −400	−180 to −450	admixture
high	<−80	<−100	<−400	<−450	no cultivation

According to the specified thresholds in Table 3 Norway spruce is the most drought-prone species, followed by European beech, the oak and Douglas-fir group and Scots pine as the most drought-resistant species. For a complete planning foundation other species are assigned to one of the four groups according to Table S8. As an adaptation measure to future dryer conditions we recommend to establish species only as primary species when classified in the low drought vulnerability class. Species should be planned as admixture species when medium drought vulnerability is projected. And finally, no cultivation should be envisaged under high drought vulnerability conditions.

In the stage of adaptive forest planning new stand types are assigned if drought restrictions are exceeded according to the rule-sets provided in Tables S9 and S10. The adaptive planning stage operates stepwise, i.e., if the leading or the admixture species of stage 1 does not meet the drought threshold the first alternative stand type is tested. If the first alternative also misses the requirements the second alternative stand type is examined, etc. In some cases two stand types are recommended as alternatives, which are then planned in equal proportions if selected. In order to guarantee stocking with forests even under severe drought conditions some stand types are taken as last planning alternatives; these are pure Scots pine, Scots pine-oak mixtures, Scots pine-birch mixtures and birch-Scots pine mixtures.

For a more lucid analysis of results simplified stand types are formulated, i.e., species mixtures, for instance, Scots pine with beech or with birch are aggregated to the stand type Scots pine-deciduous species mixture. Table 4 lists the simplified stand types and their abbreviations which are further used throughout the text.

Table 4. Abbreviations for stand types used throughout the text.

SP	Scots pine (*Pinus sylvestris* L.)
SP-CON	Scots pine-conifer mixture
SP-DEC	Scots pine-deciduous species mixture
NS	Norway spruce (*Picea abies* L.)
NS-MIX	Norway spruce mixture
DF-MIX	Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)-mixture
DF-EB	Douglas-fir-European beech mixture
GF-MIX	Grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.)-Douglas-fir mixture
EB	European beech (*Fagus sylvatica*)
EL-EB	European larch (*Larix decidua* Mill.)-European beech mixture
EB-MIX	European beech mixture
BLLRA	broadleaves of low rotation age
BLHV	broadleaves of high value
O-MIX	oak (*Quercus petraea* (Matt.) Liebl. and *Quercus robur* L.)-mixture

2.5. Adaptation Effort

It is important to define a sound reference in order to evaluate the adaptation effort in the second stage. Intuitively, it seems to make a big difference in terms of adaptation effort whether only the admixture species has to be planned differently, e.g., instead of a Scots pine-European beech stand a Scots pine-oak stand, or if the leading species does not meet the drought restrictions, e.g., instead of a European beech-Scots pine stand an oak-Scots pine stand, or even the leading and admixture species have to be changed, e.g., instead of a European beech-Norway spruce stand a birch-Scots pine stand. Therefore, we assign following scores according to the species proportion that needs to be changed, always assuming for mixed stands that the total splits into 70% leading species and 30% admixture species: (1) 0.7 if the leading species is changed and the former does not become the admixture species; (2) 0.4 if the leading species is changed and the former becomes the admixture species; (3) 0.3 if the admixture species is changed. The sum of all scores within a study region comprises the overall adaptation effort score (AES). The AES has a natural range of values between 0 (no adaptation in stage 2 is necessary at all) and 100 (absolutely no realizability of stage 1 planned species). Thus, the AES can be interpreted as the species proportion that needs adaptation to meet the drought restrictions.

3. Results

3.1. Stand Type Planning under Constant Site Conditions

Based on the distributions of current stand types pending for potential species conversion until 2070 in the two regions of Uelzen and Fläming under the three management scenarios (business-as-usual, climate protection and biodiversity), Figure 5 shows the resulting distributions planned under constant site conditions (stage 1). In addition, Figures 6 and 7 present the distributions applying adaptive planning (stage 2). The main focus of this analysis lies on the identification of uncertainty arising in the planning process due to different climate projections.

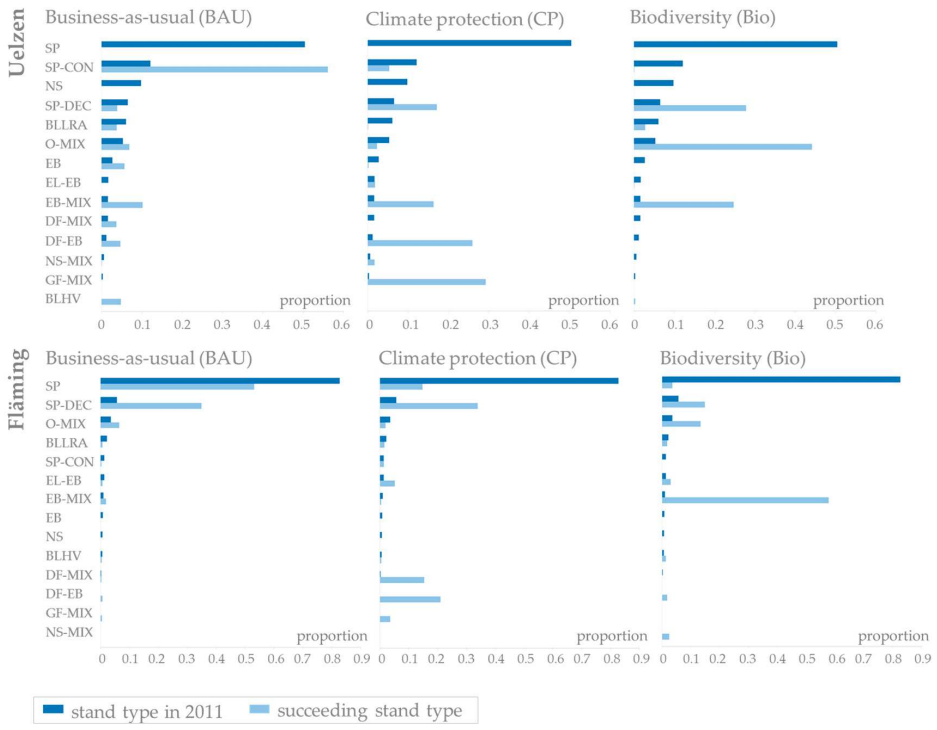


Figure 5. Frequency distribution of current stand type area (dark blue) and succeeding stand type area planned under constant site conditions (stage 1) in 2070 (light blue) under three silvicultural management strategies in Uelzen (**top row**) and Fläming (**bottom row**).

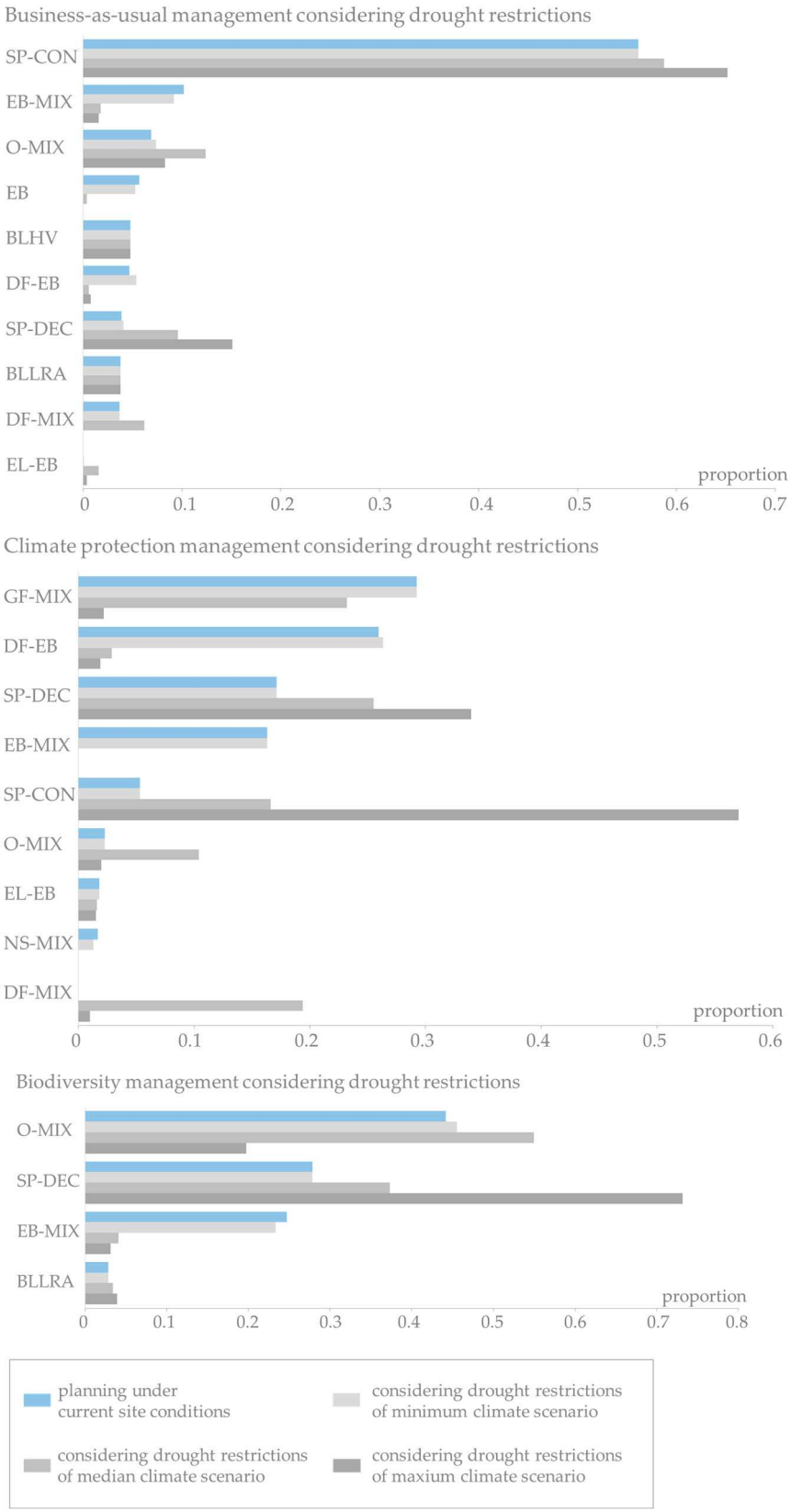


Figure 6. Frequency distribution of succeeding stand type area under constant site conditions in 2070 (**light blue**) and adaptive planning (stage 2) considering drought restrictions under minimum (**light gray**), median (**gray**) and maximum (**dark gray**) climate scenarios under three silvicultural management strategies in Uelzen.

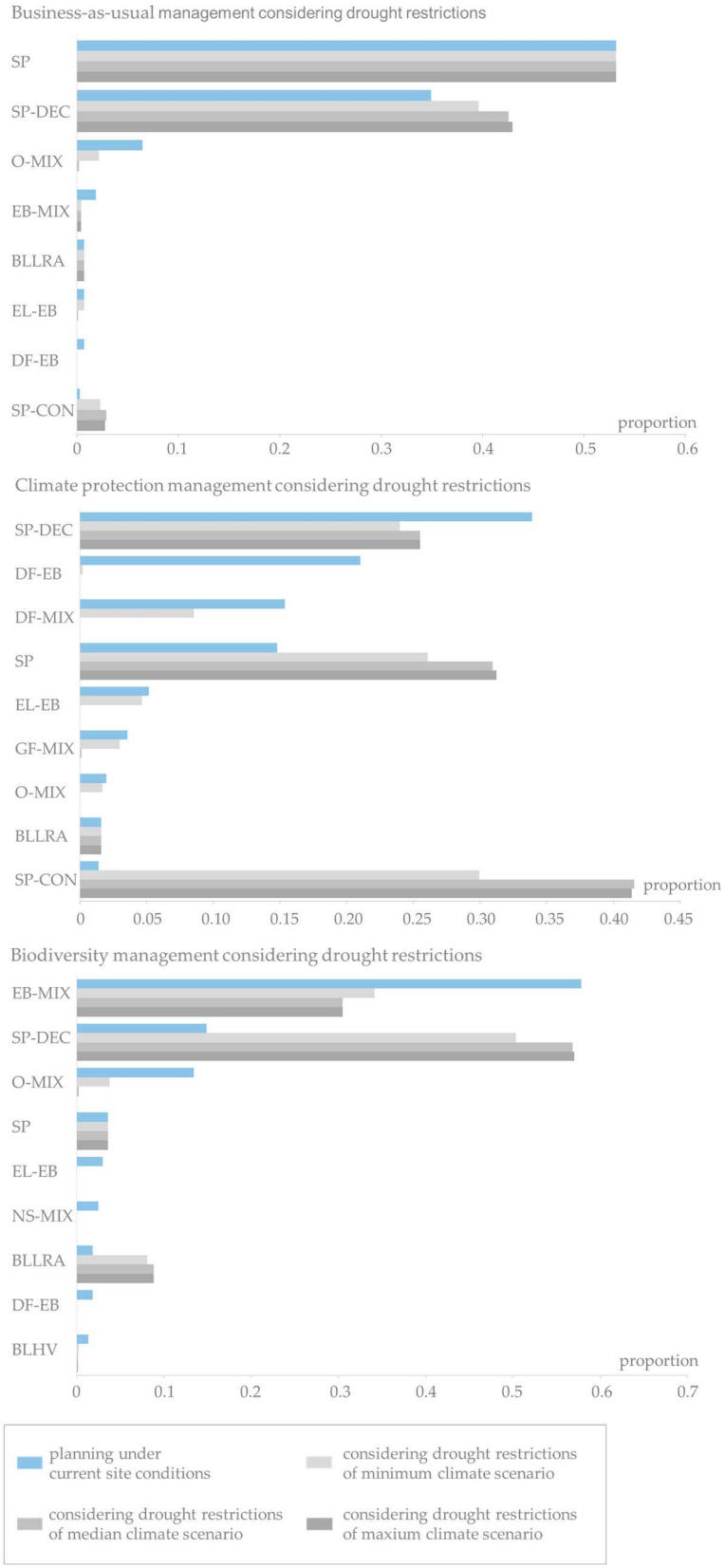


Figure 7. Frequency distribution of succeeding stand type area under constant site conditions in 2070 (**light blue**) and adaptive planning (stage 2) considering drought restrictions under minimum (**light gray**), median (**gray**) and maximum (**dark gray**) climate scenarios under three silvicultural management strategies in Fläming.

The proportions of stand types pending for potential conversion in 2011 are, of course, identical for each forest management strategy (Figure 5, upper row, dark blue bars). In Uelzen, pure Scots pine stands make up the highest proportion of the stands to be potentially converted. The proportion of Scots pine-conifer mixtures follows second. Norway spruce stands, Scots pine-deciduous species mixtures and broadleaves of low rotation age contribute considerably as well. The succeeding distributions planned under constant site conditions (stage 1), however, show significant differences between business-as-usual, climate protection and biodiversity management (Figure 5, upper row, light blue bars). Obviously, these differences reflect the different silvicultural objectives of the management scenarios. In Uelzen, no pure Scots pine and Norway spruce stands are planned in stage 1 no matter which management scenario is applied. Under business-as-usual management there is a strong shift towards Scots pine-conifer mixtures. Beech mixtures, oak mixtures, Douglas-fir mixtures as well as pure beech and broadleaves of high value are also planned to a considerable extent. Under the climate protection strategy stand types are mainly transferred to Grand fir mixtures, Douglas-fir mixtures, beech mixtures and Scots pine-deciduous species mixtures. The biodiversity strategy favors oak mixtures, Scots pine-deciduous species mixtures and beech mixtures.

In Fläming, more than 80% of the stands pending for potential conversion are pure Scots pine in 2011. Scots pine-deciduous species mixtures, oak mixtures and broadleaves of low rotation age contribute to a much lesser degree (Figure 5, bottom row, dark blue bars). In accordance with the findings in Uelzen, the distribution of succeeding stand types planned under constant site conditions (stage 1) mirrors management goals (Figure 5, bottom row, light blue bars). Under business-as-usual management mainly pure Scots pine and Scots pine-deciduous species mixtures and minor proportions of oak mixtures and very few beech mixtures are planned. Under the climate protection strategy, there is a shift towards highly productive conifers, i.e., Douglas-fir mixtures, Grand fir mixtures, and Scots pine-deciduous species mixtures as well as a few European larch-beech mixtures. Species planning under the biodiversity strategy strongly promotes beech mixtures, Scots pine-deciduous species mixtures and oak mixtures.

These resulting stand type distributions planned under constant site conditions are subject to examination under climate change conditions, in particular drought stress, in adaptive stand type planning (stage 2).

3.2. Adaptive Stand Type Planning under Drought Restrictions

The need to adjust the stand type selection under constant site conditions when considering drought stress restrictions (cf. Table 3) demonstrates in part the impact of climate change on forest planning. The results can be analyzed looking at three aspects: (1) the change in selected stand types, where a decrease indicates drought vulnerability and an increase is the result of the assignment of more drought tolerant stand types (Figures 6 and 7); (2) the absolute need of adjustment expressed by the adaptation effort score (AES) which is the percentage of necessary change in stand type area between planning under constant site conditions (stage 1) and under adaptive planning (stage 2) in regard to the three climate projections of minimum, median and maximum (Table 5); and (3) the uncertainty arising in the planning process due to different climate projections, characterized by the spread between the necessary adjustments in stand type selection, i.e., the difference between the AES values under the minimum and the maximum climate scenario (Table 5).

The detailed analysis of changes on stand type level in Figure 6 (top) reveals that in Uelzen under business-as-usual management the planned pure beech and beech mixtures as well as Douglas-fir-beech mixtures are most vulnerable. Pure beech and Douglas-fir-beech mixtures almost entirely exceed the drought restrictions under median and maximum climate scenario. Oak mixtures and Douglas-fir mixtures are seen as alternative stand types with increasing proportions in stage 2. Clearly, the proportions of the most drought-tolerant stand types, Scots pine-conifer and Scots pine-deciduous species mixtures, increase with intensifying drier conditions. Under climate protection management the proportions of the highly productive stand types Grand fir mixture, Douglas-fir-beech mixture decrease

when more extreme climate projections (median and maximum) are assumed (Figure 6, middle). Also beech mixtures, European larch-beech mixtures and Norway spruce mixtures increasingly miss the drought limits under median and maximum climate run. Oak mixtures and Douglas-fir mixtures benefit under minimum and median climate projections as other species suffer from dryer conditions. But under the maximum climate scenario these stand types almost disappear. On the other hand, the proportion of Scots pine mixtures increases drastically. Under the biodiversity strategy the area of beech mixtures strongly decreases with intensifying drier conditions (Figure 6, bottom). The oak mixtures gain proportions under the minimum and median climate scenarios. Under maximum climate scenario also a large proportion of the planned oak mixtures exceed the drought restrictions. While the small proportion of broadleaves of low rotation age stays more or less constant, the already large proportion of Scots pine-deciduous species mixtures (28% under stage 1) increases to 73% under maximum climate projection.

Table 5. Adaptation effort score (AES; see Section 2.5 for definition) under the forest management strategies business-as-usual (BAU), climate protection (CP) and biodiversity management (BIO) applying the climate scenarios of minimum, median and maximum run in Uelzen and Fläming. The uncertainty range is the difference between the AES values of the maximum and the minimum climate run.

		Climate Scenario			Uncertainty
		Minimum	Median	Maximum	Range
Uelzen	BAU	2.0	17.9	21.8	19.8
	CP	0.3	31.5	54.8	54.5
	BIO	3.2	48.5	74.1	70.9
Fläming	BAU	12.2	14.9	15.1	2.9
	CP	28.2	40.4	40.6	12.4
	BIO	50.5	56.1	56.2	5.7

The results for the Fläming region in Figure 7 show that under business-as-usual management the high proportion of pure Scots pine (53%) is constant over the planning stages and climate scenarios. A sharp decrease in the proportions to almost absence is observed for oak mixtures and beech mixtures. Scots pine-deciduous species mixtures receive a considerable gain. Under the climate protection strategy drought restrictions notably reduce especially Douglas-fir mixtures, Scots pine-deciduous species mixtures, Grand fir mixtures, larch-beech mixtures and even oak mixtures. On the other hand, pure Scots pine and, most prominently, Scots pine-conifer mixtures profit in the adaptive planning process (from 1% in stage 1 to 30% in stage 2 under minimum climate scenario and over 40% under median and maximum climate scenario). Under biodiversity management beech mixtures and oak mixtures lose large proportions with increasingly drier conditions. The in the first planning stage rarely represented European larch-beech mixtures, Norway spruce mixtures, Douglas-fir-beech mixtures and broadleaves of high value are entirely disregarded when applying drought restrictions. Scots pine-deciduous species mixtures are the alternative stand types in adaptive planning with increases of 35 percentage points under minimum climate scenario and 42 percentage points under median and maximum climate scenario. To a much lesser extent also broadleaves of low rotation age profit from the drought restrictions.

Obviously, the effort for adaptive planning increases the more extreme the underlying climate projection, for all management strategies in both regions (Table 5). The AES values, i.e., the species proportion that needs adaptation to meet the drought restrictions in stage 2, indicate a negligibly small effort under the minimum climate scenario for all management scenarios (between 0.3 and 3.2) in the Uelzen region. However, already assuming the median climate scenario the AES jumps up to considerable values of 17.9 under business-as-usual, 31.5 under climate protection and 48.5 under biodiversity management. The need to adjust is even more dramatic under the maximum climate

scenario especially in regard to climate protection and biodiversity management, reaching AES values of 54.8 and 74.1, respectively.

In terms of planning uncertainty, business-as-usual is rather robust comparing the management strategies with an uncertainty range of 19.8 percentage points and only a 3.9 percentage point difference between median and maximum climate run (Table 5, last column). Quite differently, under climate protection and biodiversity management the planning uncertainty is extremely large (range of 54.5 and 70.9 percentage points, respectively). Consequently, under these management strategies it is of high importance which climate scenario is assumed during the planning process as it has a strong impact on stand type distribution.

In contrast to the findings in the Uelzen region the effort for adaption applying the drought restrictions is already quite extensive under the minimum climate scenario for all management strategies in Fläming (Table 5). While under business-as-usual the proportion of species which need adaptive planning is 12% and 28% under climate protection, more than half of the species planned in stage 1 need to be replaced in stage 2. However, the increase in the AES with intensifying drier conditions is not as pronounced as in Uelzen, reaching AES values of 15.1%, 40.6% and 56.2% respectively under business-as-usual, climate protection and biodiversity management in regard to the maximum climate scenario.

This relatively small climate effect on stand type planning in Fläming becomes even more obvious, when looking at the inherent uncertainty. Under business-as-usual management the range between minimum and maximum climate scenarios amounts to almost negligible 2.9 percentage points and under climate protection to 12.4 percentage points. The effect of climate uncertainty on the biodiversity strategy is only just 5.7 percentage points.

The changes on the stand type level explain why already the minimum climate scenario causes a high need for adaptive planning and the rather low differences between the impacts of the three climate projections in Fläming. The drought restrictions of the site-adapted species under constant site conditions, for instance oak and beech under business-as-usual and biodiversity management and additionally Douglas-fir and Grand fir under climate protection, are exceeded on many sites in Fläming under the minimum climate scenario already. While there are more site-adapted alternatives for stand types under adaptive planning graduated to climate scenarios in Uelzen, in Fläming the most drought-tolerant stand types, pure pine and pine mixtures, make up the alternative in many cases already under minimum climate scenario. Thus, just little further adaptive planning is possible under even more severe climate projections.

4. Discussion

The findings and the knowledge gained depend on several assumptions and methodological approaches applied. Thus, before we discuss the results in more detail we elaborate on three issues, i.e., (1) tree species selection in the light of changing environmental conditions, (2) the method to assess drought vulnerability and its implications on the planning process and (3) the approach to incorporate climate uncertainty when selecting tree species in the context of forest conversion.

4.1. Tree Species Selection in Light of Changing Environmental Conditions

Forest conversion strives to optimize the achievement of forest enterprise targets in general. This specifically encompasses adaptation measures to changing environmental conditions (e.g., [13,57,58]). Forest conversion involves changes in tree species in the course of regeneration as well as in stand structure objectives, i.e., pure stands versus mixed and even-aged stands versus uneven-aged structures. This study exclusively deals with species selection under changing environmental conditions. It is not considered, whether regeneration is introduced after final harvest of the current stocking or as advance planting under shelter. Also forest management practices to convert forests from even-aged to uneven-aged structures are not presented. Then again, potential changes from pure stands to species mixtures are indeed incorporated in the rule-set for stand type planning.

While many studies develop important theoretical foundations for forest conversion based on model stands or model forest enterprises (e.g., [13,57,59–62]), we implement a forest planning procedure to select tree species for regeneration based on actual forest inventory data and subject to site information and climate projections on a regional level. As is the aim of the study we focus on the effect of changes in drought risk on future species' site suitability, and we neglect other environmental aspects such as potential reduction in nitrogen deposition [63,64], the influence of sulphur deposition [65] or rising CO_2 concentrations [66].

The presented rule-set for species selection is based on forest planning procedures which are applied in Germany today [54,67,68]. The assignment of site-suitable species according to soil nutrients and site water budget takes regional climate properties into account as precipitation and temperature determine site water budget. Furthermore, to warrant flexibility in the planning process several suitable species or species mixtures are listed, if possible. Thus, we explicitly assigned stand types for regeneration based on site-suitability and according to the respective silvicultural management strategy (cf. Tables S9 and S10). Consequently, under business-as-usual management deciduous species and mixtures are preferred, under the climate protection strategy fast-growing conifer species are favored, and the biodiversity strategy emphasizes potentially natural species compositions. These first stage assignments result in a strong predisposition for a need of adaptive planning in the second stage. The entire species selection procedure in both stages abstracts from other particulars to clarify the impact of forest management targets and the effect of climate change.

It is important to note that we did not impose any restrictions other than site-suitability and respecting the drought vulnerability thresholds on the selection of stand types. Of course, large forest enterprises will formulate targets for species distributions [69]. For example, the forest enterprise of Lower Saxony strives to establish deciduous species on 65% of the forest area [54]. Some forest areas will be excluded from forest conversion due to nature protection regulations. And on the regional level different forest owners will pursue different forest management strategies. Beyond that it is also plausible that new stand types need to be defined to meet adaptation demands. For example, the Douglas-fir-beech mixture is converted to conifer mixtures or oak mixtures if drought restrictions apply (cf. Tables S9 and S10). Just as well an alternative to meet drought thresholds could be the newly formulated stand types Douglas-fir-Red Oak or Douglas-fir-Littleleaf Linden.

Furthermore, other risk factors will hamper some species from regeneration as well. Especially in the North German Plain, biotic risk factors such as several Scots pine-related insect pests, nun moth, bark beetle, jewel beetle and root rot may cause severe damage to forest stands. These boundary conditions of additional restrictions and further risk factors need to be considered when species are selected for regeneration under real-life conditions. Extensive knowledge on the environmental conditions for cultivation, growth potential of tree species and possible risk factors as well as awareness of uncertainties are imperative, as species choice for regeneration is a long-term commitment. For example, Schou et al. [70] show how climate change-related uncertainty and the risk of stand destruction influence decision making on converting Norway spruce stands in Denmark.

By virtue of focusing solely on drought restrictions and three management strategies, our analysis adds insights to the topic of species selection, necessary adaptation measures on a regional level and, above all, the interaction between management strategies and climate change in connection with inherent uncertainty.

4.2. Drought Vulnerability Assessment in Forest Planning

It is crucial in forest planning that the information necessary for well-founded decisions is ubiquitously available. And as drought vulnerability very much depends on local site conditions (e.g., [71–73]), consequentially thresholds for species selection considering drought risk should be based on easily available site parameters. Our approach to integrate a drought vulnerability assessment in forest planning is straightforward: we employ species-specific site water budget thresholds based on observed species occurrence subject to their productivity and classify three options for cultivation,

i.e., as primary species, as admixture species and as an exclusion criteria. The ranking of species with respect to drought vulnerability coincides with various other studies in central Europe (e.g., [74–77]). Our method is in line with the often applied relative transpiration index (RTI) [78,79] which accentuates absolute water availability. Müller [78] describes how to derive the RTI based on climatic water balance and available soil moisture, whose sum equals the site water budget used in this study. Furthermore, it seems plausible to use the long-term climatic trend of site water budget as a fuzzy decision criteria for forest planning. On the other hand, short-term singular but extreme dry spells might contradict species selection recommendations (e.g., [80–87]). Choat et al. [30] conclude that these singular deviations from the long-term climatic trend are crucial for species-specific drought vulnerability. However, assessing species- and site-specific drought stress currently still lacks universal and established findings [30,31]. Allen et al. [88] extensively compiled findings of lesser vulnerability as well as more rapid mortality due to drought and they identified six generally accepted global vulnerability drivers, i.e., droughts can eventually occur everywhere, droughts become hotter with warmer climates, non-linear relationships exist between atmospheric moisture demand and temperature during drought, hotter droughts trigger mortality faster, higher frequency of short droughts will eventually trigger mortality, and time-span for forest recovery after drought is long compared to relatively rapid mortality. This underlines the complex nature of evaluating the effect of drought on forests, hence, it is important to provide a robust method for forest planning which can be refined when new insights are available.

4.3. Climate Uncertainty in the Context of Forest Conversion

Many aspects contribute to uncertainty when future developments are anticipated. Walker et al. [89] provide a conceptual framework to classify the various dimensions of uncertainty in model-based decision support. In the case of climate impact research Wilby and Dessai [90] illustrate how uncertainty amplifies in cascades, beginning with assumptions on future societies, the resulting emission scenarios, the applied global circulation models for climate projections, which are further downscaled using regional climate models, and finally the uncertainties associated with impact models and the transfer of projected results to adaptation measures.

Uncertainty in the climate projection itself arises from three distinct sources, i.e., natural fluctuations in the climate system, climate model uncertainty and scenario uncertainty [91]. As different climate models project different changes in climate variables in response to the same radiative forcing, the presented climate impact analysis substantially depends on the selected climate model STARS. STARS projects future climate based on a temperature-driven resampling scheme (TCR). The temperature trend is usually predefined by the gradient in the results of global climate models, in this case INM-CM4, ECHAM6 and ACCESS1.0. STARS' resampling scheme rearranges annual climate values in a first step and subsequently reorders 12-day-weather sequences to achieve the temperature trend. Wechsung and Wechsung [39,40] critically evaluate this methodology. They quantify a negative precipitation bias of approx. 5% per 1 K temperature increase. Despite the model limitations, Wechsung and Wechsung [40] recommend STARS for vulnerability and uncertainty studies. In any case, the potential precipitation bias introduced by STARS should be taken into account when interpreting the presented results. Overall, Hawkins and Sutton [91] conclude that the uncertainty in regional climate projections for the next few decades is strongly affected by model uncertainty and natural fluctuations, whereas for the far-future, scenario uncertainty contributes dominantly to overall uncertainty.

In our study we follow proposals by, e.g., [15,92–94] using three climate scenario projections to at least partially account for climate uncertainty in our analysis. On that part Jones [92] emphasizes that any conclusion derived from impact analysis must remain highly conditional on the underlying ranges of climate projections. Furthermore, the full range of climate uncertainty is unknown [89] and even in the framework of large climate projection ensembles the uncertainty cannot be precisely quantified [18,95]. Therefore, as our model-based decision support on species selection heavily relies on the three assumed climate projections and as the uncertainty associated with these climate projections

is only a rough approximation, any recommendations based on our results must be robust, i.e., at best species selection complies with each underlying climate scenario.

According to Dittrich et al. [96] robust decisions achieve the aspired goals under a broad range of future developments, which makes them particularly suited for deep uncertainty. Among the many strategies to adapt to uncertain futures some seem especially consistent with forest planning demands, e.g., selecting "no-regret" strategies, preferring flexible options, anticipating "safety margins" or reducing the decision time horizon (cf. [97]). Concerning our analysis of species selection under drought vulnerability, a "no-regret" strategy could be to opt for the most drought-resistant species, i.e., Scots pine, which yields benefits even under the most extreme climate scenario as well as under current conditions. Paraphrased, Scots pine has a low sensitivity to false assumptions regarding future climate conditions but, on the other hand, this security is traded for potentially higher productivity by other species. Flexible options and "safety margins" could encompass species mixtures such as Scots pine and European beech and/or oak, i.e., two or three major species spread the risk between drought-resistant but less-productive and more drought-vulnerable but also more-productive species. Furthermore, in the course of time, forest management can be adjusted to new insights and the changing climate conditions. Finally, reducing the decision time horizon can easily be achieved by adjusting the silvicultural expectation, i.e., for example, reducing the target diameter for final harvest in Douglas-fir from 70 cm to 60 cm shortens the time horizon by approximately 20 years. This could very well determine whether or not to select Douglas-fir for regeneration.

In this study we clearly show that the amount of uncertainty due to climate change concerning species selection strongly depends on the forest management strategy chosen. While it is easy for forest practitioners to opt for a certain forest management strategy, it is much more difficult for them to base their decision for species selection on a chain of model predictions, the underlying assumptions and the inherent uncertainty. Although decision support provides information on different scenarios and their implications on forests and forest enterprises, in the end one forest planning alternative has to be set into practice. As is the case with risk assessment, where decision-makers can act in a risk-averse, risk-neutral or risk-taking manner [98,99], the attitude towards uncertainty in general and climate-induced projection variability specifically is highly person-specific with a strong subjective share. Thus, although one cannot assign probabilities to climate change scenarios for theoretical reasons [15], the decision-maker ultimately needs to select one scenario as the most probable in his personal assessment, converting belief into subjective probability (cf. [21]). Yousefpour et al. [100] take decision-making in the context of adaptive forest management one step further as they show how forest managers' beliefs about the effects of climate change are altered by new insights and how this additional knowledge influences their decisions.

4.4. The Findings and Their Implications in a Broader Context

The two most important issues to be discussed concerning the results of this study are (1) whether or not the specific management goals can be realized under drought restrictions and (2) how a forest manager's belief in a certain climate scenario influences adaptive planning.

First of all, the results and their implications for forest planning are very specific for each growth zone, represented by the two study regions Uelzen and Fläming. In Uelzen, favored by site, climate and higher species diversity forests are less vulnerable to drought than in Fläming. In Uelzen, under the minimum climate scenario, the management goals of each silvicultural strategy, business-as-usual, climate protection and biodiversity, are realizable without concessions. Under median and maximum climate scenario and business-as-usual management, about one fifth of species proportions need to be adjusted to drought restrictions. Basically this involves beech mixtures being exchanged for oak mixtures and Scots pine mixtures; thus, it is feasible to deem the management goals achieved under drought restrictions as well. Therefore, in the case of business-as-usual silviculture in Uelzen, the uncertainty in climate projections plays a minor role in achieving the management goals, although adaptive planning is necessary for the median and maximum climate scenario. Under the biodiversity

strategy, beech mixtures are replaced by oak mixtures and Scots pine-deciduous species mixtures. As birch-oak mixtures and pine mixtures are potentially natural forest ecosystems in Uelzen [101], this shift does not contradict the biodiversity strategy at all. Thus, the forest manager's belief in a certain climate change scenario is insignificant for biodiversity goal achievement in Uelzen. Nevertheless, the proportion of adaptive planning rises up to 74% under the maximum climate scenario. However, adaptive planning under the climate protection strategy is not in line with management goals when applying the median or maximum climate scenario. The most productive Grand fir mixtures and Douglas-fir mixtures will not meet drought restriction thresholds and need to be exchanged for Scots pine mixtures and oak mixtures if no new alternative stand types as, for example, Douglas-fir-Red Oak or Douglas-fir-Littleleaf Linden are considered. Depending on the decision-makers' subjective choice of climate scenario, putting aside the minimum climate run, the management goals will be missed with 32% replacement under median and 55% replacement under the maximum climate scenario.

Most striking about the analysis for the Fläming region is the perception that climate uncertainty is practically meaningless for adaptive planning decisions. So no matter what the forest manager's belief and which silvicultural management strategy pursued, the maximum deviation in stand type replacement is 12 percentage points. On the other hand, even under minimum climate scenario, the necessary replacement of species proportions under adaptive planning is between 12% (business-as-usual management) and 50% (biodiversity management). For biodiversity management goals the shift from beech mixtures and oak mixtures to Scots pine-deciduous species is in line with potentially natural forest ecosystems in Fläming [102], thus the management goals are realizable. Under business-as-usual strategy oak mixtures and beech mixtures have to be exchanged for Scots pine mixed either with deciduous or with other conifer species. Therefore, concessions to meet the desired close-to-nature management goals, are necessary, especially when looking at the aim to increase the area of deciduous species. The climate protection strategy is the most crucial in respect to goal achievement. Like in Uelzen, the most productive stand types of Douglas-fir mixtures and Grand fir mixtures are replaced by pure Scots pine and Scots pine-conifer mixtures under adaptive planning to meet drought restrictions. This clearly contradicts the management goals to select fast-growing conifer tree species to a great extent.

In summary, it is important to note that adaptive planning is potentially sub-optimal in regard to forest management goals, i.e., concessions might be unavoidable concerning ecological and/or economic targets [11]. Moreover, in some special cases adaptive planning may be independent from climate uncertainty and equates to robust decision making, provided the decision maker is aware of the determining factors (e.g., [103–105]).

Altogether, in Uelzen under the minimum climate scenario and averaging the three management scenarios, 2% of the species proportions need to be exchanged to meet drought vulnerability thresholds. Under the median climate scenario the proportion is 33% and under maximum run is 50%. In Fläming the proportions for replacement range from 30% to 37%. This assessment is comparable to findings by Schelhaas et al. [13], who report that between 36% and 40% of the forest area in Europe is expected not to meet species suitability criteria by 2070 because of climate change. However, the reservation must be made that the forest area considered for active species conversion in this study is hypothetical, as financial restrictions or silvicultural principles might prevent planting. Nevertheless, the proportions of necessary stand type replacements indicate the need for adaptation measures.

In a broader context Spathelf et al. [106] conclude that close-to-nature silviculture falls short to be an adequate concept to adapt forests to climate change, when taken seriously about the two key elements of preference of natural regeneration and low-impact interventions. They argue that silvicultural concepts which allow for small-scale disturbances to promote a broad range of species to regenerate and thus to enhance stand resilience are more suitable. However, as site conditions rapidly change, rigid conceptions on the unrestricted advantageousness of natural regeneration need revision [14]. Additionally, in this study we just selected stands for potential conversion based on

the framework conditions of three different management strategies without implicitly assuming the according principles for conversion.

The presented findings rely on the applied method to assign stand types according to site properties related to soil nutrients and site water budget. Drought restrictions are considered in site water budget and are modelled dynamically over time. Bolte et al. [62] introduce an alternative method to select species according to site suitability. They propose to evaluate the regional risk for species based on their retrospective performance, to apply climate envelope analysis and to use climate matching analysis. This sophisticated procedure will certainly yield comprehensive science-based recommendations for species selection. We believe, however, that implementing a slightly advanced species selection procedure which is based on traditional methods has an increased likelihood of adoption in many forest planning practice.

5. Conclusions

As Yousefpour et al. [104] point out, it is of outmost importance for successful adaptive forest planning that decision-makers are aware of the interactive nature of management goals and limitations imposed by changing climate conditions and their intrinsic uncertainty. Complementary to more theoretical or large-scale approaches (e.g., [13,21,57,61,62]) which clarify tendencies and draw general conclusions, our regional-scale approach reveals specific management options for the next generation of forests based on given forest stands on defined sites in a region under climate change. Furthermore, we promote a method for decision support which builds on easily and ubiquitously available data, i.e., site water budget under climate change. Moreover, the presented procedure to assess site-suitability of species under climate change is an advancement of the well-established current method. Thus, acceptability in forest practice is assumed high.

Four main conclusions are drawn: (1) Obviously, the need for adaptive planning considering drought vulnerability strongly depends on the climate change scenario subjectively deemed most probable and the underlying forest management goals; (2) Adaptive planning might force a compromise between responsible forest planning decisions and forest management goals; (3) Uncertainty in climate change scenarios and, thus, the decision-makers subjective choice of a certain climate projection may influence species selection considerably, e.g., climate protection management in Uelzen, or in some other case may be irrelevant, e.g., biodiversity management in Fläming; (4) Recommendations for species selection in Uelzen imply that the need for adaptive planning is clearly lower than in Fläming and consequently, most management goals are realizable with some minor concessions. However, the choice of climate scenario has a considerable effect on the assessment of species suitability. In Fläming there is an extensive need for adaptive planning and, as a result under business-as-usual and climate protection management strategies, fairly strong adjustments to management goals are necessary. On the other hand, climate uncertainty is not an issue in Fläming.

Future research should focus on better methods to quantify the effect of drought on productivity and tree vitality, ultimately in interaction with other abiotic and biotic risk factors. To further enhance the scientific basis for forest planning, further risk factors need to be incorporated into the planning process.

Supplementary Materials: The following are available online at www.mdpi.com/1999-4907/8/10/363/s1, Table S1: Assignment of stand types in regard to soil nutrient and site water budget matrix under business-as-usual management in Uelzen, Germany, Table S2: Assignment of stand types in regard to soil nutrient and site water budget matrix under climate protection management in Uelzen, Table S3: Assignment of stand types in regard to soil nutrient and site water budget matrix under biodiversity management in Uelzen, Table S4: Assignment of stand types in regard to soil nutrient and site water budget matrix under business-as-usual management in Fläming, Germany, Table S5: Assignment of stand types in regard to soil nutrient and site water budget matrix under climate protection management in Fläming, Table S6: Assignment of stand types in regard to soil nutrient and site water budget matrix under biodiversity management in Fläming, Table S7: Selection probabilities for random draw of stand types, Table S8: Assignment of other species (limited to species relevant in the two study regions) to species groups according to drought vulnerability (leading species in group in italics), Table S9:

Assignment of stand types in Uelzen according to the silvicultural management strategy under constant site conditions (1. stage) and applying drought restrictions (2. stage), Table S10: Assignment of stand types in Fläming according to the silvicultural management strategy under constant site conditions (1. stage) and applying drought restrictions (2. stage).

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Article

Is Biomass Accumulation in Forests an Option to Prevent Climate Change Induced Increases in Nitrate Concentrations in the North German Lowland?

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Abstract: The North German Lowland is a region with locally high nitrate (NO_3^-) concentrations in seepage water, inducing an increased susceptibility to the effects of climate change. The future risk of rising NO_3^- concentrations in seepage water from forests was quantified for four regions in the North German Lowland using climate projections and a modelling system comprising submodels for forest stand development (WaldPlaner), water budgets (WaSiM-ETH), and biogeochemical element cycles (VSD+). The simulations for the period from 1990 to 2070 included three different forest management scenarios (reference, biodiversity, and climate protection) and showed a general decrease in groundwater recharge which could hardly be influenced by any of the management options. The simulated soil organic matter stocks adequately represented their past increase as expected from the National Forest Soil Inventory (NFSI), but also showed a future decline under climate change conditions which leads to higher organic matter decomposition and a long-lasting increase of NO_3^- leaching from forest soils. While the climate protection oriented scenario shows the highest increase in NO_3^- concentrations during the projection period until 2070, the biodiversity scenario kept NO_3^- concentrations in seepage water below the legal thresholds in three of four selected model regions.

Keywords: nitrate; groundwater recharge; climate change; soil organic matter; standing volume; WaSiM-ETH; VSD+; Roth-C; YASSO07

1. Introduction

Next to carbon (C), oxygen, and hydrogen, nitrogen (N) is one of the main building elements of plant biomass, being of central importance for plant metabolism and growth. Since nitrogen is mainly taken up by the roots of plants in the form of soluble nitrate (NO_3^-) or ammonium (NH_4^+), the availability of these ions in the soil solution is a precondition for plant growth and has been a growth limiting site condition in many ecosystems including forests [1,2]. During the last sixty years, atmospheric emissions of N species (NO_x, NH_3) from traffic, industrial processes, and agriculture in Central Europe have been drastically elevated. Subsequent deposition to terrestrial ecosystems increased N availability to a level exceeding the demand of forest stands' growth increment [3]. It has been shown that this long-term increase in N deposition significantly increased forest productivity [4], thereby making forest biomass a valuable sink for excess N. Unfortunately, excess N is usually not completely retained within the forest ecosystems: After a period of N accumulation in the ecosystem, forests may become N saturated and NO_3^- is increasingly leached with seepage water [5,6], causing

increased NO_3^- concentrations in groundwater and surface waters [7,8] and also leading to a loss of base cations relevant for tree nutrition [9]. The oxidation of deposited NH_4^+ in forest ecosystems by plant uptake or nitrification causes the generation of acidity which may subsequently be transferred to surface waters [10,11]. Although N deposition to forests was slightly reduced during the last two decades [12], a high proportion of forest ecosystems in Central Europe shows symptoms of N saturation [3], leading to nutrient imbalances as well as a marked loss of their N retention capacity [13].

Forests play a major role in water quality in the cultural landscapes of Europe [14], because unlike for agricultural land-use, fertilization, the application of pesticides and tillage are nearly absent in forests. Consequently, the NO_3^- concentration in the surface groundwater is usually substantially lower under forest as compared to arable land [15]. The implementation of the EU Water Framework Directive (WFD, [16]) requires integrative concepts to ensure a good quality of seepage and groundwater. The limitation of NO_3^- leaching is one of the key objectives of the WFD where a legal threshold of 50 mg L^{-1} was set as the maximum acceptable NO_3^- concentration in surface and groundwater [16,17]. As atmospheric deposition is the major input flux of N in forest ecosystems, it often determines, to a large degree, N output [18]. However, tree biomass, forest floor, and mineral soil are important ecosystem compartments that may retain huge amounts of N and significantly delay the effects of atmospheric N input on N leaching in forests [13,19–21]. Some studies show that the C/N ratio of the forest floor or the upper mineral soil can be a valuable indicator of the risk of NO_3^- leaching from forest soils [18,22,23].

As temperature and water availability are important drivers for processes involved in the N cycle, climate change is expected to have a considerable potential for the alteration of ecosystem N fluxes and in particular for the N retention in the soil [24]. Relative to 1850–1900, global circulation models (GCMs) project increases of the global mean annual surface temperature for the end of the 21st century between 1.0 and 5.5 K [25,26]. Several modelling approaches have been employed to assess deposition scenarios and climate change impacts on forest soils including NO_3^- leaching [27,28]. However, there is often a gap between models intended for systems understanding and models for decision support, hampering their application for practical purposes [29].

The present study pursues (i) an evaluation of the effects of the intensity of forest management on NO_3^- concentrations and leaching for selected model regions in the North German Lowland and (ii) an assessment of future risks for NO_3^- leaching under changing climatic conditions. In order to achieve these aims, we implemented a scale-independent modelling framework. The study has been conducted within the framework of the project Sustainable Land-Use Management in the North German Lowlands (NaLaMa-nT, [30,31]).

2. Materials and Methods

The study area comprises the North German Lowland, a mainly plain, sometimes undulated landscape with only low elevations. The landscape is formed by Pleistocene and Holocene sediments. Agricultural land-use prevails, but a considerable area, which is increasing from west to east, is forested. Climate is temperate with maritime influence in the northwestern parts and subcontinental influence in the southeastern parts.

2.1. Model Regions

Four model regions were selected for the study, representing the existing spatial gradients in continentality, N deposition, proportion of organic soils, and soil fertility in the North German Lowland. For these regions, it was possible to obtain the required retrospective and prospective data on forest stands, site conditions, and climatic drivers in a high spatial and temporal resolution in order to implement the modelling system for the simulation of forest stand development and N cycling. Measured and simulated stream chemistry data for selected catchments in the model regions are available as additional information [32].

The model region Diepholz (acronym DH) with a forested area of 15,042 ha, equaling 6.7% of its total area, is characterized by a maritime climate with 743 mm annual precipitation and a mean temperature of 9.7 °C, high N deposition from intensive agriculture (40 kg ha^{-1} a^{-1}) with an NO_x/NH_y ratio of 0.3), and a high proportion (in area) of organic forest soils, soils with predominantly high field capacity, and a large part of the forested area with connection to groundwater (42% $\leq$ 2.5 m depth to groundwater level). Tree species composition in DH is very diverse with 65% deciduous and 35% coniferous species. The majority of forest stands are relatively young (approx. 60% between 20 and 60 years).

The county Uelzen (acronym UE) comprises a forested area of 45,712 ha (34.7% of its total area) and is located within a still maritime climate with subcontinental impact and a mean annual temperature of 9.3 °C.; its annual precipitation being 721 mm, only slightly lower than that of the more maritime region Diepholz. Only 9% of its forest soils have connection to groundwater, the soils being mainly sandy with medium to low soil water availability. Nitrogen deposition is 26 kg ha^{-1} a^{-1} (NO_x/NH_y = 0.7), slightly above the average for the North German Lowland. Tree species distribution is strongly influenced by Scots pine (61%) and deciduous species account for only 20%. The age class distribution is predominated by stands aged 40 to 80 years (approx. 60%).

The model region Fläming (acronym FL; 51,368 ha forests, 41.5% of total area), in contrast, is exposed to a subcontinental climate and local emissions of N compounds (NO_x/NH_y = 0.6, on average 25 kg ha^{-1} a^{-1}). This model region receives (except on the top of hills) a very low amount of precipitation (long-term average 1991–2010: 572 mm). Mean annual temperature is 9.8 °C. Only 11% of the predominating sandy soils are connected to groundwater. The predominance of Scots pine increases from west to east. In FL, it already accounts for 74% of the forest area. Approx. 23% of the area is deciduous trees, especially European beech and sessile and pedunculate oak. The age class distribution in FL is almost balanced.

The model region Oder-Spree (acronym OS, 76,714 ha forests, 48.7% of total area) is also exposed to a subcontinental climate with very low precipitation (long-term average: 572 mm). Mean annual temperature is 9.6 °C. While the predominantly sandy soils have low field capacity, groundwater is accessible in 22% of the forested area for tree roots (<2.5 m depth). Nitrogen deposition is comparatively low in this model region with 22 kg ha^{-1} a^{-1} and a NO_x/NH_y ratio of 0.8. In OS, Scots pine covers 81% of the area and only 17% is deciduous species. Approx. 70% of the stands are between 40 and 100 years old.

2.2. Climatic Data and Climate Projections

Retrospective and prospective climatic data were obtained from the output of an ensemble of 21 global circulation models (GCM) based on the RCP 8.5 emission scenario [33,34]. With regard to the most recent years since 2010, out of all RCP scenarios, the RCP 8.5 emission scenario fits best to current emissions. The regional climate projections for the four model regions differed between the GCMs mostly in the projected mean annual temperature increase for the period 2050–2070, which varied between 1.1 K and 2.7 K. The projected change in annual precipitation varied between −220 mm and +218 mm for a period of 100 years (on average +14.6 mm) over all projections. We considered the median run with respect to climatic water balance—due to the high relevance of water seepage for the investigated processes—for further analyses. The selected climate projection is based on the GCM ECHAM6 [35].

The output of ECHAM6 was downscaled to the 2236 climate stations of the German Weather Service (DWD) using the regional climate model STARS [36] to obtain daily values of precipitation, sunshine duration, mean temperature, relative humidity and wind speed for the period 1991 to 2070 for Germany, which were further downscaled to a 100 m grid using a combination of inverse distance-weighting and an elevation-dependent regression implemented in the hydrological model WaSiM-ETH [37]. The STARS statistical model creates climate projections based on a temperature-conditioned resampling in order to estimate climatic elements for a given temperature

increase [38]. The temperature dynamic is defined as a periodic trend obtained by the GCM. The resampling is done in two steps. Firstly, by the means of newly arranged annual climate values and secondly by a rearrangement of 12-day weather sequences.

The climatic time series for the retrospective period 1991 to 2010 generated with STARS was compared to observed data from the DWD and produced a climate scenario with less than 0.1 °C deviation from the annual mean temperature in each model region and a slightly lower precipitation (−1% to −5% relative to measured values for that period). The use of simulated climate data also for the past period enabled a better consistency of the analysis over the whole simulation period.

2.3. Forest Management Scenarios

Three different options of future forest management were considered as management scenarios, hereafter referred to as 'reference', 'biodiversity', and 'climate protection' scenarios. The reference scenario reproduces close-to-nature silvicultural practices which are widely applied in northern Germany today (e.g., LÖWE, [39]). Close-to-nature silviculture favours the cultivation of broadleaf trees and mixed species stands, always considering the selection of site-adapted species. The biodiversity scenario favours tree species of the potential natural vegetation (PNV) and reduces the maximum allowed harvest volume from 70 to 50 m^3 ha^{-1} per cut. PNV trees are allowed to grow 5 to 10 cm larger in target diameter and introduced tree species are felled when they are 5 to 10 cm smaller in target diameter than in the reference scenario. Thus, in the biodiversity scenario, thinning volume is less and final harvests are delayed compared to the reference scenario. Dead wood is accumulated up to 40 m^3 ha^{-1} instead of only 20 m^3 ha^{-1} in the other two scenarios. Furthermore, under the biodiversity scenario, 5% of the forest area remains unmanaged while under the reference and climate protection scenario the unmanaged area ranges from 1% to 2% depending on the model region. The third scenario is termed climate protection, since it aims to maximize C storage in standing biomass and wood products. It favours fast-growing site-adapted coniferous trees with a 5 cm smaller target diameter compared to the reference scenario. Consequently, under the climate protection scenario, more volume is cut and final harvest is at an earlier stage compared to the reference scenario.

2.4. The Modelling System

The modelling system is based on well documented, publicly available models for forest growth, water budgets, and biogeochemical matter cycling. The individual models were externally coupled in such a way that the output of the models, necessary as the input for the other models, is exchanged at the beginning of each simulation cycle. Details on the coupling procedure between the hydrological and forest growth model are given in [40]. The individual models are established and validated models and were adapted to the purpose of this study. Therefore, we present only a short overview of each model.

2.4.1. Forest Growth Model

To model the growth of the forest stands, we employ the statistical individual tree growth model TreeGrOSS parameterized using data from Northwestern Germany [41]. For this study, TreeGrOSS was extended by implementing a climate-sensitive longitudinal diameter–height model [42]. The model, originating from a re-parameterized version of the Korf function by Lappi [43], predicts single-tree height to diameter relations as a function of soil and climate parameters (cf. [30,42]). The longitudinal diameter–height model is spatially explicit, thus it takes, among others, the strongly spatially correlated nitrogen deposition into account. TreeGrOSS and its climate-sensitive extension are the core for the forest simulation system "WaldPlaner 2.1" [41]. The WaldPlaner system projects forest development by applying silvicultural management regimes and accounting for changing climatic conditions. The system requires data on forest stands, soil properties and climate conditions as the input and silvicultural management regimes are specified using a list of control variables [30]. The control

variables used in the forest growth simulator WaldPlaner to define the management scenarios are listed in Table 1.

Table 1. Characteristics of selected control variables defining the three silvicultural management scenarios' reference, biodiversity and climate protection in the forest growth simulator WaldPlaner.

Control Variable	Reference	Biodiversity	Climate Protection
unmanaged area	status quo	5% of forest area	status quo
area under flora-fauna-habitat (FFH) directive	45% of the FFH-area as natural habitat type	100% of the FFH-area as natural habitat type	45% of the FFH-area as natural habitat type
deadwood (m^3/ha)	20	40	20
selection of future stand type	dominating deciduous species	tree species of potential natural vegetation (PNV)	dominating conifer species
thinning intensity	variable over time: high, moderate, low	moderate	variable over time: high, moderate, low
thinning type	thinning from above	thinning from above	thinning from above
start of thinning (defined by stand height)	12–16 m	12–16 m	11–15 m
limit of thinned volume per cut (m^3/ha)	max 70 (Douglas-fir max 100)	max 50 (Douglas-fir max 100)	max 70 (Douglas-fir max 100)
target diameter (cm)	oak 70, beech 60, spruce 45, pine 45, Douglas-fir 70	all species +5 cm, in FFH-areas +10 cm, except spruce −5 cm, Douglas-fir −10 cm	all species −5 cm
limit of harvested volume per cut (m^3/ha)	max 100 (Douglas-fir max 120)	max 70 (max 100 for all species not included in PNV)	max 100 (Douglas-fir max 120)

The initialization of forest stands for the forest growth model was based on forest authority data from the currently existing forests at roughly 1000 randomly chosen locations along a regular grid over each model region (altogether 3883 sampling points). Due to lacking of some data and the low proportion of forested area in the model region Diepholz, the number of sampling points was lowest in this region (874), while it was between 999 and 1008 for the other regions. The initialization data from these points comprise stand age, tree species composition, and for each species and stand layer its coverage, mean diameter at breast height (DBH), mean height, age, volume per ha, and relative stand density [31].

At the beginning of a simulation cycle, the WaldPlaner system generated model stands with individual trees based on stand parameters as listed above for each sampling point in the model regions. For each single tree, tree characteristics such as age and DBH were calculated and entered into the database. The stand development and consequently the tree dimensions are updated in 5-year prediction intervals. Besides the forward projection of stand development, it was also necessary to reconstruct forest development by backward simulations with the WaldPlaner system for the past period 1991 to 2010.

The same approach for the initialization of stands was chosen for plots of the National Forest Soil Inventory (NFSI) in the North German Lowland based on inventory data from 2012.

A comprehensive system of rules, implemented in the database, was followed to determine all stand-specific parameters from single tree data and process them for the submodels. The degree of canopy cover was calculated directly for each stand in WaldPlaner, with values ranging between 0 and 100% (complete canopy cover). If less than 85% of the stand area was under canopy cover, a secondary vegetation layer (ground vegetation) was considered. Due to an extended vegetation period as a result of changing climate conditions, we expected a changing phenology of the trees. Therefore, we calculated the vegetation period for each year separately. The start of the vegetation period was determined using a degree-day model of Menzel [44]. The termination of the vegetation period was estimated according to von Wilpert, Walther and Linderholm, and Frich et al. [45–47]. Thus, the termination of the vegetation period is based on either the short-day criterion or the temperature criterion, whichever is met first. Von Wilpert [45] selects 5 October as the short-day criterion, as day length after 5 October is not sufficient to warrant xylem growth. The temperature criterion is met

according to Walther and Linderholm as well as Frich et al. [46,47], when the moving temperature average within a 7 day span falls below 5 °C. The maximum leaf area index (LAI) was derived for each tree species based on allometric relationships [48]. As the growth model indirectly accounts for nitrogen deposition, LAI is affected as well. The forest characteristics were also coupled with the GrowUp model [49]. It is a pre-processor for VSD+ to compute nutrient uptake and litterfall from tree growth data. For nutrient content in tree compartments, data from [50] were used. The foliar N content is modelled depending on nitrogen deposition (cf. [49]).

2.4.2. Water Budget Model

The WaSiM-ETH model [37] was used to calculate the water budget at each sampling point of the model regions, driven by the projected climate data. The model uses grid-based information for meteorological drivers, site and stand characteristics. The model has been run on a daily time step. It was parameterized based on the forest inventory data of the year 2010 (leaf area index LAI, stand height, canopy cover) and forward and backward calculated forest stand dynamics from the WaldPlaner simulations. The LAI (comprising all plant surfaces, i.e., including stems and ground vegetation) of coniferous forest stands during the dormant season has been set to 80% of the maximum LAI and for deciduous forest stands to 50%. Soil water fluxes are simulated using a one-dimensional form of the Richards equation. Parameterization of soil water retention functions has been carried out according to van Genuchten [51]. The van Genuchten parameters have been obtained using soil information from a digital soil map (Forest-BÜK 1:1 Mio, [52]) and pedotransfer functions from [53]. The calculated seepage rate equals the amount of water that leaves the lowest simulated soil layer below the rooting zone and was assumed to represent the groundwater recharge.

An additional and spatially more extended simulation assuming static forest stand conditions was performed for the plots of the NFSI in Brandenburg, Saxony-Anhalt, Lower Saxony, and Schleswig-Holstein, where observed soil and stand information spread over large parts of the North German Lowland was available. This simulation serves as a baseline that allows to disentangle climatic effects from effects of stand development.

2.4.3. Element Budget Simulations

The VSD model (Very Simple Dynamic) has proven to be suitable to describe the dynamics of the acid-base status [54,55], and C and N dynamics of forest soils, e.g., for ICP Forests Level II plots in Germany [56–61]. The VSD model was chosen in this study due to its relatively low data requirements and the limited data availability in the model regions.

The dynamic development of C and N stocks within the organic layer and the upper 90 cm of the mineral soil was calculated with VSD+ version 5.2; Coordination Centre for Effects (CCE), Bilthoven, The Netherlands, [62,63], including the C model Roth-C [64] as an integrated submodel. For comparison, C dynamics in soil organic matter were additionally calculated with the model YASSO07 [65]. Aboveground and belowground litter input for both models were derived based on the model GrowUp (version 1.3.2; CCE, Bilthoven, The Netherlands, [49,66]) in which biomass expansion factors and turnover rates used in the EFISCEN model [67] were implemented. Climate and soil water conditions as well as stand characteristics are based on the climate projections and water budget and forest growth simulations described above. The N uptake efficiency (Nupeff) in the VSD+ model is an essential parameter representing the fraction (-) of N deposition that is available for uptake. The default value for Nupeff is 0.92 [63] which implies that 8% of deposited N will be leached e.g., during the dormant season [61]. We chose somewhat higher values between 0.96 and 0.99, assuming that the N leaching is less pronounced in regions with relatively low rainfall (cf. Chapter 2.1) [68].

The full list of parameters used for the VSD+ model is given in Appendix A. The N fluxes calculated with VSD+ were balanced to yield the N budget of the forest soil:

$$\text{N budget} = \text{N deposition} + \text{N litter input} - \text{N uptake} - \text{N leaching} - \text{N losses by denitrification}$$

Carbon and N stocks were initialized using data from the first NFSI with the reference year 1991 [69,70]. The initial distribution of soil organic matter content among the five C pools is done by assuming that the inert organic matter can be estimated from the total organic matter contents according to [71].

Initial soil C stocks for YASSO07 were also derived from the first NFSI. However, its distribution among the five pools cannot easily be estimated and an unbalanced pool initialization may result in unrealistic model output [72]. Therefore, the model pools were initialized using a spin-up procedure [73] running the model for 1000 years backwards with dynamic litter inputs from yield tables and constant climatic conditions (mean average temperature and drought index for the regions).

The performance of both C models was evaluated based on the observed soil C dynamics between the first and the second NFSI that was regionalized with a generalized additive model (GAM, see below and Figure 5).

2.5. Spatially Explicit Input Data

The model system described above needs a set of input data for the sampling points in the model regions that includes soil properties, N deposition, and climate characteristics. The simulations are run for each point. The physical soil characteristics are assumed to be static over the considered time, whereas the chemical soil parameters are calculated dynamically with VSD+. N deposition was included as a time series derived from air pollution abatement scenarios (see Section 2.5.2).

2.5.1. Soil Data

Physical soil properties (soil texture, bulk density, stone content, available soil water capacity, etc.) were taken from a digital soil map of scale 1:1 Mio (Forest-BÜK, [52]). More details can be found in Albert et al. [31]. Potential cation exchange capacity was calculated with pedotransfer functions of Müller and Waldeck [74].

The soil chemical input parameters (C and N stocks, base saturation) were regionalized for each sampling point with generalized additive models (GAMs) built on the evaluation of NFSI data. Statistical correspondence between 185 variables of the NFSI (Appendix B) was condensed in three GAMs in order to enable the regionalization of C and N stocks, as well as base saturation, for the sampling points for the reference years 1991 (first NFSI) and 2006 (second NFSI) based on available parameters from the digital soil map (potential cation exchange capacity, soil type, bedrock, forest type, soil region, proportion of coarse fragments, mean annual temperature, N and S deposition, degree of podsolization). Parameter selection followed a maximum likelihood based approach (R-package mgcv [75,76]). Here, continuous variables were represented as tensor product approximations with restricted curve flexibility. The exhaustive dataset of the second NFSI was used for parameter selection, whereupon the first NFSI was used as an independent dataset to test the validity of the model structure for another point in time.

The regional transfer model for organic C stocks (forest floor plus mineral soil up to 90 cm depth) has the form

$$\text{gam}(C_{org}) \sim \text{te}(CEC_{pot}) + \text{te}(N_{dep}) + \text{te}(GC) + \text{te}(T) + BR + Stype + Sregion + stand,$$

with C_{org} depending on four continuous variables: potential cation exchange capacity (CEC_{pot}), N deposition (N_{dep}), gravel content (GC), and annual mean Temperature (T), as well as on four classified variables: bedrock type (BR), soil type and soil region according to the German soil classification system (Stype and Sregion, [77]), and stand type classification (broadleaf, coniferous or mixed stand). Bedrock types were distinguished between basic bedrock, acidic/intermediate bedrock, silica based bedrock, sandstone, organic formations, and unconsolidated rock. Soil types were classified into carbonatic immature soils, lessive soils, podsols, anthropomorphic soils, and other soils.

The quantification of C/N ratios for VSD+ required an additional regional transfer model for N stocks within the same soil depth. Parameter selection resulted in the following model:

$$\text{gam(N)} \sim \text{te}(CEC_{pot}) + \text{te}(C_{org}) + \text{Pod} + \text{BR} + \text{te(hum)} + \text{broadleaf}$$

Here, the continuous variable (hum) stands for thickness of the forest floor, and additional classified variables are degree of podsolization (Pod) and purely broadleaved stand vs. other stands (broadleaf). Next to CEC_{pot} and C_{org}, each of the four degrees of podsolization was a significant variable with $p \leq 0.001$.

Base saturation from NFSI plots was integrated over 90 cm of the mineral soil and forest floor considering soil bulk density, amount of fine earth and thickness of the soil layer as weighting factors (cf. [78]). This integrated base saturation (BS) was regionalized with the model

$$\text{gam(BS)} \sim \text{Carbonate} + \text{dBR} + \text{te}(CEC_{pot}) + \text{Pod} + \text{te}(S_{dep}) + \text{Sregionclass},$$

where Carbonate means the presence of carbonates within the upper 90 cm of the mineral soil or the forest floor. dBR stands for the dominant bedrock type: While the existence of basic, carbonatic, or acidic bedrock and organic materials among the parent material was automatically considered as dominant, intermediate magmatic bedrock, non-carbonatic unconsolidated rock, intermediate/basic metamorphous bedrock, and silica-based bedrock was only considered dominant if the former types were absent. S_{dep} is the average S deposition over 4 years (1990–1993 for the first NFSI and 2004–2007 for the second NFSI) and Sregionclass is soil region according to AG Boden [66]; however, combining all mountainous soil regions (classes 8–11) into one class and all other morainic or loess-dominated soil regions (classes 3–7) into another class, next to the stream valleys (class 2) as a third class. When this GAM was applied to data from the second NFSI, all single degrees of podsolization, carbonate, and CEC_{pot} are significant variables with $p \leq 0.001$ and S_{dep} is significant with $p \leq 0.01$. Sregionclass was significant with $p \leq 0.05$, but strongly lowered spatial autocorrelation (Moran's I = 0.26). Overdispersion of the base saturation data required the use of a quasibinomial error distribution function.

2.5.2. Deposition

Following [27], the long-term trends for the deposition of N, sulphur (S) and base cations were calculated with the model MAKEDEP [79]. The model was run with grid-based estimates of Builtjes et al. [80] for a period from 2004 to 2007. To reconstruct the deposition before 2004, we used the regional trend from the EMEP database [81] and standard time series from Alveteg et al. [79]. Annual deposition from 2007 to 2020 was estimated according to the National Emission Ceilings for Europe [82] assuming constant regional distribution of deposition and taking changes in tree species composition in the model regions into account. The N emissions were assumed constant from 2020 onwards.

2.6. Statistical Analysis

All statistical analyses were performed using the statistical software R [83] in combination with the packages mgcv [75,76] and ape [84] to investigate spatial autocorrelations (Moran's I).

3. Results

Results are presented as means aggregated over 20-year periods from 1991 to 2070 in order to enhance the visibility of long-term trends and to eliminate the inter-annual variations of climate projections.

3.1. Standing Volume and Species Composition

In OS, the initial mean standing volume of 275 m^3 ha^{-1} is highest, followed by 263 m^3 ha^{-1} in FL and 261 m^3 ha^{-1} in UE. Due to the predominance of young stands, the initial mean standing volume in DH is rather low with only 175 m^3 ha^{-1} (Figure 1). For all four model regions, the projected stand development until 2070 shows the highest standing volume for the biodiversity scenario, and the

lowest values for the climate protection scenario and the reference scenario in an intermediate position. In DH, starting from a low level, standing volume accumulates over time; a slight decrease is only projected between 2051 and 2070 for the climate protection scenario. In UE, an increase in standing volume is projected for all management scenarios for the 2010 to 2030 period. A volume reduction is projected for the climate protection scenario after 2030 and for the reference scenario after 2050. In FL and OS, the development of standing volume is quite similar: For the biodiversity scenario, a steep increase until 2050 and a marked decrease afterwards was simulated. Due to the age stratification of forest stands in FL, stand development differs clearly between the three management scenarios: While standing volume decreases continuously in the reference scenario, the biodiversity scenario leads to increasing forest biomass until 2050 and biomass reductions due to aging stands thereafter. The climate protection scenario projects a strong decrease in standing volume at the beginning due to reduced harvesting dimensions and higher allowable cuts, followed by an increase in standing volume after 2050 when newly established stands with mainly fast-growing conifer species contribute considerably to the regional standing volume. In the reference scenario, standing volume is decreasing until 2070, but reduction is not so strong and is distributed over a longer period compared to the climate protection scenario.

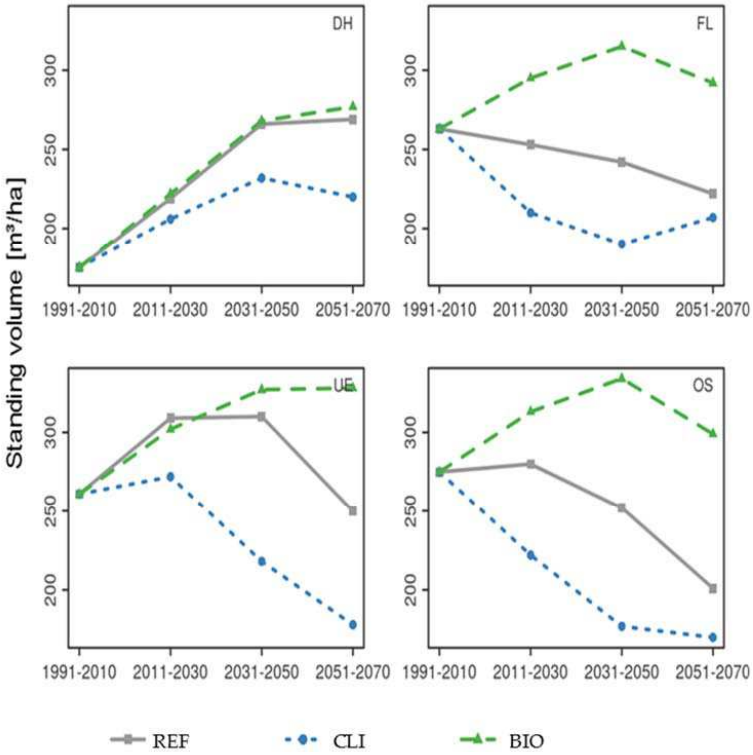


Figure 1. Simulated development of standing volume in the four model regions: Diepholz (DH), Fläming (FL), Uelzen (UE), and Oder-Spree (OS) under the three silvicultural management scenarios: reference (REF), climate protection (CLI), and biodiversity (BIO) until 2070.

An assessment of the uncertainty in the volume estimates (Figure 1) due to underlying climate projections is given in [31].

Table 2 displays the influence of the three management scenarios on tree species distribution until 2070. Generally, the proportion of Scots pine decreases in all regions and all management scenarios with the exception of DH, where an increase is projected even for the biodiversity scenario. The climate protection and reference scenarios cause an increase of Douglas-fir at all model regions. Beech and, to a lesser extent, oak also show increasing proportions under all management regimes in all regions, except oak in UE.

Table 2. Proportion of species crown cover based on the forested area of the respective region for European beech, sessile and pedunculate oak, all other deciduous species, Norway spruce, Scots pine, Douglas-fir and all other coniferous species in 2010 and change in percentage points until 2070.

		Beech	Oak	Other Deciduous	Spruce	Pine	Douglas-Fir	Other Conifers
DH	2010	8.9%	11.2%	45.2%	6.0%	19.3%	4.1%	5.4%
	REF 2070	+5.1	+2.1	−4.7	−0.8	−0.9	+1.1	−2.0
	CLI 2070	+7.8	+3.0	−25.0	+2.1	+7.4	+5.9	−1.4
	BIO 2070	+0.2	+4.6	−2.5	−2.2	+2.8	−1.5	−1.5
UE	2010	4.8%	6.1%	8.7%	13.3%	61.3%	3.9%	1.9%
	REF 2070	+7.0	+1.6	+2.3	−6.7	−17.7	+13.3	−0.1
	CLI 2070	+14.7	−0.9	−1.5	−8.9	−34.1	+26.8	+4.0
	BIO 2070	+8.0	+0.2	+0.6	−5.6	−3.2	+0.4	−0.4
FL	2010	12.8%	5.9%	4.3%	1.8%	73.5%	0.4%	1.2%
	REF 2070	+8.3	+2.5	−0.4	−0.8	−11.2	+1.9	−0.2
	CLI 2070	+8.4	+1.9	−1.2	−1.1	−30.2	+18.5	+3.8
	BIO 2070	+5.9	+0.7	+1.1	+1.6	−9.2	±0	±0
OS	2010	2.0%	5.7%	8.8%	1.1%	80.9%	0.5%	1.0%
	REF 2070	+7.1	+2.9	−1.8	−0.1	−8.3	+0.3	−0.1
	CLI 2070	+7.1	+3.4	−3.8	−0.2	−23.1	+12.9	+3.6
	BIO 2070	+0.7	+0.4	+0.7	+0.4	−2.1	−0.1	+0.1

DH (Diepholz), UE (Uelzen), FL (Fläming), and OS (Oder-Spree) represent the respective model region; REF (reference), CLI (climate protection), and BIO (biodiversity) are the management scenarios applied.

3.2. Groundwater Recharge

3.2.1. NFSI Plots (Static Forest Stands)

Under current (1991–2010) climate conditions, groundwater recharge in the lowlands of Schleswig-Holstein and Lower Saxony is mostly high (>100 mm) or very high (>200 mm), while it is only low (<50 mm) or very low (<25 mm) in the lowlands of Brandenburg and Saxony-Anhalt (Figure 2). This is a consequence of the marked precipitation gradient from the Northwestern to the Southeastern part of the North German Lowland. Groundwater recharge under future (2051–2070) conditions of the RCP 8.5 scenario (but assuming constant forest stand characteristics) will generally be considerably lower, with many NFSI plots where groundwater recharge is missing except for wet years. Few NFSI plots are directly located within the four model regions. Those in DH exhibit groundwater recharge of currently 225 mm and 145 mm in 2051–2070. In UE, groundwater recharge would decrease from currently 255 mm to 180 mm assuming constant stand characteristics. In FL and OS, where seepage was only medium under current conditions, it decreases from 90 mm to 55 mm and from 100 mm to 50 mm, respectively.

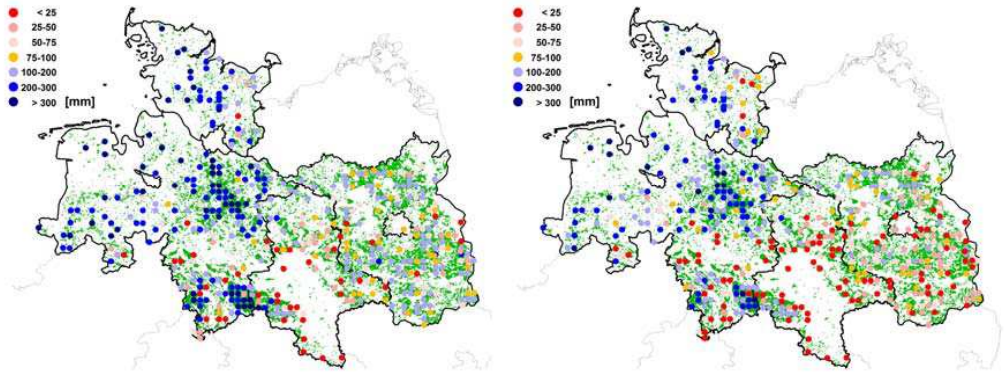


Figure 2. Average annual groundwater recharge on plots of the second National Forest Soil Inventory (NFSI) in Brandenburg, Niedersachsen, Sachsen-Anhalt, and Schleswig-Holstein under current 1981–2010 (**left**) and projected 2041–2070 (**right**) climate conditions.

3.2.2. Sampling Points in Model Regions (Dynamic Stands, cf. Figure 3)

1. Diepholz (DH)

Based on the RCP 8.5 scenario, the annual precipitation (close to 800 mm) at sampling points in DH remains almost unchanged until 2070. Average groundwater recharge in this region decreases from 138 mm (1991–2010) to 59 mm in 2051–2070 in the reference scenario. For the biodiversity scenario and the climate protection scenario, the values for groundwater recharge in the 2051–2070 period are 56 mm and 64 mm, respectively.

2. Uelzen (UE)

Precipitation remains almost unchanged in UE similar to DH, but groundwater recharge is generally higher (between 210 mm and 260 mm), since the sandy soils have a low water storage capacity. Groundwater recharge remains almost constant over the simulation period for all management scenarios with a slight decrease towards the end of the simulation period due to increasing evaporative demand. A small difference between the biodiversity scenario (214 mm) and climate protection scenario (222 mm) was simulated for the period 2051–2070.

3. Fläming (FL)

Annual precipitation in this region (600 mm) will slightly increase in 2011–2030 and 2031–2050 according to the RCP 8.5 scenario followed by a decrease to 580 mm in the last 20 years of the simulation period. Similarly, groundwater recharge with 65 mm is low from the beginning and remains constant until 2050, but decreases—parallel to decreasing precipitation—to 22 mm in 2051–2070. The marked differences in standing volume between the three scenarios only have marginal influence on the decreasing trend in groundwater recharge. The aging stands in the biodiversity scenario reduce the evaporative demand due to lower LAI and thereby allow higher annual groundwater recharge of 32 mm in 2051–2070, while the strong growth of young Douglas-fir stands (established in the simulation period) in the climate protection scenario reduce groundwater recharge in 2051–2070 to only 13 mm. All scenarios have in common the absence of groundwater recharge at many sampling points in dry years.

4. Oder-Spree (OS)

Low annual precipitation rates of 630 mm lead to groundwater recharge of, on average, 80 mm throughout the years from 1991 to 2050. During the last 20 years of the simulation period, when the projected precipitation rate decreases by 50 mm, the groundwater recharge decreases by 40 mm. The difference between the reductions of precipitation and groundwater recharge (10 mm) is compensated by a reduced evapotranspiration rate. The effect of older forest stands in the biodiversity scenario has only little influence on groundwater recharge (45 mm in 2051–2070), and the high transpiration of growing Douglas-fir stands in the climate protection scenario would further reduce seepage rates to 28 mm.

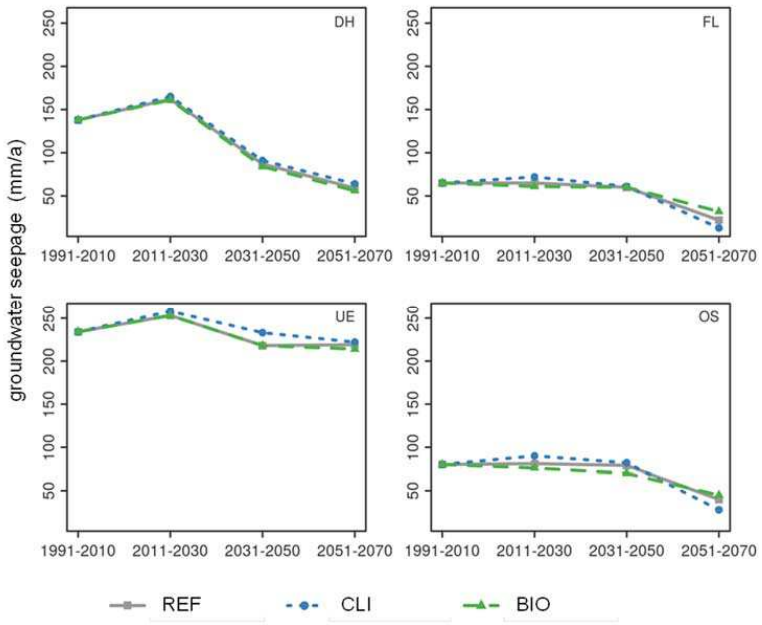


Figure 3. Simulated development of groundwater recharge in the four model regions: Diepholz (DH), Fläming (FL), Uelzen (UE), and Oder-Spree (OS) under the three silvicultural management scenarios: reference (REF), climate protection (CLI), and biodiversity (BIO) until 2070.

3.3. Element Budget Simulations

3.3.1. Regionalization of Carbon and Nitrogen Stocks and Base Saturation

The regionalization of C stocks was applied to measured data of the second NFSI in six federal states and yielded a good representation of the regional distribution of C stocks over large parts of the North German Lowland (Figure 4). Explained deviance of this soil C stock-GAM (SCS-GAM) was 80% (r^2 = 0.83), when applied to the second NFSI and 65% (r^2 = 0.66) for the first NFSI.

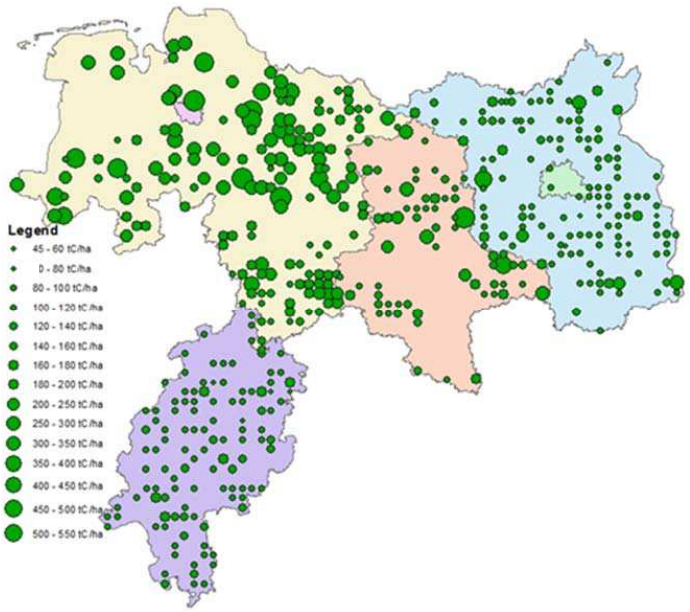


Figure 4. Carbon stocks of forest soils in and beyond the North German Lowland as regionalized with the SCS-GAM (Soil Carbon Stocks GAM) for the spatially representative plots of the second NFSI (federal states of Hesse, Lower Saxony, Bremen, Saxony-Anhalt, Brandenburg, and Berlin).

The SCS-GAM was also applied to derive C/N ratios at the same locations, employing the respective regionalization model for N stocks in combination. The N model explained 89% of the deviance in N stocks of the second NFSI (r^2 = 0.86) and 83% of their deviance in the first NFSI (r^2 = 0.8).

The base saturation model explained 73% of the variability in NFSI II data and 67% of their deviance, while it reached an r^2 of 0.71 (explained deviance of 74%) for data of the first NFSI.

3.3.2. Dynamic Simulation of Carbon Stocks

Based on NFSI data, the strongest shift in C stocks occurred in DH (annually −2.8 t C ha^{-1}), where organic soils prevail. In contrast, all three other model regions exhibited an increase in carbon stocks between 1991 and 2006 (+0.1 t ha^{-1} to +0.7 t ha^{-1}). The C models Roth-C and YASSO07 both reflect this contrasting tendency in the amount of carbon stocks between DH and the other model regions (Figure 5). A quantitative evaluation reveals, however, that the Roth-C simulations match much better the observed C stocks that were regionalized from NFSI. Both models started with the initial C stocks of the first NFSI (1990) in each region. For the year 2007, YASSO07 overestimated C stocks in the model regions by +12%, +7%, +32%, and +57% (for DH, UE, FL, and OS, respectively), while the C stocks calculated with Roth-C deviated by −0.4%, −5%, +2%, and −18% from the respective values for 2007. After about 2030, both models show a decreasing trend in C stocks that may partly be explained by increasing temperatures in the last 20 years of the simulation period, but also by reduced litter input due to a decrease in standing volume of the forest stands (cf. Figure 1).

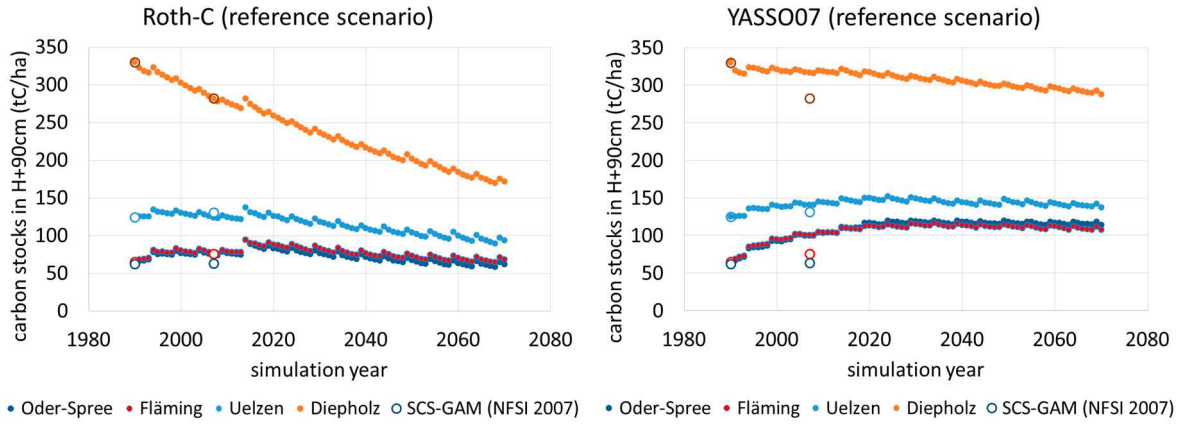


Figure 5. Development of soil carbon (C) stocks in the mineral soil up to 90 cm depth and the forest floor for the four model regions (only reference scenario) simulated with Roth-C (left) and YASSO07 (right). Statistically regionalized C stocks for both surveys of the NFSI are indicated as open circles in the color of each region.

3.3.3. Nitrogen Budget

1. Diepholz (DH)

The N budget of forests in DH is positive (inputs > outputs) under current (1991–2010) conditions and higher than in other model regions due to high N deposition and high N retention of forests on organic soils (Figure 6). The high soil organic matter stocks in DH are, however, increasingly reduced under the expected warmer conditions, such that the relation between slowly decreasing N depositions and increasing N losses shifts towards the side of N losses. In effect, the N budget is decreased to −29.3 kg ha^{-1} a^{-1} until 2050–2070 in the reference scenario. The climate protection scenario intensifies this trend during the projection period of 60 years due to decreasing biomass volume. An attenuating effect is only expected in the last 20 years of the simulation period (2050–2070), when newly established forest stands achieve their maximum growth phase resulting in a slightly higher N budget of −25.9 kg ha^{-1} a^{-1} as compared to the reference scenario. In contrast, accumulating

biomass in the biodiversity scenario provides a N sink that has a mitigating effect on the general trend of accelerating decomposition, resulting in a N budget of −22.8 kg ha^{-1} a^{-1} in 2050–2070.

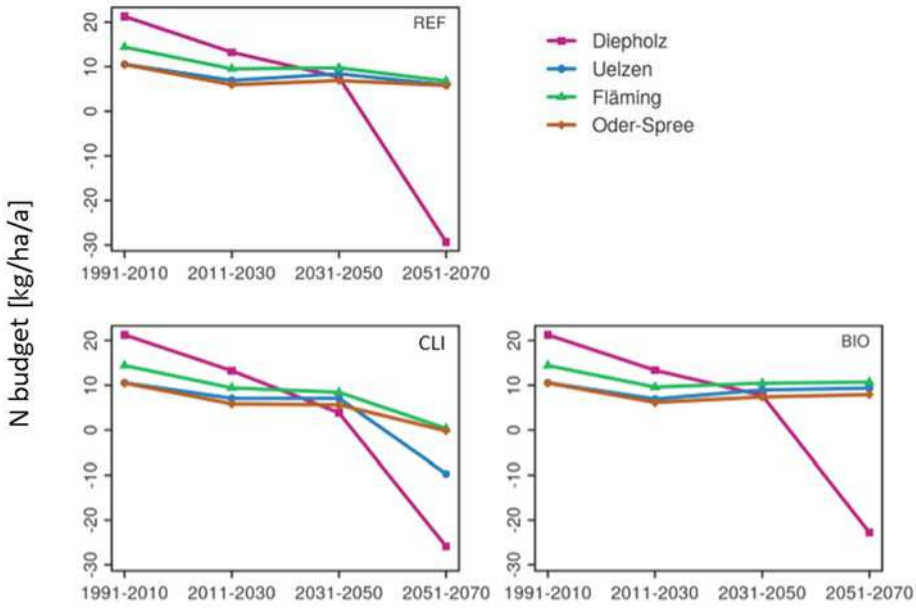


Figure 6. Simulated development of the nitrogen (N) budget in the four model regions under the three silvicultural management scenarios: reference (REF), climate protection (CLI), and biodiversity (BIO) until 2070.

2. Uelzen (UE)

In UE, at the beginning of the reference scenario simulation period, the forests may still partly retain N from the slowly decreasing N deposition that enables a N budget of +10.5 kg ha^{-1} a^{-1}. Nitrogen retention is also affected by a climate induced acceleration of decomposition, which decreases the N budget to 5.9 kg ha^{-1} a^{-1} in 2050–2070. In the climate protection scenario, the N budget is decreased by a high reduction of standing wood volume, resulting in a negative N budget of −9.7 kg ha^{-1} a^{-1} in 2050–2070. In the biodiversity scenario, tree biomass is accumulated in the period considered; thus, N is retained in the ecosystem, leading to a positive N budget of +9.4 kg ha^{-1} a^{-1} in 2050–2070.

3. Fläming (FL) and Oder-Spree (OS)

FL and OS show similar trends. An initially positive N budget is decreased due to an accelerated decomposition of soil organic matter under warmer conditions, resulting in a still positive, but lower N budget in the reference scenario in 2050–2070. In the climate protection scenario, the N budget decreases in both model regions to an almost balanced budget in 2050–2070, while the biodiversity scenario with the highest standing volume compared to the other scenarios enables a continuously positive N budget of 10.7 kg ha^{-1} a^{-1} in FL and 7.9 kg ha^{-1} a^{-1} in OS, respectively, in 2050–2070.

3.3.4. Nitrate in Seepage Water

Nitrate (NO_3^-) concentration increases continuously during the simulation period in all regions (Figure 7). The initially low NO_3^- concentrations in UE, FL and OS would increase until 2070 to values between 20 mg L^{-1} and 50 mg L^{-1}. In DH, where high N deposition occurs, even NO_3^- contents of 120 mg L^{-1} would be expected.

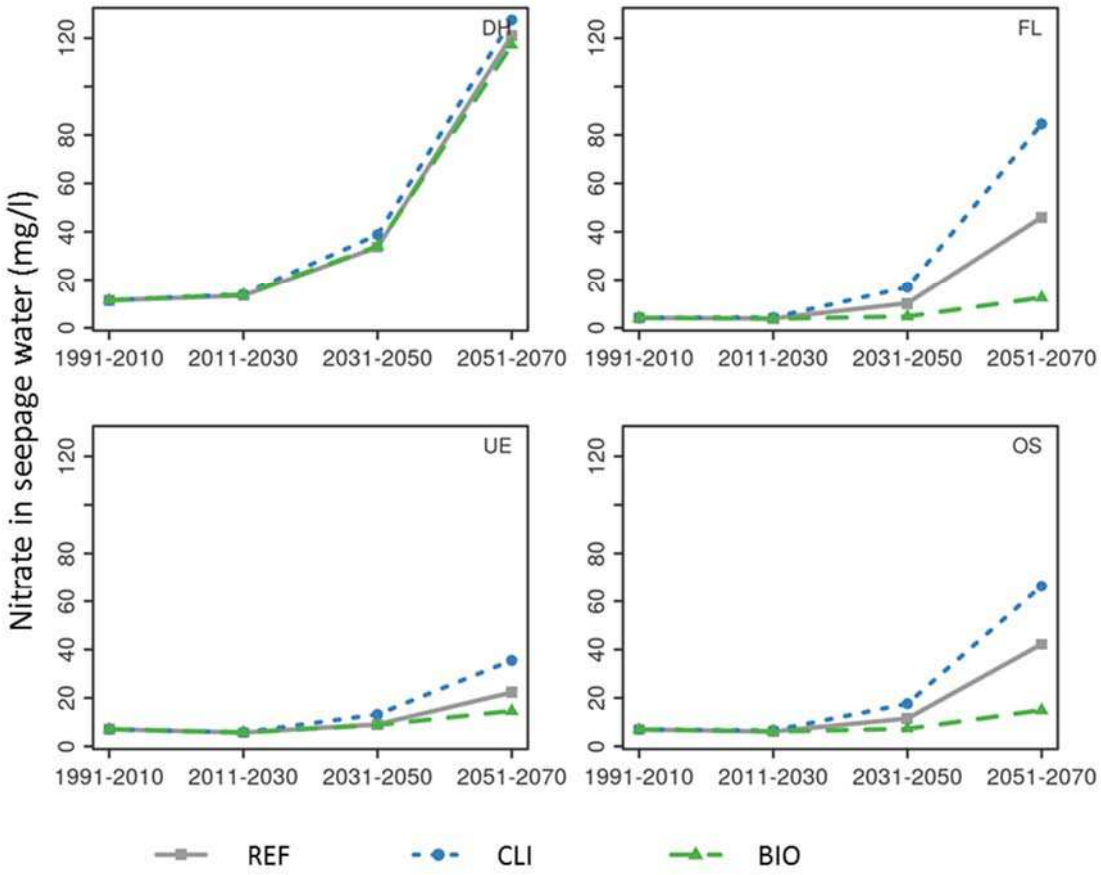


Figure 7. Simulated development of nitrate in seepage water in the four model regions: Diepholz (DH), Fläming (FL), Uelzen (UE), and Oder-Spree (OS) under the three silvicultural management scenarios: reference (REF), climate protection (CLI), and biodiversity (BIO) until 2070.

4. Discussion

4.1. Climate Projection

In general for climate change impact assessment, climate projections based on an ensemble approach are recommended. Ideally, different combinations of GCMs and regional climate models as well as several emission scenarios should be considered [33,85]. A simplified approach was chosen for our simulations. We based our impact assessment on the median run out of 21 different climate projections in order to avoid extreme scenarios. Our presented modelling approach is strongly driven by the climate projections of the Statistical Analogue Resampling Scheme (STARS) [36]. Wechsung and Wechsung [86,87] critically evaluated this approach. They quantified a negative precipitation bias of approx. 5% per 1 K temperature increase. Despite the model limitations, Wechsung and Wechsung [87] recommend STARS-based climate projections for vulnerability and uncertainty studies. For example, Bloch et al. [88] assessed the regional impact of drought events on the yield of legume-grass swards under STARS climate projections for the period 2062 to 2092 and derived conclusions for future management. In any case, a possible precipitation bias introduced by STARS should be taken into account when interpreting the results.

The climate projection used in this study, however, projects a slight increase of precipitation over 100 years. This increase would probably be higher, if STARS did not suffer from the potential bias. However, the precipitation trend obtained with the climate projection used in this study is within the range of precipitation changes produced by the application of different GCMs (−220 mm to +218 mm).

To obtain more robust estimations for decision support, the analysis of further climate and deposition scenarios is recommended.

4.2. Trends in Groundwater Recharge

The effect of the chosen climate projection on groundwater recharge can be inferred from the water budget simulations for NFSI plots (baseline scenario). Using observed forest stand and soil properties and assuming no change of these parameters, it shows how water budgets would evolve in a warmer climate, independent of changes introduced by forest management. Groundwater recharge under forests would be sharply reduced by 80 mm in DH, by 75 mm in UE, by 35 mm in FL, and by 50 mm in OS, which means most severe reductions in DH (−36%), FL (−39%) and OS (−50%), while the relative reduction is lowest in UE (−29%). Since precipitation does not change much in the climate scenario for DH, UE, and FL, the most important mechanisms leading to the reduction in water seepage rates is an increase in evaporative demand of the atmosphere due to rising temperature and an extension of the vegetation period, which increases losses due to evaporation and transpiration. The reduction is, however, higher, if precipitation is lowered additionally (OS and to some extent FL).

It is obvious, however, that todays' forest stands will evolve exhibiting other properties in the time period 2051–2070. The magnitude of the influence of evolving forest stands and better spatial representativeness may be judged by comparison with the water budget results for sampling points in the model regions. Here, groundwater recharge in the reference scenario would also be reduced, by 79 mm in DH, by 15 mm in UE, by 43 mm in FL, and by 40 mm in OS. Except for UE, the supra-regional pattern develops, thus, similar to a situation with actual stand properties. The much lower reduction of groundwater recharge rates in UE with evolving forests is not a consequence of the deviation in standing volume, since standing volume increases in this region, probably entailing an increased water consumption of the vegetation. However, it should be considered, that our modelling system does not account for the effects of increased atmospheric CO_2 concentration. On the one hand, an elevated atmospheric CO_2 concentration may increase photosynthesis, giving rise to forest growth; on the other hand, the water use efficiency is increased, resulting in a decreased transpiration [89].

The supra-regional pattern of groundwater recharge and the reductions until 2070 are mainly due to the climatic and regional differences among the model regions. The increasing evaporative demand of the atmosphere may best be fulfilled in DH, where soils with high field capacity or the access of the forest stands to groundwater facilitate the water uptake by vegetation and atmosphere, thereby strongly reducing the groundwater recharge by increased transpiration and evaporation. The sandy soils with low field capacity in UE, on the other hand, prevent a fulfillment of evaporative demand today as well as in the future; thus, the available soil water content is reduced, while groundwater recharge remains more or less constant. The low and lately decreasing precipitation in FL and OS is the main reason for lower groundwater recharge and higher reductions than in UE towards the end of the simulation period, which are most extreme in OS. The water deficit between evaporative demand and actual evaporation was also recently analyzed for Brandenburg using the A1B climate scenario regionalized with the WettReg model [90]. Similar to our study, the highest water deficits were found in OS, while the situation was less severe in FL.

The differences in groundwater recharge induced by the three forest management scenarios are small in all regions when compared to the impact of climate change. In DH, the biodiversity scenario leads to lower groundwater recharge due to higher evapotranspiration of the increasing standing volume in this scenario as compared to climate protection and reference. However, groundwater recharge rates in 2051–2070 deviate only by −5% and +8% for climate protection and biodiversity relative to the reference, respectively. Lower standing biomass is also the main reason in UE for the small difference between the climate protection (−2% relative to the reference scenario) and biodiversity scenario (+1%). However, it is important to note that biomass accumulation under the biodiversity scenario is a temporary condition during the projection period considered. By delaying thinning and harvest operations due to increased target diameters and lower limits for allowable

cuts, the accumulated volume will, in parts, be exploited after 2070. This will partly compensate the higher groundwater recharge rates of the biodiversity scenario opposed to the other two management paths. In the period 2051 to 2070, the trend in standing volume in the biodiversity scenario in OS and FL is opposite to both other regions. A strong decrease in standing biomass is due to the aging of forest stands with lower transpiration rates. Though in these regions, standing biomass in the climate protection scenario is even lower, the forest stands in this scenario are in a younger and more productive stage with increasing proportions of Douglas-fir towards the end of the simulation period, leading to higher transpiration rates. The climate protection scenario, therefore, leads to lower groundwater recharge in these regions than the biodiversity scenario. It seems plausible that the differences in species conversion between the management scenarios will affect groundwater recharge in the long-term, i.e., well beyond the end of the considered projection period, and, therefore, confirm the advantageousness of the biodiversity scenario vs. the two others.

4.3. Trends in Soil Organic Matter

The amount of C stocks in the soil is the balance of organic matter input (mainly from root litter, foliar litter, and harvest residuals) and organic matter output by decomposition of organic substances, the products of which are emitted in the form of CO_2. For constant climatic and soil conditions, input and output approach an equilibrium after infinite time, where the amount of soil organic matter allows a decomposition rate that is equal to the average input of organic matter. The relevance of soils which are apart from the theoretical steady state of actual conditions and the consequences for soil C modelling are intensively discussed in [73]. The organic matter stocks in DH are obviously higher than expected under current climate, thereby allowing high decomposition rates that cannot be compensated by the vegetation's production of organic material, leading to decreasing C stocks. In contrast, soil organic matter stocks in the other regions are still increasing due to production being higher than decomposition until about 2030. After this point in time, however, decomposition seems to be higher than organic matter input and soil organic matter stocks will decrease under all considered management scenarios.

This is due to an increase of decomposition under a higher temperature and a decrease of litter input in those management scenarios and model regions which exhibit a reduced standing volume (cf. Figure 1).

On the one hand, decomposition rates are generally higher hence soil organic matter stocks lower in regions with a warmer climate. A comprehensive analysis of the global pattern of soil organic matter stocks has e.g., directly been used for the standard parameterization of YASSO07 [65] and similar empirical data were used to derive standard mineralization coefficients for Roth-C. Observed decomposition data show that a potential inhibition of decomposition under dry conditions is actually only realized in extremely arid regions, while decomposition rates across the whole of Europe are continuously rising the warmer it gets [65]. The stabilization of soil organic matter under dry conditions may, thus, only be locally important and does not reflect the decomposition rates of whole regions in Europe. Mineralization of soil organic matter is, however, still under discussion in recent literature [91–95]. Next to temperature, soil moisture as the other important driver for organic matter decomposition is explicitly taken into account by VSD+—a direct dependence of decomposition rates on soil moisture is modelled using the approach of [96], thereby overcoming limitations of the original Roth-C model.

On the other hand, a decrease in standing volume or biomass entails decreasing litter input which is the case in the reference scenario of all model regions except DH after 2050. Both, increasing decomposition and decreasing organic matter input cause the decrease in soil organic matter stocks.

As a consequence of the enhanced decomposition of soil organic matter and still high N soil retention, a decrease of the C/N ratio in the forest soil takes place (cf. [97]). Many studies show that the risk for elevated NO_3^- leaching increases with decreasing C/N ratio in regions with high N input [18,22,23,98].

The projected increase of N release results in a decrease of the N budget of forest soils in all model regions. Parallel to the decrease in soil organic matter, the climate protection scenario induces an even stronger decrease in tree biomass that additionally lowers the sink strength of the forest ecosystem for N. As a result, the supply of forest soils with new organic matter in the form of foliar and root litter is reduced and N budgets turn negative in all model regions. On the other hand, an increase in standing volume under the biodiversity scenario keeps NO_3^- concentrations low in three of the four model regions. In DH, the high N deposition and N release from soils with high organic matter stocks may not be compensated by the N uptake of the forest stands

Several studies showed that the C sequestration rate of forest soils is increased under elevated N deposition [99–101], however, the efficiency of this effect differs considerably [102,103]. It may to some extent be accounted for in the VSD+ simulations where the foliar N content is dependent on N deposition.

4.4. Trends in Nitrate Concentrations

The validation of simulated NO_3^- concentrations at single sampling locations is generally difficult due to the high variability of NO_3^- concentrations in seepage water [104–107]. Therefore, the simulated NO_3^- concentrations were compared for the first 20 years of the simulation (1991–2010) with independent large-scale NO_3^- observations in the surroundings of the model regions. The results of the comparison confirm the magnitude of the calculated values for each of the model regions (cf. [108] (Cloppenburg), [109] (Brandenburg), [110] (Mecklenburg-Vorpommern), [27] (North German Lowland)). A good coincidence was also found with NO_3^- concentrations that we derived from 1:2 extracts of the second NFSI in the model regions including 50 km surrounding area of each region (mean values DH: 5 mg/L, UE: 4 mg/L, FL: 6.9 mg/L, and very high coefficients of variation 101%, 212% and 185%, respectively). The concentrations of OS are given elsewhere [109]. The NO_3^- concentration at field capacity of the 1:2 extracts provides a solid basis for the estimation of NO_3^- losses with seepage water [111].

Uncertainties in the simulation of future NO_3^- concentrations arise from the representation of N uptake by the trees and from deposition. Considering the N concentration in the soil solution, the N uptake efficiency (Nupeff) is an essential parameter in the VSD+ model based on the assumption that forest ecosystems will usually lose some N, even in the case that N is the limiting nutrient. Uncertainties in regionalized and modelled N deposition especially concerning the dry deposition process and the underlying emission data are discussed elsewhere [112,113].

Gaseous emissions of N species due to denitrification are an alternative process that could lower NO_3^- concentrations in the soil. They were explicitly modelled in VSD+ as first-order processes depending on available N in soil solution after deposition, uptake, mineralisation and nitrification. An adjustment is made depending on soil pH. The uncertainty in the quantification of N emissions [114], especially for sandy soils [115], does not contradict observations revealing a generally rather small contribution of denitrification to the N budget [18].

Although the model system comprises many established and validated models, some of the models have high uncertainties in the parameterization (e.g., [116] for the VSD model). In combination with uncertainties in the input data, particularly with regard to climate projections, these uncertainties may counterbalance each other or accumulate along a cascade [117,118]. Consequently, further research to improve the input data as well as the impact models is necessary to reduce those uncertainties.

However, a future increase of NO_3^- concentrations in the model regions appears to be very likely because of the markedly reduced seepage flux in combination with accelerated turnover rates of N pools in soil organic matter. The results are a hint of the weakening capacity of forests to retain N [5,6]. Mellert et al. [111] postulate that N saturated Scots pine forest stands on sandy soils bear a high risk of elevated NO_3^- leaching due to the combination of highly permeable soils with high N stocks. When comparing the management scenarios, the climate protection scenario would aggravate the risk of NO_3^- leaching in the model regions during the projection period, while the biodiversity scenario

seems to have an extenuating effect. For FL and OS, NO_3^- concentrations in seepage water will exceed the limit of the WFD for groundwater according to model simulations in the period 2051–2070 under the climate protection and under the reference scenario. For DH, forest management seems to be of minor importance, since none of the management scenarios had a marked impact on the risk of enhanced NO_3^- leaching in this model region. Regardless of the assumed management scenario, NO_3^- concentrations in seepage water are expected to exceed the WFD limit in DH.

The effect of climate change on NO_3^- concentrations has been evaluated in other scientific studies as well. In a review of climate change effects on different land-use types [119], the included studies ranged from a limited increase to a possible doubling of NO_3^- concentrations by 2010. The authors expect an increase of N leaching in forests due to rising temperature. For a forested karst area, Dirnböck et al. [120] found positive as well as negative impacts of climate change on NO_3^- leaching from forest soils. Especially historical events (e.g., forest cutting) can have significant effects on the N cycle [24].

5. Conclusions

The relevance of NO_3^- leaching from forests in a warmer and slightly drier Central European climate is a matter of human health as well as ecosystem integrity that is not limited to the selected regions, since the mechanisms are the same in other regions as well. As forests are a main source of groundwater for drinking water abstraction, the legal threshold values of NO_3^- concentrations imposed by the WFD need to be applied in order to avoid a situation where a supra-regional trend towards increasing NO_3^- concentrations in drinking water increases health risks such as cyanosis or bowel cancer. On top of that, leached NO_3^- is also transferred to stream water, where it is a source of acidity and may substantially lower biodiversity. Since leached NO_3^- cannot leave the soil without cations, it is also a threat for soil fertility and forest health as it removes basic cations from the soil.

Despite the uncertainties in the estimation of NO_3^- concentrations in seepage water, a future increase in the model regions appears to be very likely due to a markedly reduced seepage flux. Due to the strong temperature increase, the increase in NO_3^- concentrations is even likely to be disproportionately higher, based on the expectation that higher decomposition of organic matter and lower C/N ratios aggravate the risk of NO_3^- leaching. Potential losses of gaseous N compounds due to denitrification could lower this risk while causing other problems with regard to greenhouse gases, but they are not expected. However, accurate quantification is extremely difficult due to numerous uncertainties in the model chain. Therefore, the appropriate forest management options for the special situation in the North German Lowland must be carefully chosen, since they may have a strong effect on the expected NO_3^- concentrations. The sink strength of forests for N should not be additionally lowered by overly strong reductions of standing biomass, since they are already at the limit of their N retention capacity.

The simulations indicate the high vulnerability of forests in the North German Lowland to climate change. The high amounts of organic matter stored in forest soils are susceptible to an increased decomposition in a warmer and slightly dryer climate. The probable combination of low seepage fluxes with increased decomposition of soil organic matter predisposes the investigated regions to higher NO_3^- concentrations in seepage water.

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Appendix A. Parameters Used in the VSD+ Model

Parameter	Description	Unit	Value/Source
SiteInfo	Site ID	-	consecutive number
period	starting and ending time of simulation	y y	1990 2070
thick	thickness of the soil compartment	m	0.9
bulkdens	bulk density of the soil	g/cm^3	digital soil map (chapter 2.5)
Clay_ct	clay content of the soil	%	digital soil map (chapter 2.5)
Theta	water content of the soil	m^3/m^3	WaSiM-ETH (chapter 2.4)
pCO2fac	CO_2 pressure in soil solution (multiple of pCO_2 [atm] in air)	-	[67]
CEC	cation exchange capacity	meq/kg	digital soil map (chapter 2.5)
bsat_0	initial base saturation	-	generalized additive model (chapter 2.5)
ECa_0	initial Ca saturation	-	−1: determined by the model
EMg_0	initial Mg saturation	-	−1: determined by 'the model
EK_0	initial K saturation	-	−1: determined by the model
Excmod	cation exchange model option (1 = Gaines-Thomas; 2 = Gapon)	-	1
lgKAlBC	log10 of selectivity constant for Al-Bc exchange	eq/m^3	[78]
lgKHBC	log10 of selectivity constant for H-Bc exchange	eq/m^3	[78]
expAl	exponent (>0) in [Al] = KAlox [H] expel	-	[78]
lgKAlox	log10 of gibbsite equilibrium constant	$((mol/L)^{1-expAl})$	[78]
Cpool_0	initial amount of C in soil (per unit area)	g/m^2	generalized additive model (chapter 2.5)
CNrat_0	initial C:N ratio insoil	g/g	generalized additive model (chapter 2.5)
RCOOmod	organic acid model: 0 = Oliver, 1 = mono-protic	-	0
RCOOpars	1 or 3 parameters for organic dissociation model	-	a: 0.96; b: 0.9; c: −0.039
cRCOO	total concentration of organic acids (m*DOC)	mol/m^3	0.004379
TempC	average soil temperature	°C	see chapter 2.2
percol	percolation (precipitation surplus)	m/a	WaSiM-ETH (chapter 2.4)
Ca_we	weathering rate of Ca	$eq/m^3/a$	regression model based on PROFILE [121] simulations [122]
Mg_we	weathering rate of Mg	$eq/m^3/a$	regression model based on PROFILE [121] simulations [122]
K_we	weathering rate of K	$eq/m^3/a$	regression model based on PROFILE [121] simulations [122]
Na_we	weathering rate of Na	$eq/m^3/a$	regression model based on PROFILE [121] simulations [122]
SO2_dep	deposition of SO2	$eq/m^2/a$	see chapter 2.5
NOx_dep	deposition of NOx	$eq/m^2/a$	see chapter 2.5
NH3_dep	deposition of NH3	$eq/m^2/a$	see chapter 2.5
Ca_dep	deposition of Ca	$eq/m^2/a$	see chapter 2.5
Mg_dep	deposition of Mg	$eq/m^2/a$	see chapter 2.5
K_dep	deposition of K	$eq/m^2/a$	see chapter 2.5
Na_dep	deposition of Na	$eq/m^2/a$	see chapter 2.5
Cl_dep	deposition of Cl	$eq/m^2/a$	see chapter 2.5
kdenit	maximum denitrification rate	a^{-1}	4
Nfix	N fixation	$eq/m^2/a$	0
Nupeff	Uptake efficiency of available N (0-1)	-	0.96–0.99 see documentation and discussion
rf_miR	modifying factor of mineralization due to moisture and temperature for the RothC C/N model	-	MetHyd functions [123] coupled with WaSiM-ETH
rf_nit	modifying factor of nitrification due to moisture and temperature	-	MetHyd functions [123] coupled with WaSiM-ETH
rf_denit	modifying factor of denitrification due to moisture and temperature	-	MetHyd functions [123] coupled with WaSiM-ETH
N_gupt	Total annual removal (uptake) of N from the soil by the vegetation	$eq/m^2/a$	chapter 2.4
Ca_upt	Net annual removal (uptake) of Ca from the soil by the vegetation	$eq/m^2/a$	chapter 2.4
Mg_upt	Net annual removal (uptake) of Mg from the soil by the vegetation	$eq/m^2/a$	chapter 2.4
K_upt	Net annual removal (uptake) of K from the soil by the vegetation	$eq/m^2/a$	chapter 2.4
P_upt	Net annual removal (uptake) of P from the soil by the vegetation	$eq/m^2/a$	chapter 2.4
Clf	C litterfall flux	$g/m^2/a$	chapter 2.4
Nlf	N litterfall flux	$g/m^2/a$	chapter 2.4
QIlf	Quality index of litterfall (-) for the RothC model	0.25	default value valid for forests

Appendix B. Available NFSI-Parameters for the Development of GAMs

The use of parameters for the parameter selection process and their availability for different points in time (NFSI I, NFSI II) and soil depths is given, the headlines meaning the mineral soil up to 90 cm depth (M90), the mineral soil up to 140 cm depth (M140), the mineral soil up to 90 cm depth plus a humus layer (M90+), and the mineral soil up to 140 cm depth plus a humus layer (M140+).

Parameter	Unit	NFSI I	NFSI II	M 90	M 140	M90+	M140+
Federal State	-	√	√				
Ownership	-	√	√				
Forest authority	-	√	√				
County	-	√	√				
Growth zone	-	√	√				
Growth district	-	√	√				
Soil landscape	-	√	√				
Soil region	-	√	√				
Easting	m	√	√				
Northing	m	√	√				
Height above sea level	m	√	√				
Slope	-	√	√				
Exposition	-	√	√				
Form of relief	-	√	√				
Situation in relief	-	√	√				
Number of liming events	number	√	√				
Amount of lime applied	t/ha	√	√				
Liming per aera and year	number/ha/a	√	√				
Year of last liming	a	√	√				
Trophic level	-	√	√				
Degree of podzolization	-	√	√				
Forest Type (Species)	-		√				
coarse fragments	%	√	√	√	√		
Potential CEC	cmolc/kg, cmolc/ha	√	√	√	√		
pH (KCl)	log [H^+]	√	√	√	√	√	√
Effective CEC	molc/kg, molc/ha	√	√	√	√	√	√
Carbon stocks	kg/ha	√	√	√			
Base saturation	%	√	√	√	√		
C/N-ratio	-	√	√	√	√	√	√
Carbonate	Yes/No	√	√	√	√	√	√
Actual water level	cm		√				
Substrate group	-		√				
Bedrock type	-		√				
Type of loose material	-		√				
Annual precipition	mm	√	√				
Avg. temperature	°C	√	√				
Soil type	-	√	√				
Soil class	-	√	√				
Hydromorphology	Yes/No	√	√				
Forest Type	Conifer/broad/mix	√					
N-deposition (4 years mean)	eq/ha/a	√	√				
S-deposition (4 years mean)	eq/ha/a	√	√				
Sand	%		√	√	√		
Silt	%		√	√	√		
Clay	%		√	√	√		
Weathering surface	m^2/ha		√	√	√		
Fine soil	t/ha	√	√	√		√	
N-stocks	kg/ha		√	√			
Precipitation in winter	mm		√				
Temperature in winter	°C		√				
Precipitation in summer	mm		√				
Temperature in summer	°C		√				
Eff. Field capacity	%		√	√			
Main rooting depth	cm		√				
Rooting depth fine roots	cm		√				
Rooting depth coarse roots	cm		√				
Ca^{2+}-excange. capacity	kg/ha		√	√		√	
K^+-excange. capacity	kg/ha		√	√		√	
Mg^{2+}-excange. capacity	kg/ha		√	√		√	
Thickness of humus layer	cm		√				
Humus type	-	√	√				

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Climate change impact assessment—A simulation experiment with Norway spruce for a forest district in Central Europe

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ABSTRACT

Projected climate change implies that site conditions can no longer be expected to remain constant over a tree's lifetime. The fast and complex changes in site characteristics and growth patterns diminish the value of traditional knowledge and profoundly alter the conditions of forest management. One way to tackle the inherent uncertainties are simulation studies addressing these new dynamics and mechanisms. The aim of this study is to present such a simulation model system comprising various established and validated process-based and statistical models assessing the complex and dynamic response of a forest stand to climate change.

For a given climate scenario, these coupled models estimate the potential growth and yield and various risks considering changing site and stand conditions. As an example, the model system is applied to managed forest stands of Norway spruce (*Picea abies* (L.) H. Karst.) in a forest district located in central-western Germany. For the changing climate conditions according to SRES B1 and A1B, the model results suggest a positive effect on the site index and, by contrast, a negative impact on tree survival of increasing risks regarding drought stress mortality, wind damage, and bark beetle infestation given the climate change scenario. The annual contribution margin of timber production under consideration of damage risks by drought stress mortality, wind, and bark beetle infestation reveals that, in this case, the increased growth is able to compensate for the higher risks with few exceptions. Furthermore, we discuss the advantages and challenges of employing a dynamic complex simulation model system for climate change impact assessment based on high-resolution climate data.

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1. Introduction

Changes in global climate are a natural part of Earth's history, but the current rate of change driven by anthropogenic factors is unprecedented (Jansen et al., 2007; Smith et al., 2015). Global circulation models (GCMs) project increases of global mean annual surface temperatures depending on the emission scenario of between 0.3 and 4.8 °C as well as changes in precipitation patterns by the year 2100 (Collins et al., 2013). Regional climate models (RCMs) account for regional variations by downscaling GCMs to higher spatial resolution, typically between 10 and 50 km (Kotlarski et al., 2014). Central Europe will likely experience an increase in the annual average air temperature above the global mean as well as a reduction of summer precipitation with a concurrent increase in winter and spring precipitation (Christensen et al., 2007). Furthermore, increases in the frequency and intensity of extreme weather events such as heat waves, torrential rain, summer droughts, storms, and spring temperature backslashes are projected for Europe (e.g., Ballester et al., 2010; Beniston et al., 2007; Christensen et al., 2007; Raisanen et al., 2004). A changing climate with an increase in extremes has already been observed in recent decades (e.g., Munich Re, 2011; Trenberth et al., 2007).

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Some positive but mostly negative effects of climate change are anticipated for Central European forests (e.g., Lindner et al., 2010; Spathelf et al., 2014). The projected climatic changes may have positive effects on tree growth, as described, for example, by Albert and Schmidt (2012, 2010); Boisvenue and Running (2006); Hasenauer et al. (1999); Nothdurft et al. (2012); Pretzsch et al. (2014). However, several biotic and abiotic disturbances (direct as well as indirect) are expected to increase in frequency and intensity. Allen et al. (2010) as well as Birdsey and Pan (2011), for example, observed an increase in tree mortality as a consequence of drought and heat in forests. Seidl et al. (2008) and Hlásny and Turčáni (2009) have shown an increase in insect infestations. Fink et al. (2009) and Schelhaas et al. (2003) projected an increased vulnerability to wind damage (cf. review by Gardiner et al., 2010). Furthermore, for some regions, an increased risk of forest fires is expected (e.g., Schumacher and Bugmann, 2006), as well as changes in the frequency and/or intensity of other disturbances such as fungal diseases (e.g., Porta et al., 2008). However, the reactions of forest ecosystems to changing climate conditions are not uniform but may differ considerably based on stand structure and tree species (Kint et al., 2012). According to current knowledge, climate change is expected to alter forest production conditions profoundly.

Norway spruce (*Picea abies* (L.) H. Karst.) in Central Europe is expected to be particularly vulnerable to the projected climate change (Hanewinkel et al., 2013). Because of its high growth potential, timber quality and usability as well as rather modest demands regarding site quality, Norway spruce has become one of the major commercial tree species in Central Europe (Hanewinkel et al., 2013; Yousefpour et al., 2010). Many stands were planted beyond the natural range of Norway spruce and with high structural uniformity and will probably suffer from low adaptation potential and resilience (Brosinger and Östreicher, 2009; Spiecker, 2000). An assessment of the anticipated damage risks by disturbance agents to Norway spruce outside its natural range would provide highly needed information for adaptation strategies in Central Europe.

Past forest management planning was typically based on the implicit assumption of constant production conditions over a tree's lifetime. Because of the projected rapid change in the climate, this assumption may become untenable in the future (Lindner, 2000). In contrast to annual cropping systems in agriculture, where systems can be adapted sufficiently rapid to respond to climate change, forest management decisions have long-lasting effects (Loehle and LeBlanc, 1996; Lindner, 2000). Rotation periods, depending on region and tree species, currently range between 80 and 180 years in Central Europe (Lower Saxony Ministry of Food, Agriculture and Consumer Protection, 2016). Thus, the choice of tree species, rotation period, and forest treatment based solely on past experiences is likely to become inadequate due to new combinations and dynamics of environmental factors and their changes throughout a tree's lifetime (Spittlehouse and Stewart, 2003). Therefore, new approaches are needed to find optimal forest management strategies.

Several modeling approaches have been employed to assess climate change impacts on forests. For example, (bio-) climatic envelop models (e.g., Box, 1981; Huntley et al., 1995), also known as niche-based, habitat or species distribution models, have been used to project shifts in the potential distribution areas of certain tree species. These models are based on the relationships between a set of climatic variables and observed presence/absence of a species. Kölling et al. (2009) adapted this method to tree species in Germany to support forest practitioners with a preliminary vulnerability estimation and gained large attention (e.g., Ammer et al., 2007; Hanewinkel et al., 2010a; Seiler et al., 2007; Storch and Claussen, 2012). This method assumes that the current species distribution area defines the adaptation potential based on aggregated climate signals. This approach can be categorized as an indirect impact assessment because aggregated climate signals are used as a proxy to predict future species distributions, and based upon this, assumptions about future production conditions are indirectly derived. Although the method is easy to use, understand, and communicate and exhibits good performance (Kramer et al., 2010) it has been criticized because it ignores the projected increase in extreme events and does not consider other important factors, such as soil properties (Bolte et al., 2008; Pearson and Dawson, 2003).

Other direct modeling approaches using climate time series at different temporal and spatial scales include dynamic global vegetation models, adaptations of so-called gap models, carbon accounting models, terrestrial biogeochemical models, and individual-tree stand models (cf. Medlyn et al., 2011 for a review). In addition to models focusing on the description of forest growth and species composition, a number of models describe the effect of single disturbance agents on forests such as storms (e.g., Blennow et al., 2009; Panferov et al., 2009) or insects (e.g., Berec et al., 2013; Jonsson et al., 2011). However, an obvious gap remains between models intended for understanding systems and scientific advancement and models to answer practical questions. Often scientific models are not sufficiently elaborated to be directly applicable by forest managers. Typically, they provide neither quantifications of possible timber losses nor economic metrics for the assessment of climate change impacts (Hanewinkel et al., 2010b). Furthermore, they are usually too coarse spatially or temporally to support forest management and forest operations. The Decision Support System-Forest and Climate Change (German: Decision Support System-Wald und Klimawandel, DSS-WuK) attempts to fill this gap (Jansen et al., 2008; Thiele et al., 2009; Thiele and Nuske, 2016). It provides a scale-independent modeling framework comprising well-established models. The employed models cover various climate change impacts on forests. The quantitative impact description is extended by a risk evaluation and an economic assessment. Although DSS-WuK was parameterized and implemented for the entire area of Germany, we show in this study that the model framework, because of its scale-independent design, can be employed in a spatially explicit manner for individual single forest management units using data with a much finer spatial resolution.

The present study pursues two major goals: (1) to present a model system coupling several submodels that describe the forest-climate interactions: soil and climate, forest growth and productivity, abiotic and biotic hazards and finally the economic valuation; and (2) to demonstrate the model systems' capabilities to provide valuable decision support for forest planning under climate change.

This paper is structured as follows. We start with a detailed description of the modeling system and the coupling of the submodels in the simulation process. We then introduce the "indicator stand" concept, which is essential to obtain comparable simulation results over the projection periods. The theoretical foundations of the applied submodels are subsequently briefly presented. We then present the case study of Norway spruce in the forest district "Arnsberger Wald", North Rhine-Westphalia, Germany. We use two climate scenarios to demonstrate the system's capability to project forest development until 2100. For the analysis, the simulation results for the entire period of 2011–2100 are aggregated into three 30-year (climatological) periods, 2011–2040, 2041–2070, 2071–2100, and compared to the reference period 1971–2000. The results are presented in terms of changes in site index, stand characteristics, risks (storm, drought, and insects), and economic measures. We conclude with a discussion of the suitability of the system for its purpose and relate our assessment of climate change impacts to current literature.

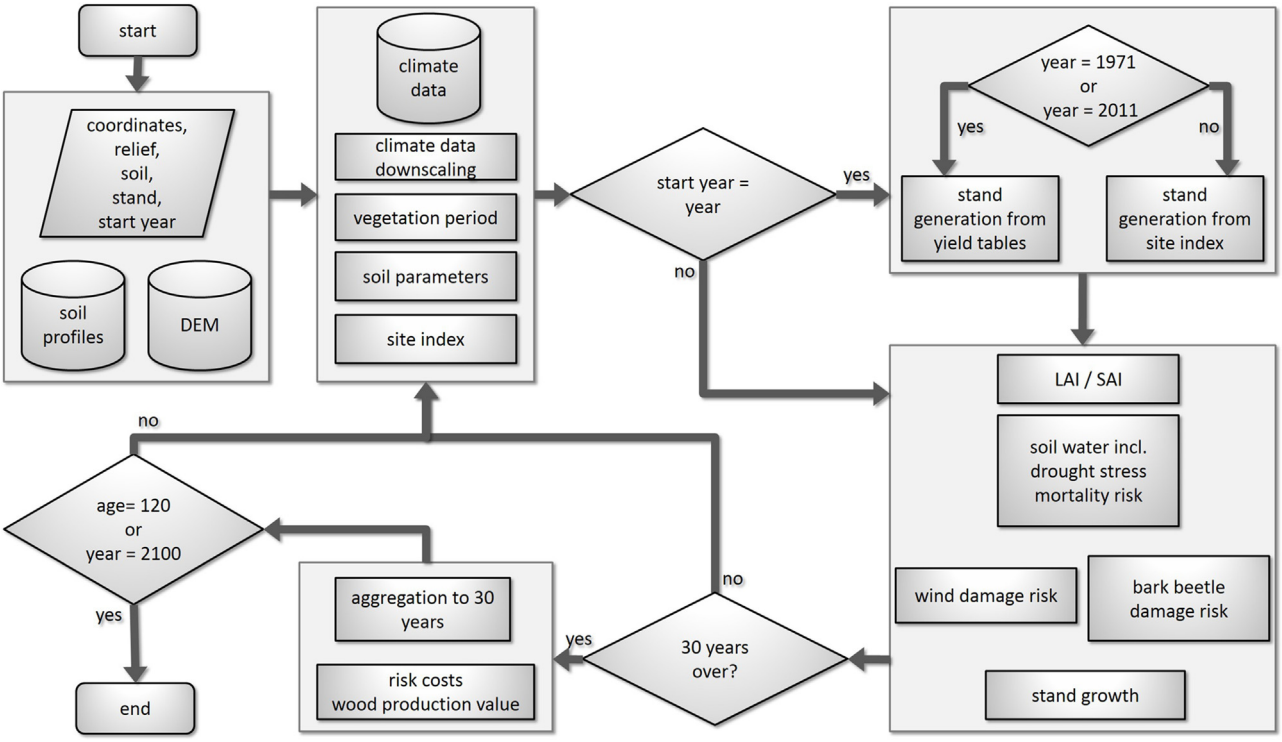


Fig 1. Schema of the mastermodel controlling the coupled submodels, showing the process flow beginning at top left (start) and ending at bottom left (end).

2. Material and methods

2.1. Model system

The DSS-WuK (Jansen et al., 2008; Thiele et al., 2009; Thiele and Nuske, 2016) follows the direct impact assessment approach by coupling a number of process-based and statistical submodels describing various aspects of the impact of climate change. It links a climate downscaling model, an individual-tree stand growth and management model, a site index model, a physical soil water model, a physical wind field model, a phenoallometric tree model, and an insect phenology model with damage risk models of windbreak and −throw, lethal drought stress, and pests as well as an economic valuation model. The system functions in a spatially explicit manner at given coordinates using spatial input data for soil, climate, nitrogen deposition, and topography. The spatial resolution of the model is specified by the input data, and thus the system is scale independent. At every considered location, the system simulates a representative stand. Currently, the system can handle only pure stands of one species. We introduce the "indicator stand" concept, described below, to evaluate the future production conditions of managed stands of Norway spruce. With respect to the temporal scale, the system is implemented to be driven by daily climate data, with submodels exchanging data in a 10-year time interval, and to output results in 30-year climate periods. However, the model is not bound to this temporal resolution.

The various submodels are integrated by defined data input and output interfaces (see Supplementary A). Therefore, the selection of submodels is not fixed but can be changed if the submodel candidate can support the defined data exchange interfaces. It is also possible to extend the system using further submodels, such as additional disturbance agents. The composition of submodels used in this study is presented in Section 2.3 and described in more detail in Supplementary A.

The central unit of the model framework is a mastermodel (Fig. 1) that defines the orchestration and choreography of the submodels. The mastermodel coordinates the preprocessing of the input data and the control and data flow among the submodels and stores the intermediate and final results to a database. The submodels exchange data after each coordinating 10-year time step, which is a compromise between complexity and accuracy. The 10-year results are then aggregated for the 30-year periods 1971–2000, 2011–2040, 2041–2070, and 2071–2100. A simulation for one climate scenario runs over the four time periods for each forest stand within the study area.

The simulation starts with the regionalization of ten years of daily climate data to 1-km resolution. The vegetation period is determined separately for every year and forest stand based on regionalized and downscaled local weather data. The climatic water balance and temperature sum within the vegetation period are then modeled simultaneously, and the stand- and soil-dependent rooting depth and distribution as well as a nutrient index value are calculated. From these site conditions, a site index is derived for the growth model. A new indicator stand is generated if necessary, and the leaf area index of the current stand is subsequently computed for the soil water model. The model of drought stress mortality is embedded in the soil water model. Thereafter, the wind damage model is executed, which consists of two parts: the model of the wind load and the damage model. The last risk model is the biotic model, which, again, contains two models: a phenological model predicting the number of bark beetle generations per year and a damage model. The final model in every time step is the stand growth model. Stand growth is projected based on the site index estimated by the climate-sensitive site index model. If the last period or the maximum stand age (120 years) is not reached, this loop continues, and another ten years are modeled. If the simulation time is complete, we leave the loop and aggregate the collected 10-year results to 30-year periods, as recommended by the usage notes of the regional climate model (DKRZ, 2007). Aggregation of the site index is straightforward using an arithmetic mean. Risks of damage are described by the conditional probability that a stand, that survived until a certain age drops out at this age. The risk of dam-

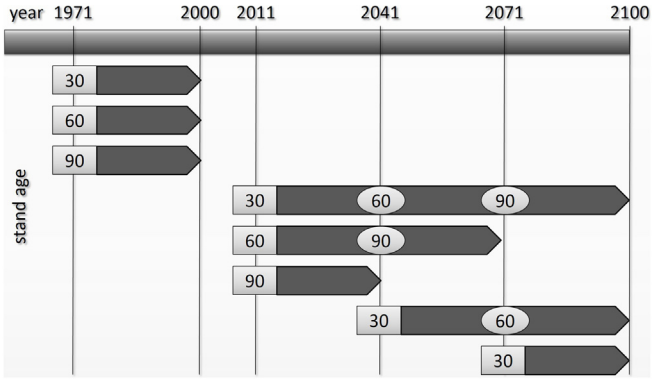


Fig. 2. Indicator stand concept covering the four simulated time periods. The rectangles at the beginning of arrows symbolize newly generated stands with their respective ages. The ellipses give the ages of the continued stands at the beginning of the subsequent periods.

age within a period of 30 years is calculated separately for drought, storms and insects by the following:

$$Risk_{30} = 1 - (1 - Risk_{1-10}) * (1 - Risk_{11-20}) * (1 - Risk_{21-30})$$

where 1-Risk provides the conditional survival probability, which is the complement of the conditional drop-out probability (cf. Staupendahl, 2011). The three resulting risk values are combined in the same way to obtain the total risk in a period. The total conditional probability that a stand that survived until the beginning of the period still exists at the end of the period is then one minus the total risk. The 30-year results were used as input in the economic model calculating the contribution margin of timber production and the risk costs. After completing this process, all results are written to the database for further analysis.

2.2. Indicator stand concept

Because we are striving to extract the climate effect on forest productivity and on potential risk factors, we use exemplary spruce stands ("indicator stands") of the age classes 30 to <60, 60 to <90 and 90 to <120 years for each time period (Fig. 2) instead of the stands' actual stocking information. We create imaginary pure Norway spruce stands for all forest inventory polygons of the study area. However, the stand characteristics depend on the specific site conditions at the respective location and time of creation. Stand generation is carried out using the site index model and the stand generator of the employed individual-tree stand growth and management simulator.

Once generated, the stand grows under the conditions of the applied climate scenario and passes over into the next period, e.g., a stand of age class 30–60 years becomes the "indicator stand" of the age class 60–90 years in the following period, and a stand of age class 60–90 becomes the "indicator stand" of the age class 90–120 years. Thus, the climate history of a stand and, therefore, its realized growth depending on ever-changing site-indices and stand structure are taken into account.

This approach permits an evaluation of the effects of climate on tree growth and risks at different development stages (tree ages) by comparing the results of the climate period of the past with the results for the projection periods.

2.3. Description of the submodels

The submodels are versions of established and validated models adapted to the purpose of this model system. Therefore, we present only the general outline of each submodel, our adjustments, and the reference to the publication containing the original model description. Fact sheets, including the input and output variables of each submodel indicating the data exchange of the submodels as well as their influence is provided in Supplementary A.

2.3.1. Regionalization of climate

The regionalization of climate data is performed using the modified SVAT-Regio model by Olchev et al. (2008), which is based on the Kriging method (Cressie, 1993). The variables are scaled down from a resolution of 0.2° to 1 km. The regionalization is based on climate data of 3 × 3 CLM grid cells. Depending on the variable, different factors are used for the regionalization, such as elevation differences, relief characteristics, wind direction, and distances to measuring stations.

2.3.2. Phenological and allometric models

Due to an extended *vegetation period* as a result of changing climate conditions, we expect a changing phenology of the trees. Therefore, we calculate the vegetation period for each year separately. The start and end dates of the vegetation period are determined using climate-dependent functions by Menzel (1997); Menzel and Fabian (1999); von Wilpert (1990).

Following Sogachev et al. (2011), we estimate the *leaf area index* (LAI) with the model by Law et al. (2001) in combination with the litterfall model from Ahrends et al. (2010). The calculated maximum value is modified by the seasonal variation induced by the vegetation period model (Hammel and Kennel, 2001).

For estimating the *effective rooting depth*, a proxy of the maximal depth for water and nutrient uptake, the rules by Czajkowski et al. (2009) based on tree species, soil texture, tree age and annual precipitation sum are applied.

2.3.3. Nutrient index

The site index model from Albert and Schmidt (2010) requires information about soil nutrient classes from site mapping, which is a classification method based on physical and chemical soil properties. To estimate these classes, we parameterize a multiple linear regression model with soil profiles from the first National Forest Soil Inventory in Lower Saxony (Bartens and Büttner, 1997) and soil profiles from Eberl (1998). Examples of such regression models can be found in Albert et al. (2016); Sutmöller et al. (2013).

2.3.4. Soil water modeling

For modeling the soil water balance, we use the detailed, process-based one-dimensional Soil-Vegetation-Atmosphere Transfer Model BROOK90 by Federer et al. (2003). In BROOK90, soil water transport is described by the Darcy-Richard equation with daily resolution. Soil water fluxes, parameters of the water retention curve and hydraulic conductivity function are deduced from soil texture using the pedotransfer function of Clapp and Hornberger (1978) for each horizon. Since the values for porosity are too low for most forest soils, we use the correction by Federer et al. (1993). Soil texture classification is carried out using the Triangle software (Gerakis and Baer, 1999). Because BROOK90 uses the water potential of the top layer to estimate soil evaporation, large differences in the estimated thickness of the first soil horizon affect the ratio of soil evaporation to transpiration. Therefore, we add a 5 cm humus layer to all soil profiles, as no information on humus layer is provided in the available soil map (BK 1:50,000), and parameterize the forest floor with the hydraulic parameters for peat (Lee and Pielke, 1992).

2.3.5. Model of drought stress mortality

To estimate drought stress mortality, we employ the critical limits concept from air pollutant monitoring. Following Czajkowski et al. (2009), a critical limit of plant water status occurs when

cavitations in tree xylem lower the (stem) xylem conductivity considerably. The surviving trees after an event with exceeded critical limits are quantified as a share of the total stand, which is a function of the number of days with exceeded critical limits of soil water availability. We describe the relationship of the critical limits of soil water availability with tree mortality using a Weibull-function (cf. Linton et al., 1998).

2.3.6. Wind damage model

The site-dependent wind load is calculated using a modified version of the three dimensional boundary layer model SCADIS (Sogachev et al., 2002; Sogachev and Panferov, 2006; Panferov and Sogachev, 2008). The model calculates the three-dimensional wind field and turbulent kinetic energy for complex landscapes, considering structural information of different vegetation types. Therefore, it is able to estimate the mean- and gust-wind loads on trees taking into account stand characteristics such as height, LAI, and crown closure, delivered by the forest growth submodel. The estimation of wind damage also implements the critical limit approach. A windthrow or windbreak event occurs after one of the critical limits of wind load is exceeded, either for throw or for break. The critical level of a windthrow event is a function of the tree anchorage, which is determined by the soil moisture content calculated by the soil water model and the soil temperature. The critical level for stem break is a function of stem properties, i.e., the modulus of rupture. The conditional drop-out probability is then calculated depending on the wind load as described by Panferov et al. (2009).

2.3.7. Bark beetle damage model

To calculate damage, we first estimate the number of bark beetle (*Ips typographus*) generations per year using the model PHENIPS (Baier et al., 2007). The modeling approach is based on triggering different phenomenological stages of bark beetles by the thermal sums of daily mean and maximal temperature (in degree-days). The conditional drop-out probability of a stand is then calculated depending on the number of beetle generations per year, the soil moisture calculated by the soil water model, the stand age, and the basal area of the stand using the model of Seidl et al. (2007) calibrated with data from Saxony-Anhalt State Forest.

2.3.8. Site-index model

The climate sensitive site index is estimated by the statistical model of Albert and Schmidt (2012, 2010) fitted to data from the German National Forest Inventory I and II and the inventory plots of the Lower Saxon State Forest. The site index is given as the theoretical mean stand height in meters of a forest at age 100 years and growing under assumed fixed site conditions. The Generalized Additive Model uses the explanatory variables nutrient class, available soil moisture, nitrogen deposition, mean temperature in the vegetation period, and mean climatic water balance in the vegetation period as well as the geographic coordinates. The effect of non-lethal drought is also accounted for as the model projects a significant reduction of the site index as a function of decreasing climatic water balance.

2.3.9. Forest growth model

To model the growth of the forest stands, we employ the statistical individual-tree stand growth and management model TreeGrOSS parameterized for northwestern Germany (Nagel, 2011; Döbbeler et al., 2002). TreeGrOSS is the core for several forest simulation systems, such as the Decision Support Systems "BWinPro" and "Waldplaner 2.0". Both are used for operational silvicultural planning, for instance, in Northwest Germany (Böckmann, 2016). Usually a 5-year update interval is used in simulations. The site index in TreeGrOSS is updated with new values from the site index model in step with the coordinating time intervals of the mastermodel (10 years), and thus the growth rate changes every ten years and is applied to the current tree status. We choose crop tree selection with selective thinning and subsequent harvesting by target diameter following the management rules of the Federal State of Lower Saxony (Niedersächsische Landesforsten, 2011) as the management strategy for all stands. Growth and harvesting is not carried out if it results in less than 200 stems per hectare, which is defined as the end use criterion of a stand. In this case, the stand is fixed to its last condition, and risks are simulated accordingly to obtain full time series and avoid compromising the "indicator stands" concept.

2.3.10. Economic model

The aim of the economic model is to express both the various risks and the growth potential using a single economic indicator. For this purpose, for each age class, the mean annual contribution margin of timber production within the particular period is calculated. The difference between this value and the corresponding periodic annual contribution margin without consideration of risk is interpreted as risk costs.

The mean annual contribution margin is calculated for each 5-year step within the period by the felling value at this age plus the contribution margins and costs, respectively, of all intermediate harvesting and tending operations within the period up to that age, minus the felling value at the beginning of the period. The probability that the stand drops out at that age and therefore that the corresponding mean annual contribution margin is realized depends on the risk. Thus, there is a distribution of mean annual contribution margins, and its expected value is then calculated as a weighted mean (cf. Staupendahl and Möhring, 2011). The weights are derived by a linear survival function defined by the points $(t_1,1.0)$ and (t_2,s), where t_1 and t_2 denote the ages at the beginning and the end of the period and s gives the probability that the indicator stand survives the period.

The volume of the remaining and removed stand at the time steps are provided by the forest growth model described above; the cost and revenue models are derived from accounting data of the Lower Saxony State Forest and the work of Rüping (2009).

2.3.11. Analysis of results

All statistical analysis and plots were performed using the statistical software R (R Core Team, 2015) in combination with the packages ggplot2 (Wickham, 2009), sp (Bivand et al., 2013), rgdal (Bivand et al., 2015), maptools (Bivand and Lewin-Koh, 2015), lattice (Sarkar, 2008), RColorBrewer (Neuwirth, 2014), RPostgreSQL (Conway et al., 2013), reshape2 (Wickham, 2007), and plyr (Wickham, 2011). Correlation analysis were carried out using Kendall rank correlation coefficient with a non-parametric tau test for statistical dependence. Distribution comparisons were performed using the non-parametric two-sample Kolmogorov-Smirnoff test.

2.4. Input data

The DSS-WuK needs a set of input data on the considered forest stands that includes soil properties, local topography, nitrogen deposition, and climate characteristics. The locations of the 462 stands are represented by their centers of mass (centroids). The simulations are run for each centroid.

The topography and the soil characteristics are assumed to be static over the considered time, whereas the climate and nitrogen deposition are time series derived from scenarios of future development.

Table 1
Stand characteristics at the end of the 30-year simulation periods for each age class and climate scenario (B1, A1B; as a common reference, C20 is printed in the middle of both scenario columns) averaged over all 462 stands. Dq: quadratic mean diameter of trunks, Hq: height of trees with the quadratic mean diameter, BA: basal area is the total cross-sectional area of stems in a stand measured at breast height.

Age class [years]	Climate period [years]	Stems/ha [N]		Dq [cm]		Hq [m]		BA [m^2/ha]	
		B1	A1B	B1	A1B	B1	A1B	B1	A1B
30–60	1971–2000	786		24.5		15.8		34.3	
	2011–2040	795	800	24.5	24.5	15.8	15.8	34.6	34.7
	2041–2070	681	653	27.8	28.5	17.8	18.5	37.3	38.7
	2071–2100	634	636	29.5	30.9	19.6	21.6	41.2	45.9
60–90	1971–2000	376		37.8		24.8		41.5	
	2011–2040	375	375	37.8	37.8	24.7	24.7	41.4	41.4
	2041–2070	319	322	39.1	39.0	24.1	24.3	37.1	37.4
	2071–2100	288	284	42.3	42.9	26.0	26.9	38.9	39.9
90–120	1971–2000	268		45.1		29.5		42.6	
	2011–2040	269	270	45.1	45.1	29.5	29.5	42.8	42.9
	2041–2070	239	229	45.6	45.7	28.4	28.7	39.2	37.6
	2071–2100	227	234	45.1	45.0	27.0	27.3	36.1	37.2

2.4.1. Soil

Soil properties (soil texture, bulk density, stone content, organic matter, available soil water capacity, etc.) were taken from a digital soil map of scale 1:50,000 (BK 50, source: Geological Service North Rhine-Westphalia) resulting in 289 potentially unique values for the 462 stands. The potential cation exchange capacity was calculated with pedotransfer functions of Müller and Waldeck (2011).

2.4.2. Topography

The elevation, slope, and aspect were derived from a ~90 m resolution digital elevation model based on the Shuttle Radar Topography Mission (SRTM) dataset Version 4 edited by the CIGAR Consortium for Spatial Information (Jarvis et al., 2008).

2.4.3. Nitrogen deposition

Long-term trends for the deposition of nitrogen were calculated with the model MAKEDEP (Alveteg et al., 1998) as described by Albert and Schmidt (2010); Hauck et al. (2012). The model was run with grid-based estimates of Gauger et al. (2008) for a period from 1995 to 2004. To reconstruct the deposition before 1995, we used the regional trend from the EMEP database (Tarrasón and Nyíri, 2008) and standard time series from Alveteg et al. (1998). From 2004 onward, the annual nitrogen deposition was maintained constant. Mapping the nitrogen deposition grid of 1-km spatial resolution to the centroids of the stand polygons resulted in 141 unique grid points in the study area.

2.4.4. Climate

We employed the climate scenario 20C3M for the period 1971–2000 (reference) and SRES B1 and A1B (IPCC, 2000) for the projection period 2011–2100 modeled by coupled AOGCM ECHAM-5-MPIOM (run 1), regionalized with the RCM Climate-Local-Model (CLM; Hollweg et al., 2008) and interpolated to a spatial resolution of 0.2° (Datastream 3, Lautenschlager et al., 2009a, 2009b). Data with a daily timestep were used, i.e., the daily sum of precipitation and solar radiation, daily means for temperature, vapor pressure, and wind speed, and daily extreme values of maximal and minimal temperature and maximal wind gust. The data were further statistically downscaled (see Section 2.3.1) taking into account the elevation and the exposition of the slopes. The downscaling resulted in 458 potentially different climate time series mapped to the centroids of the stands within the study area. The climate data were then bias corrected using the observation data of the German Weather Service (German: Deutscher Wetterdienst, DWD), and the delta-change and linear transfer functions of Mudelsee et al. (2010) and considering plausible conditions such as $T_{min} < T_{mean} < T_{max}$. The vapor pressure was adjusted to bias-corrected temperatures.

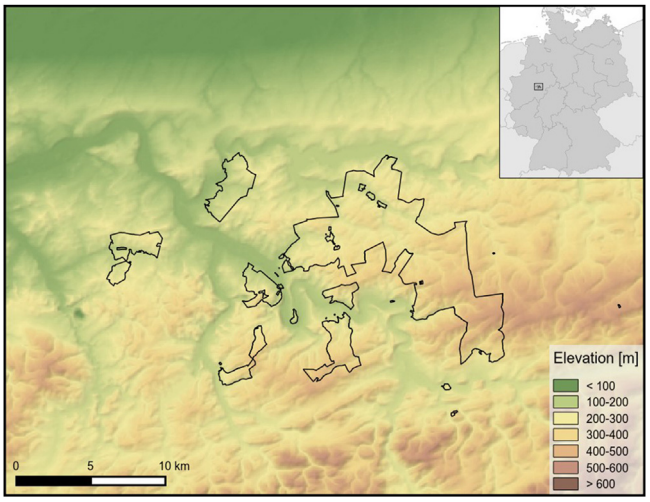


Fig. 3. Location of the study area "Arnsberger Wald" (black polygons, 51.3°–51.5°N and 7.8°–8.4°W) derived from the forest inventory map depicted with the elevation of the surrounding landscape based on SRTM data (Jarvis et al., 2008).

2.5. Site description

The forest district "Arnsberger Wald" with a size of approximately 10,000 ha is located in the northern part of the Rhenish Massif, which is in the western part of Germany (cf. Fig. 3). It is characterized by the bends of the river Ruhr. The dominant tree species (45%) is Norway spruce (*Picea abies* (L.) H.Karst.). Other species are European beech (34%), Oak (7%), Scots pine (1%), other deciduous wood (8%) and other coniferous wood (5%; Wald und Holz NRW, 2016). Since Norway spruce is by far the most economically important species in the "Arnsberger Wald", the presented case study focuses exclusively on Norway spruce.

The terrain is dominated by steep slopes with elevations ranging between 200 and 550 m a.s.l. The northwest is generally lower than the southeast (Fig. 3). The forests are located on the higher grounds covering hill tops and slopes. Depending on the elevation, the current annual mean temperature decreases from +9 °C in the northwest to +6.4 °C in the higher southeast. By contrast, the annual precipitation increases with height from 850 mm in the north-western to 1100 mm in the hilly south-eastern regions. The study area is dominated by shallow soils with available soil water capacity in the rooting zone below 120 mm in the south and above 200 mm for deeper soils in the north. Due to various geological sub-

strates and relief intensities, the spatial heterogeneity of the soils is high, and adjacent areas might have very different properties.

3. Results

3.1. Climate change

In the following, we summarize the main results of the downscaling model driven by bias-corrected daily climate data (C20, B1, A1B) in the regional climate model CLM. Visualizations are provided in Supplementary B1–B11. The target grid resolution is 1 km^2, and the temporal resolution is 1 day.

The annual mean temperature averaged over 30-year periods is projected to increase in scenario B1 and A1 B by 2.0 and 2.9 °C, respectively, from 1971–2000 to 2071–2100 in the study area. An increase in the total annual precipitation of rather small magnitude is projected: 4.2% (B1) and 3% (A1B) from 1971–2000 to 2071–2100.

The climatic water balance of the vegetation period using evapotranspiration of a hypothetical grass reference crop (Allen et al., 1998) is an input parameter of the site index model (Albert and Schmidt, 2010) and an indicator for drought stress (cf. Albert et al., 2016). The 30-year average of climatic water balance of vegetation period shows a strong decrease toward the end of the 21st century. The average climatic water balance over all forest stands decreases by 31 mm (24%) in scenario B1 and 71 mm (55%) in scenario A1 B from 1971–2000 to 2071–2100. Furthermore, the mean sum of hot days, i.e., days with a daily maximum temperature above 30 °C, increases from 161 during the 30-year reference period to 380 days in scenario B1 and 577 days in scenario A1B in the period 2071–2100. In summary, the water supply deteriorates over time, and the sum of drought events, i.e., a year with a negative climatic water balance in a forest stand, increases from 464 events in the reference period to 559, 2019, 2362 events in the projection periods under climate scenario B1 and 1790, 2946, and 4260 events under climate scenario A1B.

The mean number of days with storm events, i.e., days with maximum wind speed above 20.8 m/s at 10 m height, increases from 83 for the first 30-year period to 110 (B1) and 147 (A1B) days during 2071–2100. The variation between the different forest stands is rather small. A similar pattern but with less events and higher spatial variation is observed for heavy storm events, i.e., days with maximum wind speed above 24.5 m/s. The mean number of days with heavy storm events in 30 years increases from 4 days in the reference period to 8 (B1) and 14 (A1B) days in the last period.

This analysis provides a basic overview of the general climate trends in the region. A more thorough examination of the interannual climate dynamics at a specific forest stand is revealing. In the last period, the highest monthly mean temperature averaged over 30 years coincides in time with the lowest precipitation sum in scenario A1B. Furthermore, analyzing the changes not only in 30-year periods but on an annual scale reveals years of disruption of the general trend of increasing temperatures and precipitation sums. Although the number of dry years increases over time, the increase in temperature at annual resolution is not monotone.

The effects of these changes on the site index, stand characteristics, risks, and aggregated economic measures are evaluated in this simulation experiment. The results are presented in the following.

3.2. Changes in growth potential

In our simulation, we found an increase in the site index (growth potential of forest sites) during the 21st century, with a slight initial decline in scenario B1 in the period 2011–2040 (Fig. 4). The site index increases by 17% (B1) and 25 % (A1B) from the reference to the last period (2071–2100). The differences in growing capacity between the climate periods are statistically significant for both climate scenarios, with the exception of the first projection period compared to the reference period in scenario B1 (two-sample Kolmogorov-Smirnov test, two-sided alternative hypothesis: for all 30-year periods with $\alpha = 5$ %).

Table 2
Age when stands reach the end use phase. The minimum, maximum and mean stand ages of all 462 stands for both climate scenarios (B1, A1B; as a common reference, C20 is printed in the middle of both scenario columns).

Climate period	Min. age [years]		Mean age [years]		Max. age [years]	
	B1	A1B	B1	A1B	B1	A1B
1971–2000	105		106		110	
2011–2040	105	105	105	105	110	110
2041–2070	85	85	93	93	100	100
2071–2100	85	85	89	89	90	95

Fig. 5 shows the spatial distribution of the site indices for the considered periods for scenario A1B as an example. The influence of the relief (cf. Fig. 3) and associated temperature gradient are clearly visible throughout all periods: the higher the elevation, the lower the site index. This general pattern remains unchanged over time, although the differences gradually diminish under the A1B scenario, and the different inventory areas become more homogeneous with respect to their site indices. This effect is also reflected by the decreasing correlation between the site index and the elevation toward the end of the century under scenario A1B (for 1971–2000: Kendall's tau = -0.67*, for 2071–2100: -0.45*, * significant at $\alpha = 5\%$). Under the B1 scenario, this correlation remains unchanged.

3.3. Stand characteristics

The predicted stand characteristics for each age class (indicator stands), climate period, and both climate scenarios are shown in Table 1. For the age class 30–60 years, we find an increase in the quadratic mean diameter (Dq) and height of trees with the quadratic mean diameter (Hq) along the climate periods concurrent with a reduced stem number. The relative increase in diameter is 20% (B1) and 26% (A1B), and the increase in height for this age class is 24% (B1) and 37% (A1B). For the age class 60–90 years, we also find an increase in diameter and height between the reference and the last climate period combined with a decreasing stem number and basal area. The Dq of the oldest age class remains relatively constant over time due to target diameter thinning carried out by the stand growth model. Simultaneously, the number of stems, the height, and the basal area decrease over time because the target diameter is reached earlier (cf. Table 2). The forest management phase "end use" is initiated if the next target diameter thinning would result in less than 200 stems per hectare.

3.4. Changes in forest damage risks

3.4.1. Drought-induced tree mortality risk

As mentioned in the model description, drought-induced mortality should not be confused with drought stress leading to, for example, reduced growth. Tree death due to water shortage is a very rare phenomenon in the study area (cf. Table 3). The model estimates at least some drought stress mortality in the projection periods. In particular, in the period 2041–2070, which features very hot and dry summers, the drought-induced conditional drop-out probabilities increase sharply on some sites. Although most of the conditional drop-out probabilities are rather small, the highest values are 0.48 (B1) and 0.63 (A1B).

The drought stress affects areas where the available soil water capacity in the rooting zone is extremely low (less than 110 mm).

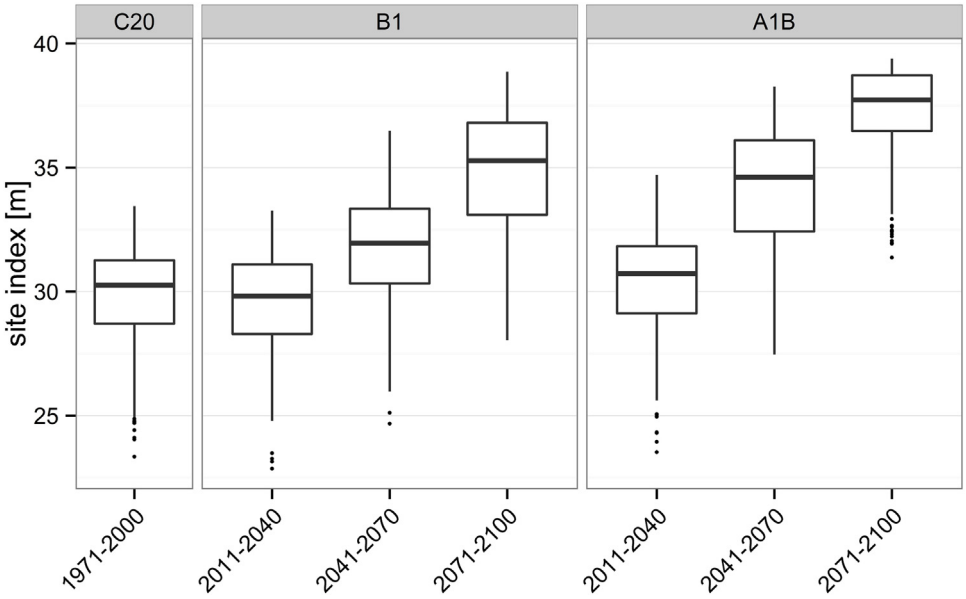


Fig. 4. Box-and-Whisker plots (median, 25th and 75th percentile, 1.5 interquartile range, outliers) of the site index for climate periods of the C20 reference and two climate scenarios B1 and A1B.

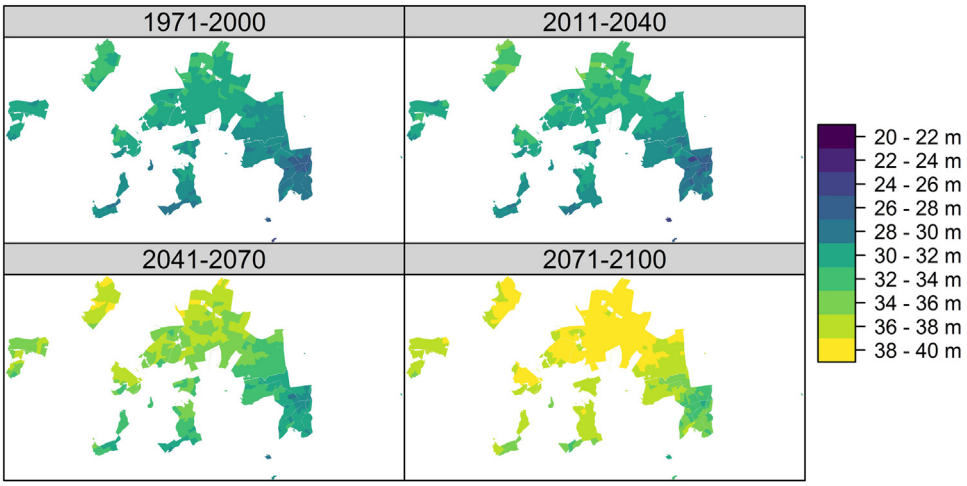


Fig. 5. Maps of the site indices [m] of climate scenario A1B (and C20 reference).

Table 3
Number of forest stands (N = 462) where drought stress mortality, i.e., drop-out probability > 0, occurs depending on age class, climate period and climate scenario (B1, A1B; as a common reference, C20 is printed in the middle of both scenario columns).

Climate period	*Age class*					
	30–60		60–90		90–120	
	B1	A1B	B1	A1B	B1	A1B
1971–2000	0		0		0	
2011–2040	0	3	0	1	0	3
2041–2070	2	26	1	16	0	30
2071–2100	77	4	57	4	21	4

We find a negative correlation between the drop-out probability caused by drought stress mortality and the available soil water content, meaning the lower the water content, the higher the risk of drought stress mortality event due to long durations of drought (Kendall's tau = -0.52* over all age classes for period 2071–2100 with climate scenario B1; Kendall's tau = -0.35* over all age classes for period 2041–2070 with climate scenario A1B; * significant at $\alpha = 5\%$).

3.4.2. Bark beetle damage risk

According to the results of the bark beetle damage risk model, damage is expected only in the older age classes (cf. Fig. 6) because, in the employed model, bark beetles attack only trees older than 60 years. For both climate scenarios, we observe a monotone increase of the bark beetle-induced drop-out probability over the periods with a higher level in the age class 90–120 years due to stand-dependent damage predisposition. This increase results in a mean conditional drop-out probability of 0.09 (B1) and 0.1 (A1B) for the oldest age class in the last 30-year period. The drop-out probability increases by a factor of 1.5 (B1) and 1.7 (A1B) from the reference to the last climate period. The differences in damage probabilities between the reference period and all climate periods of both climate scenarios are statistically significant for both age classes, 60–90 and 90–120 years (two-sample Kolmogorov-Smirnov test, two-sided alternative hypothesis: for all 30-year periods and age classes 60–90 and 90–120 years with $\alpha = 5\%$).

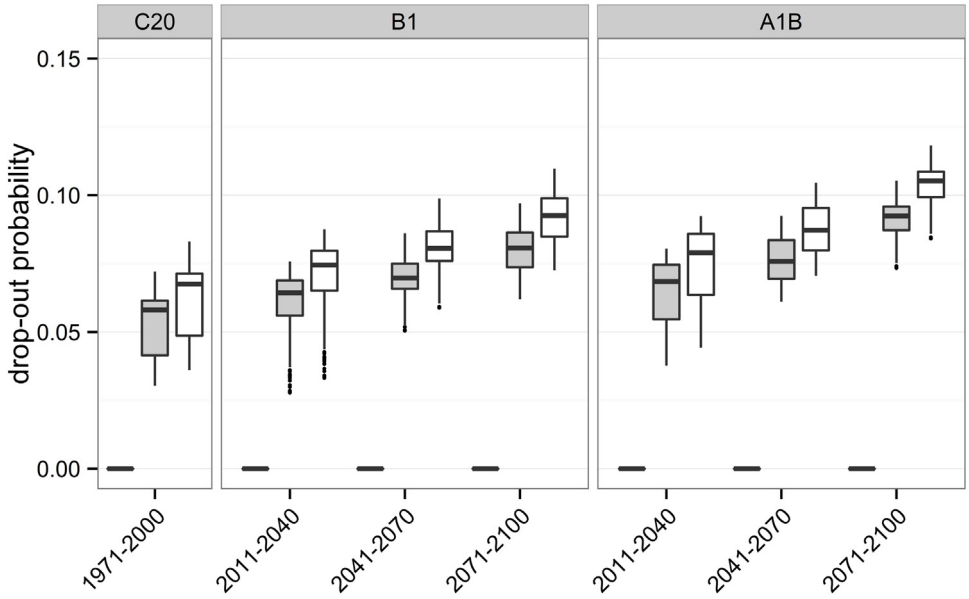


Fig. 6. Box-and-Whisker plots (median, 25th and 75th percentile, 1.5 interquartile range, outliers) of the bark beetle given as the drop-out probability depending on stand age class and climate period for the C20 reference and two climate scenarios B1 and A1B. Dark gray: age class 30–60 years; light gray: age class 60–90 years; white: age class 90–120 years.

The lower northern part of the study area is more vulnerable to bark beetle infestations than the hilly southern parts (see Supplementary B12). This pattern is identical for the stand age classes 60–90 and 90–120 years. The negative correlation between elevation and bark beetle damage risk is significant in the period 2071–2100 (for age class 60–90 years: Kendall's tau = -0.81* (B1) and -0.81* (A1B); for age class 90–120 years: -0.81* (B1) and -0.80* (A1B); * significant at $\alpha = 5\%$).

3.4.3. Wind damage risk

Wind damage includes drop-out probabilities due to windthrow and windbreak of trees (Fig. 7). In the reference period (1971–2000) as well as in the period 2041–2070 with climate scenario B1, the damage risk is significantly higher for younger stands. The same applies for the period 2011–2040 with climate scenario A1B. During the period 2071–2100, the risk for old stands is notably higher than for young- and mid-aged ones for both climate scenarios (for the spatial pattern, see Supplementary B13). The damage risk differences are significant between the periods for all age classes in both climate scenarios (two-sample Kolmogorov-Smirnov test, two-sided alternative hypothesis: for all 30-year periods and age classes with $\alpha = 5\%$). Starting with conditional drop-out probability levels in the reference period (1971–2000) of less than 0.1 on average over all forest stands, the risk of wind damage increases by factors of 2.8 (B1) and 3.1 (A1B) in the 90–120 year age class in the last period. Under the climate scenario B1, the risk for all age classes increases from the reference to the first projection period and decreases in the second projection period before it reaches its maximum in the last period. Under climate scenario A1B, the risk increases for the young- and mid-age classes from the reference over the first to the second projection period and then remains relatively unchanged in the last period. For old stands (age class 90–120), the pattern is different, and the wind damage risk also increases in the last period. For both climate scenarios and all age classes, there is a strong increase in the interquartile range, i.e., spatial heterogeneity, over the climate periods. For climate scenario B1, this increase is especially notable in the last period, whereas for the climate scenario A1B, the interquartile range increases considerably between the first and the last two projection periods.

3.5. Economic valuation

The risk costs indicate the economic effect of aggregated biotic and abiotic damage risks and how it changes over time. In addition, the annual contribution margin of timber production summarizes positive climatic effects caused by an enhanced volume increment and the negative economic effects due to increased costs of damages.

Fig. 8 (top) shows that the range of risk costs among the different forest stands increases strongly over time under both climate scenarios (for the spatial pattern, see Supplementary B14). This effect also increases with age class and is relatively low for young stands and largest for old stands, except for period 2041–2070 under climate scenario B1. The risk costs of all projection periods differ significantly from the risk costs of the reference period as well as between all age classes under both climate scenarios (two-sample Kolmogorov-Smirnov test, two-sided alternative hypothesis: for all 30-year periods and age classes with $\alpha = 5\%$). We find an increase in the mean annual contribution margin over time for the first two age classes under both climate scenarios, except a slight decrease in the first B1 projection period (cf. Fig. 8, bottom). For the oldest age class, we note a small decrease when comparing the projection periods with the reference period. However, the mean annual contribution margin remains positive. The differences between all climate periods are statistically significant for all age classes under both climate scenarios except between the reference period and the first B1 projection period (two-sample Kolmogorov-Smirnov test, two-sided alternative hypothesis: for all 30-year periods and age classes with $\alpha = 5\%$).

Notably, the mean annual contribution margin remains relatively stable or even increases over the three periods, although risk costs are simultaneously increasing significantly.

4. Discussion

The discussion is divided into three main sections: (1) the design and implementation of a complex dynamic model system; (2) the critical evaluation of submodels; (3) the assessment of the impact of climate change on forest growth and risk.

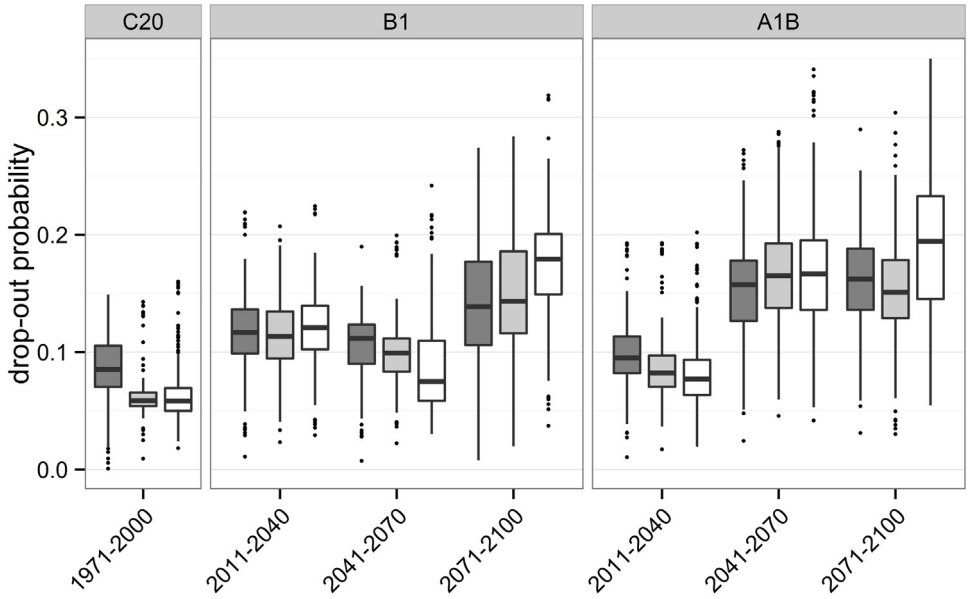


Fig. 7. Box-and-Whisker plots (median, 25th and 75th percentile, 1.5 interquartile range, outliers) of the wind damage risk given as the drop-out probability depending on stand age class and climate period for the C20 reference and two climate scenarios B1 and A1B. Dark gray: age class 30–60 years; light gray: age class 60–90 years; white: age class 90–120 years.

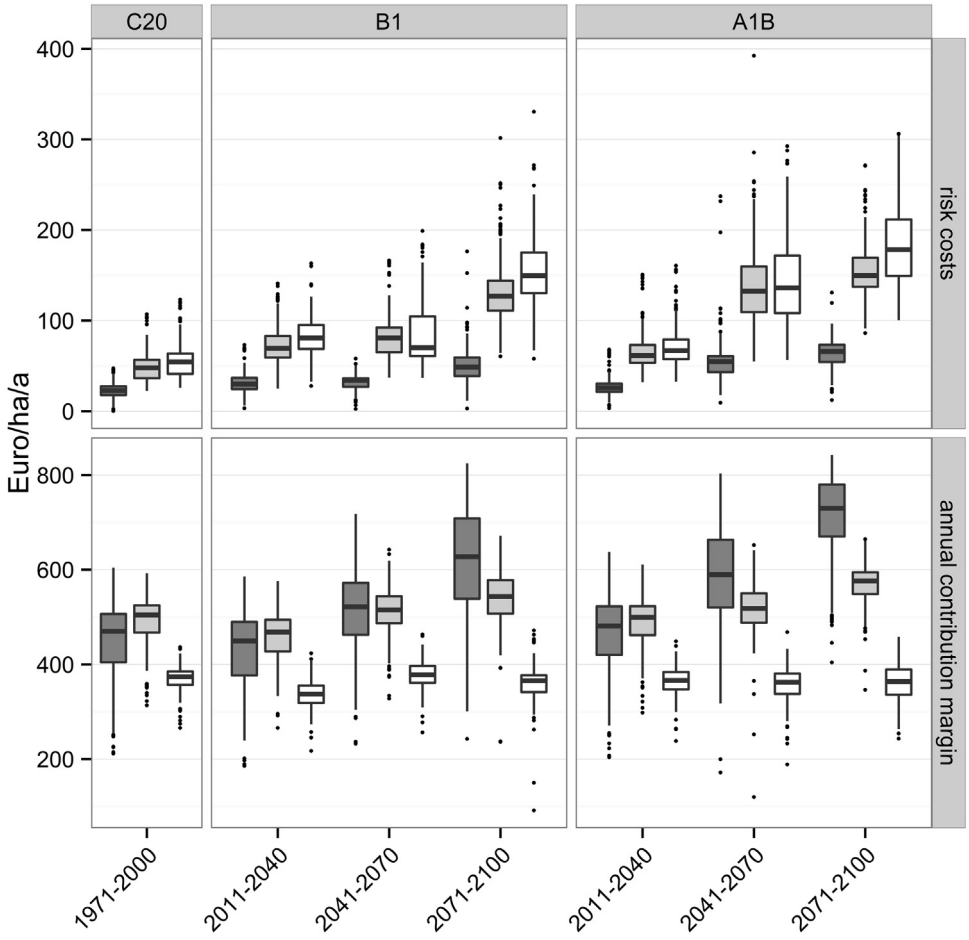


Fig. 8. Box-and-Whisker plots (median, 25th and 75th percentile, 1.5 interquartile range, outliers) of the risk costs (top) and the mean annual contribution margin of timber production under consideration of risks costs (bottom) both depending on stand age class and climate period for the C20 reference and two climate scenarios B1 and A1B. Dark gray: age class 30–60 years; light gray: age class 60–90 years; white: age class 90–120 years.

4.1. Design and implementation of a complex dynamic model system

In the present study, we have demonstrated that it is possible to build a complex model system covering forest growth, damage risk evaluation, and economic assessment under climate change. The model system comprises various established and validated process-based and statistical models driven by temporal high-resolution climate data. Using this direct impact assessment approach, the system is able to quantify the impacts of climate change, in contrast to indirect methods, which deliver only qualitative measures of vulnerabilities. The analysis of the interannual variability of the projected climate indicates that it is very important to model the entire timespan, as performed in this study, to adequately evaluate the future growth conditions of forests. The comparison of merely two points in time with different growth conditions and ignoring the dynamic changes in between is not advisable for damage risk evaluation. Thus, climate change has to be viewed as a complex process and not just as a new state of environmental conditions that immediately drops in, as performed, for example, by Asche (2009).

Forests are, in contrast to agricultural systems, long-lasting: several processes run for long periods of time using different stores, e.g., soil for water and nutrients or biomass for carbon storage. Only dynamic simulations driven by time series of climate data can incorporate the dynamics of these stores and are therefore the appropriate modeling approach to quantify climate change impacts on scales of operational forest management. Using such a dynamic simulation system in combination with the concept of "indicator stands" (cf. Subsection 2.2), we have been able to quantify the age-dependent differences in climate change impacts on forests at stand level. The indicator stand concept enables climate effects to be separated from age-dependent effects on growth and damage risks while retaining feedback between changing stand characteristics and biotic as well as abiotic risks. Therefore, we have been able to trace the impacts of climate change on the given sites over time. Indicator stands in the same location with identical stand age classes permits the separation of climate effects from growth and location effects.

We based our impact assessment on two climate scenarios (B1 and A1B) to demonstrate the model system's capabilities. To obtain more robust estimations for thorough decision support, the analysis of climate impacts on forest stands should be based on ensembles of multiple and, where possible, fundamentally different climate scenarios (Moss et al., 2008).

Some risks are not always inherently lethal but increase the vulnerability to other risks. Some of these feedbacks are currently present in the model system, e.g., drought stress increases the vulnerability to bark beetle attacks, but, for example, feedbacks between vegetation and climate, which could be relevant, are not taken into account (Bonan, 2008; Tölle et al., 2014). However, including the interaction of vegetation and climate would increase the complexity enormously by requiring climate models to be run in parallel. Moreover, genetic variations can lead to varying responses to changing climate conditions. We used an "average" Norway spruce, although one adaptation strategy to climate change is to establish different genotypes, e.g., seeds from regions facing the projected climate already today (e.g., Spittlehouse and Stewart, 2003). Such genetic or provenance adaptations are not yet implemented explicitly but can be realized by different parameterizations of tree species.

Although the model system comprises many established and validated models such as the soil water model and the growth model, some of the damage risk models were developed especially for this model system and are difficult to parameterize. In combination with uncertainties in the input data, particularly with regard to climate projections, these uncertainties accumulate along a cascade (Schneider, 1983; Reyer, 2013). Further research to improve the input data as well as the impact models is necessary to reduce those uncertainties. However, for the mastermodel, we chose a modular design that permits the replacement of any submodel by a different implementation that uses the same interface. We used specialized programming techniques to bind submodels of different programming languages to the mastermodel (cf. Thiele and Nuske, 2016). With this flexible approach, improved submodels can be included once available.

4.2. Critical evaluation of submodels

4.2.1. Regionalization of climate

As mentioned above, the implemented downscaling model published in Olchev et al. (2008) is based on the well-known "ordinary kriging" method with height correction. However, when downscaling several interdependent variables, the interrelationships between variables should be taken into account. In the present study, the variables were adjusted to the mean daily temperature.

4.2.2. Phenological and allometric models

To calculate the start and end dates of vegetation periods, the functions by Menzel (1997); Menzel and Fabian (1999); von Wilpert (1990) are commonly applied in combination with the Brook90 model (Baumgarten et al., 2014; Schwärzel et al., 2009). Furthermore, the site index of Albert and Schmidt (2010) uses this approach to summarize daily climate data for the vegetation period. It was therefore obvious to implement a corresponding approach, although the uncertainties were known, as described below. The work of Linkosalo et al. (2008) showed that simple thermal time models, as mentioned above, are very robust in predicting bud burst under current climate conditions. They commented that precautions were needed under changing climate conditions because the relative importance could be modified. Chuine et al. (2016) also postulated great uncertainty if using these models with climate change scenarios.

The LAI crucially affects the results of water budget models (Gigante et al., 2009; Wellpott et al., 2005). Since the LAI is difficult to measure directly, high uncertainties are also introduced at this early stage (Nilson et al., 1999; Richardson et al., 2011). The simple approach to modeling LAI dynamics from Law et al. (2001) used in this study considers only the interactions with stand characteristics (Dq, stem number). However, some studies have shown that there are feedbacks between the site water balance and LAI (Le Dantec et al., 2000; Schleppi et al., 2011), although Leuschner et al. (2006) failed to find a limiting effect of drought stress on LAI. It also has been shown that the site indices of forests correlate with the respective LAI (Bequet et al., 2012).

Specifications of effective rooting depth are very important for water budget modeling and drought stress mortality assessment. The architecture of root systems is mainly influenced by the parent material, the soil type, the bulk density, the chemical soil conditions, the depth of ground water, and the species and age of trees. Due to this complexity, the root depth and the distribution in the soil profile are critical model parameters. The linking rule from Czajkowski et al. (2009) is based on numerous studies.

4.2.3. Nutrient index modeling

The soil nutrient index classes are an input parameter for site index modeling. During preprocessing, the nutrient classes are pooled into three to four classes. Therefore, we decided to use a simple approach, which was very robust when applied in different federal states. However, nutrient regime modeling is more uncer-

tain than modeling of the water regime for forests (Köhler et al., 2016).

4.2.4. Soil water and drought stress mortality modeling

All water model predictions are linked to uncertainties, which are generated either by the model input data (climate, soil, and vegetation), the model structure itself or by the uncertainty of model parameters (Beven, 2012).

In a model comparison by Bouten and Jansson (1995), deviations from the average seepage flow rate of −6% to +12% resulted from the selection of different models. Although many models have been developed to address water budgets, the Brook90 model has demonstrated its potential in many studies (Baumgarten et al., 2014; Vilhar, 2016).

Despite the high potential mortality risk of forest trees, existing drought stress projections are based on models that lack functionally realistic mortality mechanisms (Adams et al., 2009). Following Bréda et al. (1995); Czajkowski et al. (2009), who demonstrated that plant water status can be linked to soil matrix potential at the lower limit of the effective rooting depth (ERD), we implemented a drought mortality function in the water budget model discussed above. Accordingly, there are three main sources of uncertainty: the soil water model itself and its parameterization; the determination of the ERD, which is highly dependent on tree species structure and soil characteristics; and the parametrization of the mortality function, which is the main uncertainty. The results of Pedersen (1998) indicate that tree mortality is usually a decades-long process involving a combination of environmental stresses. However, the work of Bolte et al. (2016) showed that there is very low survival probability if the soil water availability falls below values of 20% and approaches zero. This is the case if the critical limits of soil water potential are exceeded (Czajkowski et al., 2009).

4.2.5. Site index and forest growth model

The main purpose of the modeling system is to provide decision support for forest planning. Thus, the use of a statistical approach to project the site index under climate change is considered appropriate. For instance, Pretzsch (1996) argued in favor of statistical models as the best method to provide forest management information because these model formulations primarily project stand or tree development on a scale appropriate for practical decision support. However, many researchers view process-based models as best suited to analyze the effects of climate change on forest growth as they strive to understand the ecophysiological functionality of forests (e.g., Landsberg, 2003; van Oijen et al., 2008a).

The presented site index model incorporates main effects of climate parameters, nitrogen deposition and soil properties, in accordance with results from van Oijen et al. (2008b), who analyzed past growth trends applying four process-based models. However, interaction must be considered, e.g., between nitrogen deposition and soil nutrients (cf. Egli et al., 1998). Although highly significant, including the interaction term of nitrogen and nutrients did not improve the model's coefficient of determination considerably.

Furthermore, variable selection must be critically evaluated because major predictors of forest growth might be missing, e.g., level of CO_2 (e.g., Handa et al., 2006; Körner et al., 2005). We also observed a highly significant linear effect of the mean atmospheric CO_2 concentration on site index, and even an interaction term with soil nutrients was highly significant. Unfortunately, site index projections under elevated CO_2 concentrations yielded unrealistic high values. Thus, extrapolation of the linear trend is not permitted. The problem of projections outside the range of the parameterization data is generally discussed by Mendoza and Vanclay (2008). A comprehensive evaluation of the site index model is given in Albert and Schmidt (2010).

In addition to evaluating the site index model itself, it is important to examine the impact of projected site index values as an input parameter in the forest growth model. The site index plays a major role as an independent variable in the tree height growth function. The sensitivity of the growth model to the site index is clearly visible when comparing the values in Table 1 within an age class. While height growth is modeled in a site-sensitive manner, diameter growth is indirectly influenced because the predictor variable crown surface area is a function of crown length, which in turn is a function of tree height. However, the overall satisfying performance of the growth model has been proven in other simulation studies (cf. Albert et al., 2016, 2015).

4.2.6. Wind damage model

The present study uses the 3D SCADIS model to evaluate wind load on trees in heterogeneous forest stands. Its implementation is substantiated and described in detail in Panferov and Sogachev (2008). It could be argued that a three-dimensional approach with a high spatial and temporal resolution is rather time-consuming and considerably slows the system. However, realistic wind load estimations for heterogeneous landscapes can only be obtained using a 3D approach. The model can be switched to 1D if the stand and topographical conditions can be reasonably approximated as horizontally homogeneous. The implemented estimation methods for critical wind speeds are well known and validated (Panferov et al., 2009). It is arguable whether empirical parameters obtained elsewhere, e.g., in Great Britain, are applicable to German forests. In the present study, we used the best available data. The modular structure of the system allows easy replacement of any parameter once better (i.e., stand specific) values are available. The novelty of the employed approach is the combination of empirical functions for critical levels with detailed information about wind load on trees, as well as interactions with other risk factors.

4.2.7. Bark beetle damage model

The employed bark beetle damage model consists of two parts: a phenological model predicting number of beetle generation per year based on temperature sums and a damage model based on the output of the first part and predisposition caused by stand structure and soil moisture. Both model parts incorporate climatic conditions and are thus able to respond to a changing climate.

For the simulation of the phenology of bark beetle populations, we selected the PHENIPS model developed by Baier et al. (2007). It is based on the well-known relationship between temperature and activity as well as reproduction of *Ips typographus* (Jönsson et al., 2007; Wermelinger and Seifert, 1999). The model predicts the number of complete insect generations per year and is thus well-suited for the estimation of bark beetle outbreaks. A recent study by Berec et al. (2013) validating the PHENIPS model with measurement data confirmed this utility for a region outside of the area for which the model was developed.

The second part consists of a predisposition model and a damage probability model. We used the models developed by Seidl et al. (2007), which are based on the work of Netherer and Nopp-Mayr (2005). The approach is based on the number of generations, stand characteristics and the soil moisture index as a drought stress indicator. Therefore, this approach was well-suited for our purpose. However, the approach could be improved by incorporating further predisposing factors, such as windthrow and snow breakage, that are currently not considered. Another potentially confounding variable is silvicultural activity, which pools factors such as active measures to reduce infestation risk and the intensity of thinning and harvesting operations to attain forest hygiene. Overbeck and Schmidt (2012) quantified the effect of silvicultural activity based on the random effects on the forest sub-district level in their mixed model approach on infestation risk. Furthermore, conditions

in neighboring stands are not included in our model. Moreover, a main challenge remaining in modeling bark beetle damage to managed forests is the availability and quality of measurement data for model development and validation. Recorded data is often not available to the public due to business secrets.

4.2.8. Economic model

The mean annual contribution margin of timber production under risk within a given period is determined using a survival function based on an approach presented in detail by Staupendahl and Möhring (2011). The survival function gives the probability that a given stand reaches or even exceeds a specific age. Because the prediction of the time of occurrence of calamities, which are assumed to completely destroy the stand, is associated with high uncertainties, the survival function is a simple linear function starting with 1 at the beginning of the respective period and ending with the probability that the indicator stand survives the period. Thus, the conditional drop-out probability is constant within the period.

This approach enables the determination of the discrete frequency distribution of the stand's survival time and thus of the distribution of the periodic annual contribution margin and its expected value. These properties obviate Monte Carlo simulations. The Monte Carlo approach, which has been used by many other authors (e.g., Brumelle et al., 1990; Dieter, 2001; Kuboyama and Oka, 2000), requires more complex software, large numbers of iterations, long extrapolation periods, and, consequently, more time to answer the user's request.

However, the level of abstraction in the economic model and, consequently, the deviation from reality cannot be ignored. Calamities regularly create small gaps that will reduce the density of stands. The alterations in the growth of the remaining stand due to the reduced stand density are not accounted for. Furthermore, interdependencies between risk and stand treatment are not considered, although the timing, type, and intensity of thinnings drastically influence the risk disposition of stands (e.g., Dobbertin, 2002; König, 1995). Finally, other sources of risk, e.g., the risk of timber price fluctuation, were ignored, thus permitting, however, the identification and analysis of the pure effects of natural hazards.

4.3. Assessment of climate change impact

4.3.1. Ecological impact

The simulation of the growth potential (site index) showed that, in total, a remarkable improvement of tree growth can be expected for spruce in the study area under climate scenarios B1 and A1B, mainly due to the increasing temperature sums in the vegetation period. The elevation-dependent growth differences diminish in the projection periods because stands on higher elevations benefit disproportionally from the temperature increase, which is especially pronounced under climate scenario A1B. The spatial pattern of the site index in Fig. 5 indicates the effect of the temperature rise and extended vegetation periods, which overcompensates the effect of the decreasing water balance, resulting in the increase in the growth potential of the stands over time. These results are difficult to compare to those of other regional studies because the response of growth appears to differ greatly depending on species and region (e.g., Albert et al., 2015; Lasch-Born et al., 2015 Lasch-Born et al., 2015). Drought seems to be a particularly limiting factor for other regions. However, Lasch-Born et al. (2015) indicated that an increase in the site index is plausible in the study region, in good accordance with observations by Pretzsch et al. (2014).

Thus far, one could assume better growing conditions in the study area in the future under the applied climate projections. However, our damage risk assessment dampened expectations. We found a strong increase in the probability of drought stress-induced tree mortality in the period 2071–2100 for scenario B1 and in period 2041–2071 for scenario A1B. This increase in risk is mainly driven by several single extreme events. However, projecting the exact time and strength of extreme events is impossible; therefore, these findings are interpreted as probabilities. Furthermore, trees dying due to water shortage is currently a very rare phenomenon in the study area and in Central Europe in general (Allen et al., 2010). Therefore, models predicting the risk of tree mortality caused by drought stress contain large uncertainties. Studies compiled by Adams et al. (2009) suggest, however, that tree mortality risk will increase due to the projected future warming and drought, even in regions that are not considered water limited.

However, the main and more important effect of dryer soil conditions is the higher risk of bark beetle outbreaks. The detection of trends of those extreme events is one of the main advantages of the direct model approach. For the bark beetle infestation risk, we observed a more general trend of increase over the years, reflecting the temperature increase and changes in the seasonal distribution of precipitation. We observed a higher vulnerability, especially in the lower northern part of the study area, which has higher temperatures than the hilly southern parts. The general pattern of infestation risk increasing under climate change is in good accordance with studies by Overbeck and Schmidt (2012) of the Harz region in Central Germany and Seidl et al. (2007) of Austria.

The risk of wind damage also increases over time. Furthermore, the risk distribution between the age classes changes. The first two periods are characterized by higher risks in younger tree stands, possibly due to the lower wind level threshold for tree damage, which could be eventually attributed to smaller rooting depths and higher levels of soil moisture, which weaken the anchorage of younger trees more. Thus, younger trees might be damaged even by weaker (slower) winds. The results are in agreement with those of a study by Panferov et al. (2009) of Norway spruce and Scots pine. In the projection periods, the values of the critical wind speed (wind that damages the tree) become similar for the young and old age classes. However, older trees, which are taller, experience higher wind speeds (wind speed increases with height), and this, under the same threshold values, might be responsible for the higher damage risk probability for older compared with younger trees. The increased probability of wind damage for all age classes in the projected periods is a direct response to the increased probability of stormy days as well as the increased temperature projected by the climate scenarios. This effect might be strengthened by changes in stand structures due to improved and differentiated growth and, consequently, intensified harvesting driven by reaching the target diameter earlier. In turn, this results in larger inter-tree distances, which is an important input for determining critical wind speeds (Panferov et al., 2009). This change increases the wind damage risk. The general trend of increased wind damage risk is in good accordance with studies of other regions by Leckebusch et al., 2007; Blennow et al. (2010); Albert et al. (2015). Furthermore, our findings correspond with the results for projected wind damage predisposition in the study area by Klaus et al. (2011). The near tripling of the drop-out probability in both climate scenarios seems to be plausible because Schelhaas et al. (2010) presented a tripling of exposure under a climate change projection for the year 2100 for Denmark as well. Moreover, Schelhaas et al. (2003) identified wind as the most important disturbance agent in the past. Our simulation results show that wind could also be the strongest disturbance agent in the future.

4.3.2. Economic impact

Integrating the different risks into a joint economic assessment revealed a strong increase in risk costs, reflecting increases in the three modeled individual risks. Whereas the strongest increase was observed in the last period in scenario B1, driven by a sharp increase in the drop-out probabilities of wind and drought, risk costs already

increase strongly in the second projection period for scenario A1B. These results substantiate a profound change in production conditions.

Although a strong increase in risk costs was projected, we found an increase in the mean annual contribution margin under consideration of risk costs to the end of the century for the first two age classes and a slight decrease for the age class 90–120 years. The higher productivity (site index) compensates for the higher risks under climate change at several sites. Therefore, earlier harvesting, even due to hazards, produces an increased economic return. However, macroeconomic effects in case of large-scale hazards are not covered by the economic submodel. Market prices may change after hazards, and timber prices and costs may no longer be constant. Moreover, since stand survival is calculated solely by combining the conditional survival probabilities of drought, wind, and biotic risks, the assessment neglects some feedback effects. Without any potentially intensifying feedback effects, e.g., bark beetle attack after windthrow, the simulated risks are a conservative estimate. Damage is interpreted as area loss and is not realized in the model stands. Reducing the number of trees due to risks would result in lower tree density and more deadwood and, in turn, could further increase the vulnerability of the stands to biotic and abiotic risks (cf. Hanewinkel et al., 2008). For example, opening up of the stand by bark beetle damage can increase the vulnerability to wind damage. In turn, foresters can actively reduce these risks by appropriate management and planning.

4.3.3. *Consequences for forest management*

From a forest management perspective, the simulation results indicate that under the applied climate scenarios, Norway spruce should not be established in areas with low available soil water capacities. To reduce the wind damage risk, the stability of the stands should be increased through appropriate measures. For instance, an early increase in the height-diameter relation by reducing the number of stems per hectare and avoiding intensive thinning in later phases can increase stability. Furthermore, it is advisable to shorten the rotation period since the risk costs increase with the stand age and might counterbalance the positive effects of growth improvements for old stands. Because the site index simulation projected accelerated growth in the future, target diameters will likely be reached earlier (cf. Table 2). Last but not least, careful pest control and forest management have a very high influence on the damage risk due to bark beetle infestation.

5. Conclusion

The complex dynamic simulation model system is a promising approach to assess the impact of climate change to Norway spruce and forests in general based on high-resolution climate data. The “indicator stand” concept permits a comparison of the effects of climate change at different stand ages. We have shown that the application of the modeling system to the “Arnsberg Wald” produces plausible results and enables forest managers to plan site-specific adaptation and risk avoidance strategies. This study employs only one realization of two climate scenarios and is thus limited in its prediction of damage impacts. If more climate scenarios, realizations, and models are available to the user, the model system can easily be used to process comprehensive ensembles.

We believe that dynamic modeling approaches are most appropriate to assess climate change impacts if these changes are characterized by extreme events, shifts in temporal distributions and non-monotonous trends.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2016.11.013.

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Auswirkungen von klimatischer Unsicherheit auf die Forstplanung am Beispiel von vier Regionen im norddeutschen Tiefland[1)]

Aus der Nordwestdeutschen Forstlichen Versuchsanstalt, Göttingen

(Mit 7 Abbildungen und 8 Tabellen)

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SCHLAGWÖRTER – KEY WORDS

Waldwachstum; Forstplanung; Wirkungsanalyse; Trockenstress; Vulnerabilität; Klimawandel; Unsicherheit.

Forest growth; forest management; impact study; drought; vulnerability; climate change; uncertainty.

1. EINLEITUNG

Der beobachtete Klimawandel und die atmosphärischen Stoffeinträge der letzten Jahrzehnte bewirken eine rasante Veränderung der forstlichen Standorte, dass eine Konstanz der Standort-Leistungsbeziehung während eines Bestandeslebens nicht gegeben ist und als Konsequenz neuartige Wachstumstrends resultieren (Spiecker et al., 1996; Hasenauer et al., 1999; Boisvenue und Running, 2006; Pretzsch et al., 2014; Kohnle et al., 2014). Neben positiven Effekten durch den Temperaturanstieg und entsprechend längeren Vegetationsperioden (Albert und Schmidt, 2010; Nothdurft et al., 2012; Pretzsch et al., 2014) oder die konträr wirkende zunehmende Trockenheit (Hanson und Weltzin, 2000; Zang et al., 2011a) sind in diesem Zusammenhang höhere Stickstoffeinträge (Egli et al., 1998; Laubhann et al., 2009), eine Verringerung der Schwefeleinträge (Hauck et al., 2012; Kolár et al., 2015) und eine erhöhte CO_2-Konzentration (Körner et al., 2005; Pretzsch et al., 2014) zu nennen.

Die Umweltveränderungen führen des Weiteren zu einer veränderten Risikostruktur in der Forstwirtschaft. Eine Zunahme abiotischer und biotischer Gefahren sowie neu auftretende Risiken sind zu erwarten (Lindner et al., 2010; Seidl et al., 2011; Overbeck et al., 2012; Overbeck und Schmidt, 2012). Millar et al. (2007) und Bolte et al. (2009) weisen in diesem Zusammenhang darauf hin, dass Anpassungsstrategien kein schablonenhaftes Vorgehen sein dürfen, sondern adaptiv lokale Besonderheiten und neue Erkenntnisse einbeziehen müssen.

Obwohl sich die Veränderungen auf das Waldwachstum und die Risikostrukturen schon in den letzten Jahren und Jahrzehnten beobachten und nachweisen lassen, bestehen nach wie vor noch erhebliche Unsicherheiten und Wissenslücken, die es schwierig machen, die Forstplanung und Waldbesitzer zu beraten (Spellmann et al., 2011; Lindner et al., 2014).

Eine Quelle der Unsicherheit ist die zu erwartende Klimaentwicklung, die je nach unterstelltem Emissionsszenario, verwendetem globalen Klimamodell und Regionalisierungsansatz zu einer erheblichen Variabilität in den Klimaprojektionen und folglich auch zu einer breiten Streuung in den Auswirkungen auf Waldökosysteme führen kann (Jones, 2000). Borchers (2005) schlägt daher vor, im Entscheidungsprozess durch Offenlegung und Einbeziehung von Unsicherheitsfaktoren die Streuung der erwarteten Auswirkungen z. B. auf die Waldproduktivität zu quantifizieren, anstatt vermeintliche Genauigkeit in Simulationsergebnissen vorzutäuschen. Jones (2000) führt dazu weiter aus, dass die Verwendung mehrerer Szenarien, z. B. im Ensemble-Ansatz der Klimaforschung (Knutti, 2010), die Abschätzung eines Unsicherheitsbereiches in den Projektionen ermöglicht. Das gesamte Ausmaß der Unsicherheit ist dennoch unbekannt.

Das übergeordnete Ziel der nachfolgend vorgestellten Untersuchung ist es, die Auswirkung verschiedener Klimaprojektionen auf ertragskundliche Kenngrößen und die Konsequenzen für Forstplanungsentscheidungen am Beispiel von vier Regionen im norddeutschen Tiefland aufzuzeigen. Die klimatische Unsicherheit wird in dieser Studie durch die Verwendung von Klimaprojektionen dreier Globalmodelle, INM-CM4, ECHAM6 und ACCESS1.0 quantifiziert, die alle mit dem Emissionsszenario RCP 8.5 angetrieben wurden (IPCC, 2013). Es soll des Weiteren die Frage beantwortet werden, ob die klimatische Unsicherheit ein relevanter Faktor für die Forstplanung ist oder ob andere Effekte diese überlagern, z. B. unterschiedliche waldbauliche Konzepte. Dafür wird in dieser Untersuchung der waldbauliche Handlungsraum anhand von drei Entwicklungspfaden charakterisiert: *Referenz*, *Klimaschutz* und *Biodiversität* (vgl. Abschnitt 2.6). Im Einzelnen werden die Reaktionen der Wälder in vier Regionen auf die Effekte des Klimawandels und der unterschiedlichen Bewirtschaftungskonzepte untersucht. Die Waldentwicklung wird dabei ohne Rückkopplung mit möglichen Risikofaktoren simuliert. Die Ergebnisinterpretation ist jedoch nur unter Berücksichtigung einer nachträglichen Risikobewertung vollständig. Als Risikofaktoren für die hier

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untersuchten Waldbestände gelten u. a. Trockenstress, Windwurf, Waldbrand, Kieferngroßschädlinge, Kiefernprachtkäfer, Buchdrucker und Wurzelschwamm. Auf dieser Basis können dann auch Anpassungsstrategien an den Klimawandel abgeleitet werden.

Folgende drei Ziele werden mit dieser Wirkungsanalyse verfolgt: (1) die Spannbreite der ertragskundlichen Kenngrößen Vorrat, Nutzungsmasse und Zuwachs und der forstplanerischen Größe Nachhaltshiebsatz wird unter drei Klimaprojektionen quantifiziert, (2) die so ermittelte klimatische Unsicherheit wird mit dem Einfluss der drei waldbaulichen Entwicklungspfade verglichen und (3) die Auswirkungen von Klimaprojektionen und waldbaulicher Behandlung auf Risikofaktoren wird am Beispiel der Trockenstressvulnerabilität untersucht.

2. MATERIAL UND METHODEN

2.1 Untersuchungsgebiete

Das norddeutsche Tiefland ist geologisch hauptsächlich durch die Saale- und Weichselvereisung geprägt, die zu räumlich stark differenzierten Standortsverhältnissen geführt hat. Die Untersuchungen finden in den vier Regionen Diepholz, Uelzen, Fläming und Oder-Spree im Altpleistozän (Saale-Kaltzeit) des norddeutschen Tieflandes statt (*Tab. 1*). Die dort herrschende Standortsvielfalt sowie ein bereits heute bestehender ausgeprägter Klimagradient mit von West nach Ost abnehmenden Niederschlägen und zunehmender Kontinentalität ermöglichen eine fundierte Untersuchung der Effekte von Standort und Klima auf die Waldentwicklung.

Die absolute Waldfläche, der Waldanteil und die mittlere Bestandesgröße nehmen in den vier Regionen von West nach Ost zu. Die klimatische Wasserbilanz der Sommermonate (meteorologischer Sommer: 1. Juni bis 31. August) zeigt die erhöhte Sommertrockenheit in den beiden östlichen Gebieten an.

2.2 Modellsystem *WaldPlaner*

Die Projektion der Waldentwicklung wird im Modellsystem *WaldPlaner* (HANSEN und NAGEL, 2014) simuliert, dessen Einzelbaumwachstumsmodell durch die Kopplung an das longitudinale Durchmesser-Höhen-Modell (Schmidt, 2010) sensitiv auf verschiedene standörtliche und klimatische Parameter reagiert (vgl. *Abb. 1*).

Der *WaldPlaner* wird mit ertragskundlichen, standörtlichen und klimatischen Eingangsgrößen initialisiert. Die waldbauliche Entwicklung sowie naturschutzfachliche Vorgaben werden durch interne Parameter definiert (vgl. Kap. 2.6). Die Projektion der Waldentwicklung läuft in 5-Jahresschritten.

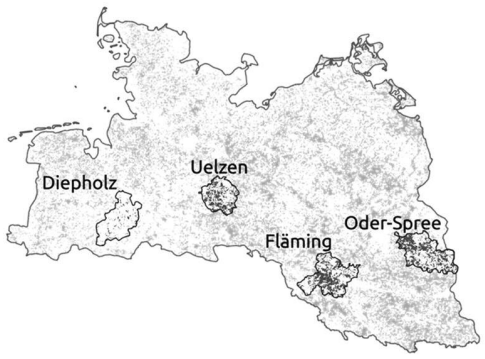
2.3 Ertragskundliche Datenbasis

Auf der Grundlage von Bestandesdaten aktueller Forsteinrichtungen wurde für jede Region ein repräsentativer Modellbetrieb erstellt. Auf der Basis eines regelmäßigen Gitternetzes wurde je Region von allen Bestandespolygonen mit verfügbaren vollständigen Forsteinrichtungsdatensätzen besitzartenübergreifend eine Stichprobe ($n \approx 1000$) gezogen. Der ertragskundliche Datensatz war jedoch auf Grund von unvollständigen oder für Teilflächen gänzlich fehlenden Forsteinrichtungen nicht flächendeckend verfügbar, so dass die Stichprobenpunkte nicht flächenrepräsentativ sind. Die Stichprobe erlaubt daher eine Abschätzung der Verteilungen der wichtigsten standörtlichen Größen und Bestandesparameter für die Gesamtregionen nur unter der Annahme, dass die Datenverfügbarkeit nicht mit den Ausprägungen dieser Parameter korreliert ist, z. B. dass Jungbestände nicht systematisch auf Grund ihres Alters im verfügbaren Datensatz unterrepräsentiert sind. Die Hochrechnung für die Gesamtregion aus der Stichprobe erfolgte mit Hilfe von stratenspezifischen Gewichtungsfaktoren. Hierzu wurde die Gesamtwald-

Tab. 1

Untersuchungsgebiete und charakteristische Kennzahlen (die Klimadaten sind Mittelwerte der jeweiligen Region und des Zeitraums 1991 bis 2010, Landbedeckungsdaten in der Übersichtskarte © ESA / ESA GlobCorine Projekt, unter Leitung der Université Catholique de Louvain).

Study areas and characteristic key figures (climate data are mean values of the respective region and the period 1991 to 2010, land cover data in the overview map © ESA / ESA GlobCorine Project, led by Université Catholique de Louvain).



	Diepholz	*Uelzen*	*Fläming*	*Oder-Spree*
Waldfläche [ha]	15.042	45.712	51.368	76.714
Waldanteil [%]	6,7	34,7	41,5	48,7
Mittl. Bestandesgröße [ha]	1,05	1,51	2,98	2,93
Jahresmitteltemperatur [°C]	9,8	9,2	9,8	9,6
Jahresniederschlag [mm]	706	727	572	585
Klimat. Wasserbilanz [mm]	-90,5	-82,0	-157,8	-147,2

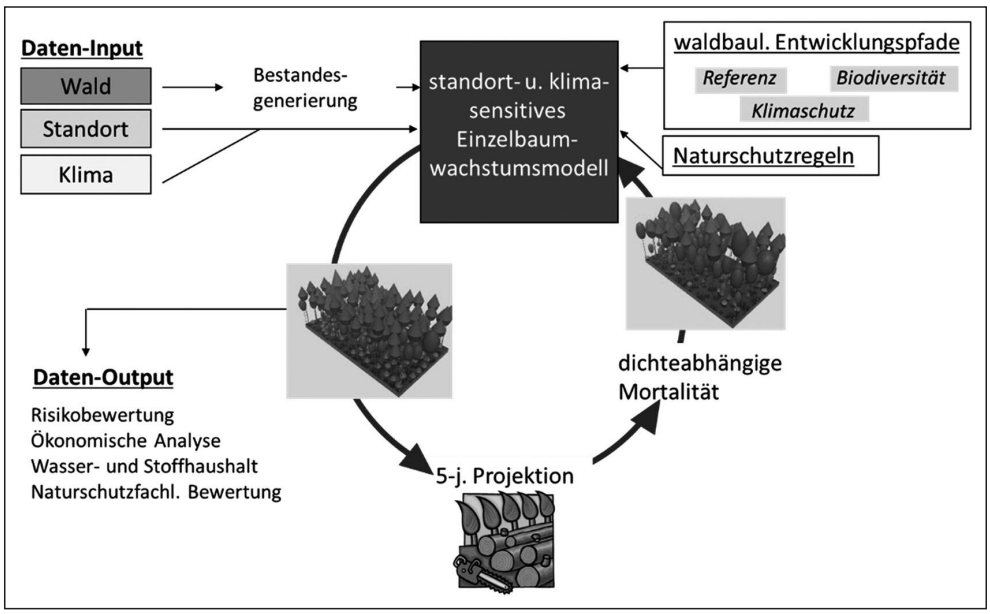


Abb. 1
Schema des Modellsystems *WaldPlaner* zur Projektion der Waldentwicklung.
Scheme of the *WaldPlaner* model system to project forest development.

fläche nach Bestandestyp und Altersklasse stratifiziert. Für die Stichprobenpunkte wurden die Gewichtungsfaktoren (g_{ij}) je Modellregion wie folgt ermittelt:

$$g_{ij} = F_{ij} / f_{ij} \quad [1]$$

mit F_{ij}: nach Bestandestyp j und Altersklasse i stratifizierter Flächenanteil der Grundgesamtheit aller Bestände in einer Region, für die die Minimalinformationen Baumart und Alter zur Verfügung stehen,
f_{ij}: nach Bestandestyp j und Altersklasse i stratifizierter Flächenanteil der Stichprobe (Anzahl n).

Jeder Modellbestand ij repräsentiert demnach einen Flächenanteil von g_{ij}/n der Gesamtwaldfläche der Region.

Die Rohdaten, d. h. die Forsteinrichtungsinformationen an jedem Stichprobenpunkt (im Einzelnen sind dies je vorkommender Baumart und Bestandesschicht: Alter, Durchmesser des Grundflächenmittelstammes, Höhe des Grundflächenmittelstammes, Bonität, Flächenanteil, Bestockungsgrad und Volumen pro Hektar), wurden für 874 Stichprobenpunkte in Diepholz, 999 in Uelzen, 1008 im Fläming und 1002 in Oder-Spree in den *WaldPlaner* eingelesen. Der implementierte Bestandesgenerator erzeugte für jeden Stichprobenpunkt einen 0,2 ha großen Modellbestand mit Einzelbäumen. Da die ursprünglichen Forsteinrichtungsinformationen aus unterschiedlichen Erhebungsjahren stammten, wurden alle Modellbestände im *WaldPlaner* zunächst auf das einheitliche Startjahr 2010 fortgeschrieben.

2.4 Standörtliche Eingangsgrößen

Das longitudinale Durchmesser-Höhen-Modell (SCHMIDT, 2010) benötigt als standörtliche Eingangsvariablen Angaben zur nutzbaren Feldkapazität (nFK), zum Grundwassereinfluss in der Vegetationszeit (GW_{veg}) und zum Nährstoffstatus des Bodens. Um in allen vier Regionen auf eine homogene Datengrundlage zurückgreifen zu können, wurde die nutzungsdifferenzierte Bodenübersichtskarte der Bundesrepublik Deutschland im Maßstab 1:1.000.000 (Wald-BÜK; RICHTER et al., 2007) verwendet. Die für die Wald-BÜK hinterlegten Bodenprofile sind jedoch nur für die im CORINE-Landcover ausgewiesenen Waldflächen verortet. Somit ist für einige Stichprobenpunkte kein Waldboden ausgewiesen. Für diese Stichprobenpunkte wurde eine Kartiereinheit in Abhängigkeit von der Klimagroßregion und dem Ausgangsmaterial (Bodeneinheit) unter der Annahme forstlicher Nutzung zugewiesen. Für die hinterlegten Leitprofile wurde die nFK nach der Berechnungsvorschrift von OVERBECK et al. (2011) ermittelt. Zur Herleitung des mittleren GW_{veg} wurde zunächst der langjährige mittlere Grundwasserflurabstand (MGW) aus der Differenz der Grundwasseroberfläche (in m ü. NN) aus hydrogeologischen Übersichtskarten der Länder Niedersachsen, Sachsen-Anhalt und Brandenburg in verschiedenen Maßstäben (1:25.000 bis 1:300.000) und der Geländeoberfläche (DGM25) ermittelt. Aus dem MGW wurde anschließend der mittlere Grundwassertiefstand (MNGW) abgeschätzt (vgl. AG BODEN, 2005, Tab. 59). Hierbei wird angenommen, dass der ermittelte MNGW im langjährigen Mittel, meist zwischen Juli und Oktober, den GW_{veg} beschreibt.

Der Nährstoffstatus von Waldböden kann mit Hilfe verschiedener Standortsparameter charakterisiert werden (Ulrich und SHRIVASTAVA, 1978; JANSEN et al., 2002; ARBEITSKREIS STANDORTSKARTIERUNG, 2003; KOPP, 2004;

AHRENDS et al., 2008). Im Rahmen dieser Arbeit wurde die Nährstoffstoffversorgung an den Leitprofilen der Wald-BÜK mit der folgenden Schätzfunktion ($r^2 = 0{,}76$) abgeleitet:

$$NZ = -0{,}1285 + 1{,}2364 * \ln\text{Ake} + 0{,}4381 * \ln\text{BS} + 0{,}9928 * \ln\text{T} + 0{,}5616 * \ln\text{U} \quad [2]$$

mit:

NZ: numerischer Schlüssel der Nährstoffziffer
Ake: effektive Kationenaustauschkapazität [mmolc/kg]
BS: Basensättigung [%]
T: Tongehalt [%]
U: Schluffgehalt [%]

Die Schätzfunktion wurde anhand von Bodenprofilen der bundesweiten Bodenzustandserhebung im Wald (BZE I; BARTENS und BÜTTNER, 1997) und weiterer Bodenprofile von STÜBER et al. (1999) parametrisiert. Die numerischen Nährstoffziffern wurden bei der Parametrisierung des longitudinalen Durchmesser-Höhen-Modells in fünf Nährstoffklassen zusammengefasst.

In *Tabelle 2* sind die Anteile der Kategorien der Nährstoffversorgung und des GW_{veg} an den Standorten sowie die Mittelwerte der nFK der Modellbestände in den vier Regionen wiedergegeben. Für die Projektion der Waldentwicklung wurde unterstellt, dass die Bodengrößen im Simulationszeitraum konstant bleiben.

2.5 Klimatische Eingangsgrößen

Die für eine standortsensitive Waldentwicklungsprojektion notwendigen Klimagrößen werden basierend auf dem Emissionsszenario RCP 8.5 (MOSS et al., 2010; VAN VUUREN et al., 2011) mittels der Globalmodelle INM-CM4 (VOLODIN et al., 2010), ECHAM6 (STEVENS et al., 2013) und ACCESS1.0 (BI et al., 2013) berechnet. Die drei mit dem regionalen Klimamodell STARS (ORLOWSKY et al., 2008) für Deutschland regionalisierten Klimaprojektionen zeichnen sich bezüglich der Temperaturentwicklung dadurch aus, dass die auf INM-CM4 basierende Projektion im Jahr 2070 die geringste Jahresmitteltemperatur und die auf ACCESS1.0 basierende die höchste Jahresmitteltemperatur aufweist. Die ECHAM6-Projektion liegt 2070 zwischen den beiden anderen Temperaturwerten. Somit ergibt sich für das norddeutsche Tiefland, gemittelt über die vier Regionen, ein Minimum-, Median- und Maximumszenario der Klimaprojektion mit Abweichungen von 1.1°C, 1,6°C und 2,7°C für den Zeitraum 2051–2070 bezogen auf die heutige Jahresmitteltemperatur (1991–2010). Es besteht dabei allerdings ein Gradient mit zunehmenden Temperaturen von West nach Ost.

Des Weiteren standen vom *Potsdam Institut für Klimafolgenforschung* homogenisierte Klimadaten des *Deutschen Wetterdienstes* (DWD) in täglicher Auflösung für die Periode 1951 bis 2010 an den DWD-Klimastationen zur Verfügung. Für eine konsistente Zeitreihe wurde mit STARS auf dieser Basis eine retrospektive Projektion für die Periode 1951 bis 2010 simuliert und entsprechend prospektiv die Klimagrößen unter Verwendung der beschriebenen Szenarien Minimum, Median und Maximum von 2011 bis 2070 berechnet.

Das longitudinale Durchmesser-Höhen-Modell (SCHMIDT, 2010) verwendet als klimatische Prädiktoren die Temperatursumme in der artspezifischen Vegetationszeit und den Ariditätsindex. Der Beginn der Vegeta-

Tab. 2

Kennwerte der bodenkundlichen Modellparameter (NK: Nährstoffklasse 1 = arm, 2 = schwach versorgt, 3 = mäßig versorgt, 4 = ziemlich gut versorgt, 5 = gut versorgt; GW_{veg}-Stufen: 0 = kein Grundwasseranschluss (MNGW > 2,5 m), 1 = schwacher Grundwassereinfluss (MNGW 0,95–0,25 m), 2 = mäßiger bis starker Grundwassereinfluss (< 0,95 m); nFK: nutzbare Feldkapazität).

Characteristics of soil parameters (NK: nutrient class 1 = very poor, 2 = poor, 3 = medium, 4 = good, 5 = rich; ground water classes in the growing season GW_{veg}: 0 = no ground water (MNGW > 2,5 m), 1 = weak ground water influence (MNGW 0,95–0,25 m), 2 = medium to strong ground water influence (< 0,95 m); nFK: available soil moisture).

	NK	Diepholz	Uelzen	Fläming	Oder-Spree
Anteil[%]	*1*	-	-	-	-
	2	6	-	25	49
	3	47	75	49	21
	4	24	7	23	29
	5	23	18	1	1
	GW_{veg}	Diepholz	Uelzen	Fläming	Oder-Spree
Anteil[%]	*0*	60	92	91	80
	1	17	5	7	15
	2	23	4	2	5
nFK [mm]		196	110	123	116

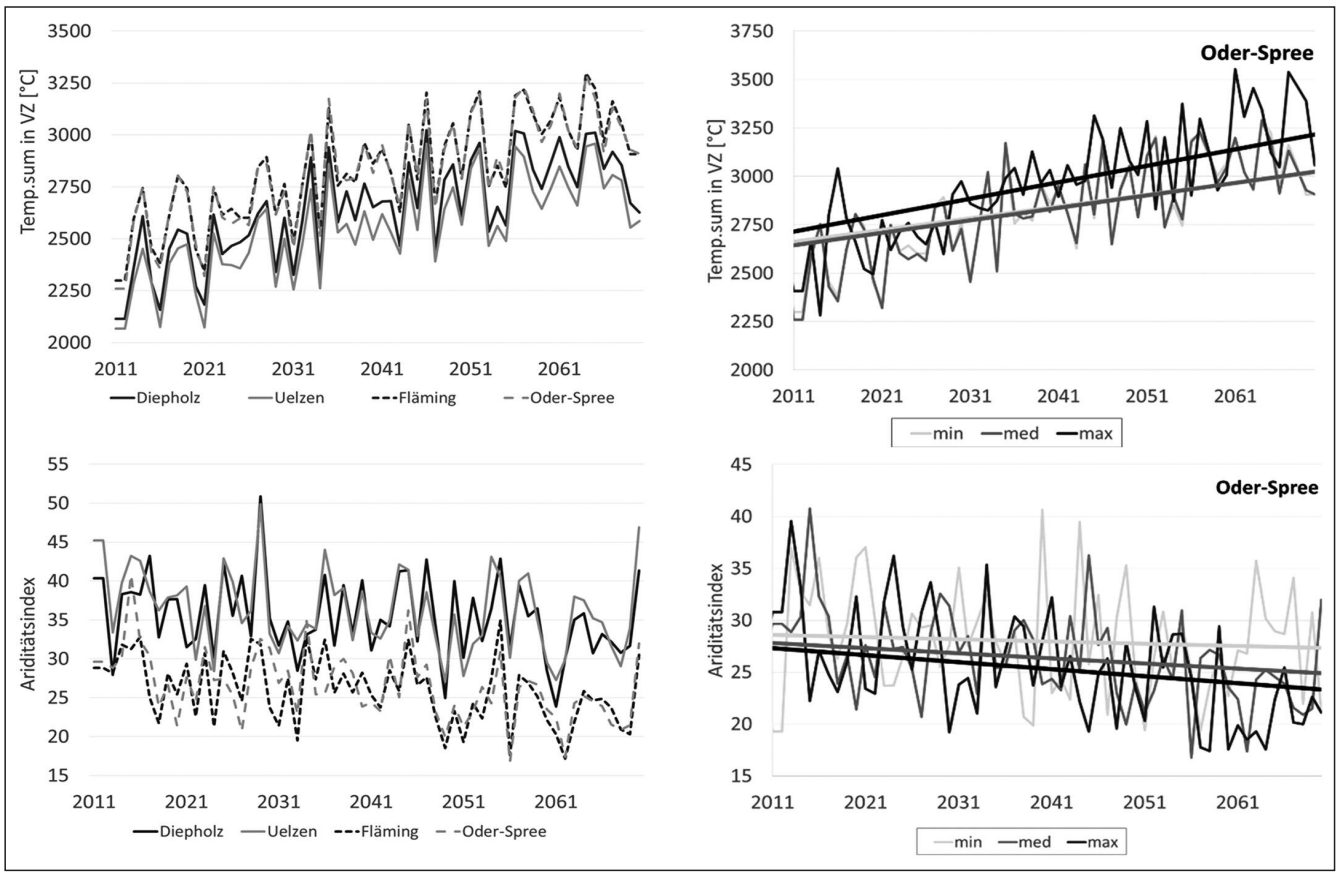


Abb. 2

Verlauf der Jahresmittel/-summen der Klimaparameter für die Projektionsperiode 2011 bis 2070 (oben links: Verlauf der Temperatursumme in der Vegetationsperiode (alle Baumarten und Stichprobenpunkte gemittelt) mit dem Median-Klimalauf als Antrieb für die vier Regionen Diepholz, Uelzen, Fläming und Oder-Spree; unten links: entsprechende Darstellung für den Ariditätsindex; oben rechts: Verlauf der Temperatursumme mit dem Minimum-, Median- und Maximum-Klimalauf als Antrieb für die Region Oder-Spree; unten rechts: entsprechende Darstellung für den Ariditätsindex).

Development of the climate parameters' annual means or annual sums for the projection period 2011 to 2070 (above left: development of temperature sum in the growing season (mean for all tree species and all inventory points) using the median climate run for the four regions Diepholz, Uelzen, Fläming and Oder-Spree; below left: corresponding figure for the aridity index; above right: development of temperature sum in Oder-Spree using minimum, median and maximum climate run; below right: corresponding figure for the aridity index).

tionszeit wird dabei nach dem Modell LNVAR von MENZEL (1997, S. 52 ff) und das Ende der Vegetationszeit wird nach Vorschlägen von WALTHER und LINDERHOLM (2006) sowie FRICH et al. (2002) berechnet. Das Ende der Vegetationszeit wird somit entweder durch das Temperaturkriterium oder das Kurztagskriterium festgelegt. Das Temperaturkriterium wird erfüllt, wenn das gleitende Temperaturmittel einer 7-Tagesperiode einen Schwellenwert von 5°C im Zeitraum Juli bis Oktober unterschreitet. Das Kurztagskriterium, definiert als die Tageslänge, welche zur Einstellung des Xylemwachstums führt, wird von v. WILPERT (1990) auf den 5. Oktober festgelegt. Der Ariditätsindex nach DE MARTONNE (1926) ist definiert als Quotient aus Jahresniederschlagssumme [mm] und Jahresmitteltemperatur [°C] +10. Mit Hilfe des Wasserhaushaltsmodells WaSiM-ETH (SCHULLA, 2015; SCHULLA und JASPER, 2007) wurden für jeden Stichprobenpunkt die benötigten Klimagrößen bereit gestellt, in dem die mit STARS projizierten Werte aller DWD-Stationen im Umkreis von 20 km um den Stichprobenpunkt mit einem entfernungsgewichteten Regressionsmodell interpoliert wurden.

Die Verläufe der Temperatursumme in der Vegetationszeit mit dem Median-Klimalauf als Antrieb in *Abbildung 2* (oben links) illustrieren einen zunehmenden Trend über der Zeit für alle Regionen, wobei die jährlichen Schwankungen die Zunahme der Temperatursumme zwischen 2011 und 2070 teilweise deutlich übersteigen. Eine räumliche Staffelung ist ebenfalls ersichtlich mit den geringsten Werten in Diepholz, etwas höheren Werten in Uelzen sowie den höchsten Temperatursummen mit fast identischem Verlauf in Fläming und Oder-Spree. Der Vergleich der Temperatursummen unter den drei Klimaläufen Minimum, Median und Maximum, dargestellt am Beispiel der Region Oder-Spree (*Abb. 2*, oben rechts), zeigt größere zeitliche Schwankungen innerhalb eines Verlaufs als zwischen den Varianten. Die linearen Trendgeraden des Minimum- und Medianlaufes verlaufen sogar fast deckungsgleich. Erwähnenswert ist die Tatsache, dass sich die

Temperatursummenkurven mehrfach schneiden, der Verlauf der Maximumvariante erst gegen Ende der Projektionsperiode die höchsten Werte aufweist, vorher jedoch teilweise deutlich unter den Kurven des Minimum- und Medianlaufes liegt.

Die Verläufe des Ariditătsindex unter dem Medianklimalauf weisen keinen ausgeprägten zeitlichen Trend auf, jedoch zeigen sie deutlich die trockeneren Bedingungen in den beiden östlichen Regionen Fläming und Oder-Spree gegenüber den sehr ähnlichen Ariditătsverläufen in Uelzen und Diepholz an (*Abb. 2*, unten links). Wie auch bei der Temperatursumme zeigt ein Vergleich des Ariditătsindex unter den drei Klimavarianten die größere Wertespreitung innerhalb eines Verlaufes als zwischen den Szenarien (*Abb. 2*, unten rechts). Eine zeitlich zunehmende Trockenheit ist im linearen Trend für den Medianlauf schwach und für den Maximumlauf deutlich stärker erkennbar.

2.6 Waldbauliche Entwicklungspfade

Die Nutzungsstrategien sind (1) als *Referenz* der Entwicklungspfad eines naturnahen Waldbaus im Anhalt an das LÖWE-Programm (Otto, 1989), (2) der Entwicklungspfad *Biodiversität*, der sich an die Biodiversitätsstrategie des Bundes (BMUB, 2007) anlehnt und sich an der potenziell natürlichen Vegetation orientiert, und (3) der Entwicklungspfad *Klimaschutz*, der eine Maximierung der Kohlenstoffspeicherung im stehenden Vorrat und besonders in langlebigen Holzprodukten anstrebt (*Tab. 3*).

Die drei waldbaulichen Entwicklungspfade sind möglichst kontrastreich definiert, d. h. es wird in den Projektionen ein möglichst breiter Bereich der Waldentwicklung abgedeckt. Die in *Tabelle 3* aufgeführten Kriterien zeigen die wesentlichen Unterschiede zwischen den drei Pfaden.

Die Baumartenwahl, ein zentrales Element zur Steuerung der mittel- und langfristigen Waldentwicklung, wird über die Nährstoff- und Wasserversorgung der Standorte, die die Waldentwicklungstypen-Matrizen aufspannen, gesteuert (Albert et al., 2016). Je nach waldbaulichem Entwicklungspfad werden, immer unter Beachtung der Standorteignung, unterschiedliche Zielsetzungen verfolgt. Die regionstypische Waldentwicklungsmatrix des Referenz-Pfades setzt den Schwerpunkt auf eine naturnahe Forstwirtschaft, wie sie derzeit u. a. für die Niedersächsischen Landesforsten vorgegeben ist und eine Laub- und Mischwaldvermehrung anstrebt (Nds. MFDLRELV, 2004). Unter dem Klimaschutzpfad werden in der regionstypischen Waldentwicklungsmatrix verstärkt Mischbestandstypen mit führendem Nadelholz vorgeschlagen. Die Baumartenwahl unter Biodiversität hingegen orientiert sich vorrangig an der potenziell natürlichen Vegetation (PNV) der Standorte. Im Referenzszenario wird derjenige unter den standortsgemäßen Waldentwicklungstypen (WET) ausgewählt, der der aktuellen Bestockung am ähnlichsten ist. Die Kosten eines Waldumbaus durch Pflanzung anderer bzw. zusätzlicher Baumarten werden somit minimiert. Beim Klimaschutz- und Biodiversitätspfad wird bei

Tab. 3

Charakteristika der waldbaulichen Entwicklungspfade zur Umsetzung der Nutzungsstrategien und Naturschutzregeln im Waldplaner (LRT: Lebensraumtyp; PNV: heutige potenziell natürliche Vegetation; Lbh: Laubbaumarten; Ndh: Nadelbaumarten; Df: Durchforstung).

Characteristics of the three silvicultural treatments and nature conservation rules to implement the management strategies Referenz, Biodiversität and Klimaschutz (LRT: habitat type; PNV: potential natural vegetation; Lbh: deciduous trees; Ndh: conifer species; Df: thinning).

	Referenz	Biodiversität	Klimaschutz
Prozessschutz:	Status quo	5 % der Waldfläche	Status quo
FFH-Gebietskulisse:	Fläche der LRT erhalten und ausbauen	LRT auf ganzer FFH-Fläche anstreben	Fläche der LRT erhalten
Totholz (m³/ha):	20	40	20
Habitatbäume (N/ha):	3	10	3
Schutz seltener Baumarten:	ja	nein	ja
Baumartenwahl:	Führendes Lbh	Naturnahe Waldgesellschaften (PNV)	Führendes Ndh
Verjüngung:	NV und Voranbau von Lbh.	Lbh.-NV und Voranbau von Lbh.	NV und Voranbau von Ndh.
Pflege:	gest. Df.: st. > mäß. > schwach	mäß. Df.	gest. Df.: st. > mäß. > schwach
Durchforstungsbeginn:	12 – 16 m	12 – 16 m	[L (- 3 m)] 14 – 18 m
Durchforstungsmasse je Eingriff:	max. 70 Vfm.m.R./ha (Dgl max. 120 Vfm.m.R./ha)	max. 50 Vfm.m.R./ha (Dgl max. 120 Vfm.m.R./ha)	max. 70 Vfm.m.R./ha (Dgl max. 120 Vfm.m.R./ha)
Zielstärke (cm):	Status quo Ei 70, Bu 60, Fi 45, Ki 45, Dgl 70	Status quo + 5 cm PNV bzw. + 10 cm in FFH-Gebieten andere Baumarten – 5 bzw. – 10 cm für eingeführte Baumarten	Status quo - 5 cm
Endnutzungsmasse je Hieb:	max. 100 Vfm.m.R./ha	max. 70 Vfm.m.R./ha nicht zur PNV gehörende Baumarten max. 100 Vfm.m.R./ha	max. 100 Vfm.m.R./ha

Tab. 4

Definition der Vulnerabilitätsklassen bei Trockenstress für die Hauptbaumarten.
Definition of drought vulnerability classes for five major tree species.

Trockenstress-vulnerabilität	Trockenstressindikator [mm]			
	Fichte	Buche	Eiche/Douglasie	Kiefer
gering	> 0	> -25	> -150	> -180
mittel	0 bis -80	-25 bis -100	-150 bis -400	-180 bis -450
hoch	< -80	< -100	< -400	< -450

mehreren WET-Vorschlägen für einen Standort aus der Liste der WET mit unterschiedlichen Wahrscheinlichkeiten zufällig gezogen.

Auf dieser Datengrundlage und den jeweils für die Entwicklungspfade formulierten Waldbau- und Naturschutzregeln wurde die Waldentwicklung in den vier Regionen in 5-Jahresschritten bis 2070 projiziert. Dabei wurde jeder waldbauliche Entwicklungspfad unter dem Median-Klimalauf simuliert, so dass die Auswirkungen der waldbaulichen Steuerung verglichen werden können. Der Referenzpfad wurde zusätzlich noch unter der Minimum- und der Maximumvariante gerechnet, um auch die durch die Unsicherheiten in der Klimaprojektion verursachten waldwachstumskundlichen und forstplanerischen Implikationen abschätzen zu können. Insgesamt wurden somit fünf Szenarien simuliert: *Referenz* unter Minimum-, Median- und Maximumklimalauf (*Ref_min*, *Ref_med*, *Ref_max*), *Biodiversität* unter Medianlauf (*Bio_med*) und Klimaschutz unter Medianlauf (*Kl_med*).

Die Simulationen erfolgten unter der Annahme, dass keine Einzelbaum- oder Bestandesausfälle durch abiotische und biotische Risikofaktoren auftreten und folglich auch keine Rückkopplung auf die Waldentwicklung erfolgte. Eine Ausnahme hiervon bildete die dichteabhängige Mortalität, die über ein Teilmodell des Waldwachstumssimulators prognostiziert wird. Diese Annahme ist notwendig, um den Klimaeffekt und die Auswirkungen unterschiedlicher waldbaulicher Behandlungen untersuchen zu können. Die Simulationsstudie ist eine Wirkungsanalyse, die nicht unmittelbar als waldbauliche Planung verstanden werden darf. In der Ergebnisinterpretation müssen die Risiken jedoch betrachtet werden, um die verschiedenen waldbaulichen Entwicklungspfade diesbezüglich beurteilen zu können.

2.7 Methodik zur Beurteilung der Trockenstressvulnerabilität

Allgemein ist Vulnerabilität definiert als ein Maß der Anfälligkeit eines Systems gegenüber nachteiligen Auswirkungen der Klimaänderung (vgl. FÜSSEL und KLEIN, 2006). Konkret ist die Trockenstressvulnerabilität abhängig von den Faktoren Exposition (Dauer und Grad des Wassermangels), Sensitivität der Baumart gegenüber Schwankungen in der Wasserverfügbarkeit und der Anpassungsfähigkeit der Baumart, klimabedingtem Trockenstress zu begegnen. Trockenstress ist ein wesentliches abiotisches Risiko für den Einzelbaum und ganze Bestände, welches durch den Klimawandel auf vielen Standorten verschärft wird. Die Folgen von Trockenstress reichen dabei von Vitalitäts- und Wachstumsverlusten bis hin zu Mortalität (VAN HEERDEN und YANAI, 1995; HANSON und WELTZIN, 2000; ALLEN et al., 2010). Für die Beurteilung der Trockenstressvulnerabilität erscheint vor dem Hintergrund der verfügbaren Daten die Summe aus Klimatischer Wasserbilanz (KWB) und der nFK als ein geeigneter Indikator (SPELLMANN et al., 2007 und 2015). Die KWB ist definiert als Differenz zwischen Niederschlag und potenzieller Evapotranspiration, basierend auf der Grasreferenzverdunstung der FAO (ALLEN et al., 1998) in der Vegetationszeit. Die so definierte Standortwasserbilanz (KWB + nFK) nach GRIER und RUNNING (1977) kann für jeden Stichprobenpunkt in den vier Untersuchungsregionen berechnet werden. Diese kontinuierliche Indikatorvariable wird unter Verwendung der Schwellenwertmethode im Anhalt an GRIER und RUNNING (1977) nach SPELLMANN et al. (2011 und 2015) in Vulnerabilitätsklassen eingeteilt (*Tab. 4*).

Die Schwellenwerte der Vulnerabilitätsklassen ordnen die Fichte als gefährdetste Baumart ein, gefolgt von der Buche, der Eiche und Douglasie sowie schließlich der Kiefer als der trockenstresstolerantesten Baumart (SPELLMANN et al., 2015). Für eine umfassende Trockenstressanalyse im Rahmen dieser Untersuchung wurden die anderen vorkommenden Baumarten einer der vier Baumartenklassifikationen zugeordnet (ALBERT et al., 2016).

3. ERGEBNISSE

3.1 Klimatische Unsicherheit und waldbauliche Variabilität

Die naturale Ausstattung in den vier Modellregionen zu Beginn der Simulationsperiode 2011 bestimmt entscheidend die Ergebnisse der Waldentwicklungsprojektionen. Insbesondere spielt die Altersklassen- und die Baumartenverteilung für den Waldumbau eine entscheidende Rolle (*Abb. 3* und *Tab. 5*). Der Flächenanteil einer Baumart bezieht sich im Folgenden auf das Verhältnis der artspezifischen Kronenschirmfläche zur Gesamtkronenschirmfläche. Im Vergleich der Regionen sind zwei generelle Merkmale der Ausgangssituationen auffällig. Zum einen ist die stark zunehmende Dominanz der Kiefer von West nach Ost beachtlich (Diepholz 19 %

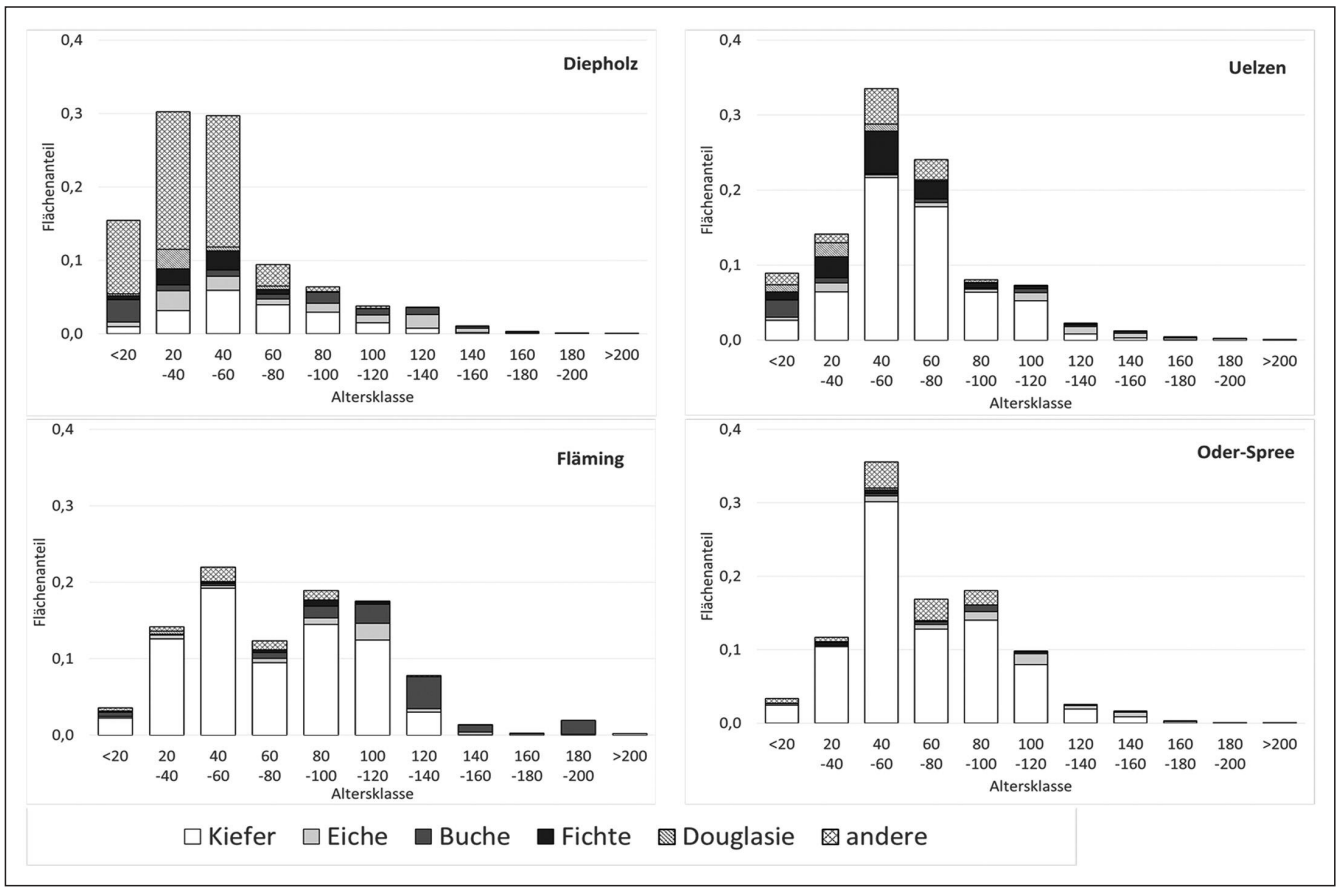


Abb. 3

Baumartspezifischen Flächenanteile (bezogen auf die Kronenschirmflächen) in den Altersklassen für die vier Regionen zu Beginn der Projektionsperiode (2011).

Histograms of proportions of species-specific areas (referring to crown cover) in the four regions in 2011.

Flächenanteil der Kiefer, Uelzen 61%, Fläming 74% und Oder-Spree 81%). Zum anderen ist die Altersklassenverteilung zumeist unausgeglichen mit einem starken Anteil an Jungbeständen in Diepholz bzw. mittelalten Beständen in Uelzen und Oder-Spree.

Anhand der Altersklassenverteilung kann das Potenzial an Flächen abgeschätzt werden, die im Rahmen der Waldentwicklungsprojektionen durch Nutzung der hiebsreifen Bestände bis 2070 bei der Baumartenwahl für eine bessere Anpassung an sich ändernde klimatische Verhältnisse und ökonomischen sowie ökologischen Zielsetzungen in Frage kommen (*Abb. 3*). Alternativ könnte der Waldumbau jedoch auch bei noch nicht hiebsreifen Beständen vorangetrieben werden, was allerdings zu großen ökonomischen Verlusten führen würde.

Die Kiefer ist in allen Regionen die dominierende Baumart (*Tab. 5*). Die Baumartenverteilung in Diepholz ist im Vergleich mit den anderen Regionen recht divers, geprägt vom hohen Anteil anderen Laubholzes mit 45%, insbesondere Birke. Der hohe Anteil organischer Böden (insb. degenerierte Hochmoore) in der Modellregion ist hierfür die Ursache. Mit nennenswerten Anteilen sind aber auch Eiche und Buche mit jeweils ca. 10% und Fichte, Douglasie und anderes Nadelholz mit jeweils ca. 5% vertreten. Die Region Uelzen weist mit 13% einen im Vergleich recht hohen Fichtenanteil auf. Eiche, Buche und Douglasie haben hier einen Anteil von jeweils ca. 5%. Im Fläming kommen als Hauptbaumarten neben der Kiefer nur die Buche mit 13% und die Eiche mit 6% vor. Ähnlich ist die Situation in Oder-Spree mit einem Eichenanteil von ebenfalls 6% und einem recht geringen Buchenanteil von 2%.

Drei Faktoren führen während der Projektion zu veränderten Flächenanteilen der Baumarten: (1) das altersabhängige Baumwachstum mit sich entsprechend verändernden Kronendimensionen, (2) die Bestandesbehandlung und (3) die Verjüngung durch Einwuchs bzw. der Baumartenwechsel nach der Ernte des Altbestandes. Die Veränderungen in den Flächenanteilen der Baumarten zeigen erwartungsgemäß deutliche Unterschiede zwischen den drei waldbaulichen Entwicklungspfaden. Hingegen ergeben sich nur minimale Abweichungen zwischen den unter den drei Klimaläufen realisierten Referenzszenarien.

Im Vergleich der drei waldbaulichen Entwicklungspfade ergeben sich zwei generelle Erkenntnisse für die

Tab. 5

Baumartenspezifische Flächenanteile zu Beginn der Simulationsperiode 2011 in Prozent und deren Veränderungen in Prozentpunkten bis 2070 unter den drei waldbaulichen Entwicklungspfaden Referenz (Ref), Klimaschutz (Kl) und Biodiversität (Bio), wobei Kl und Bio unter dem Median-Klimalauf und Ref unter den drei Läufen Minimum (min), Median (med) und Maximum (max) simuliert wurden.

Proportions of species-specific areas [%] in 2011 and the corresponding change [%-points] under the three management strategies Referenz (Ref), Klimaschutz (Kl) and Biodiversität (Bio) with Kl and Bio being simulated using the median climate run and Ref being simulated using the minimum (min), median (med) and maximum (max) climate run.

		Buche	Eiche	anderes Laubholz	Fichte	Kiefer	Douglasie	anderes Nadelholz	*Veränderungsrate*
Diepholz	*2011*	8,9 %	11,2 %	45,2 %	6,0 %	19,3 %	4,1 %	5,4 %	
	Ref_min	+4,6	+2,6	-4,4	-0,6	-1,4	+1,0	-2,0	*8,3*
	Ref_med	+5,1	+2,1	-4,7	-0,8	-0,9	+1,1	-2,0	*8,3*
	Ref_max	+4,3	+2,6	-4,4	-0,7	-1,6	+1,4	-1,7	*8,3*
	Kl_med	+7,8	+3,0	-25,0	+2,1	+7,4	+5,9	-1,4	*26,3*
	Bio_med	+0,2	+4,6	-2,5	-2,2	+2,8	-1,5	-1,5	*7,6*
Uelzen	*2011*	4,8 %	6,1 %	8,7 %	13,3 %	61,3 %	3,9 %	1,9 %	
	Ref_min	+4,5	+1,7	+0,9	-7,1	-14,4	+14,6	-0,2	*21,7*
	Ref_med	+7,0	+1,6	+2,3	-6,7	-17,7	+13,3	-0,1	*24,3*
	Ref_max	+4,3	+1,6	+0,7	-6,4	-14,3	+14,4	-0,3	*21,0*
	Kl_med	+14,7	-0,9	-1,5	-8,9	-34,1	+26,8	+4,0	*45,5*
	Bio_med	+8,0	+0,2	+0,6	-5,6	-3,2	+0,4	-0,4	*9,2*
Fläming	*2011*	12,8 %	5,9 %	4,3 %	1,8 %	73,5 %	0,4 %	1,2 %	
	Ref_min	+7,7	+2,0	-0,3	-0,7	-10,8	+2,3	-0,1	*12,0*
	Ref_med	+8,3	+2,5	-0,4	-0,8	-11,2	+1,9	-0,2	*12,7*
	Ref_max	+7,7	+2,5	-0,4	-0,6	-11,2	+2,2	-0,1	*12,4*
	Kl_med	+8,4	+1,9	-1,2	-1,1	-30,2	+18,5	+3,8	*32,6*
	Bio_med	+5,9	+0,7	+1,1	+1,6	-9,2	+/-0	+/-0	*9,3*
Oder-Spree	*2011*	2,0 %	5,7 %	8,8 %	1,1 %	80,9 %	0,5 %	1,0 %	
	Ref_min	+7,1	+2,7	-1,8	+/-0	-8,1	+0,3	+/-0	*10,0*
	Ref_med	+7,1	+2,9	-1,8	-0,1	-8,3	+0,3	-0,1	*10,3*
	Ref_max	+6,9	+2,9	-1,7	-0,1	-8,0	+0,4	-0,3	*10,2*
	Kl_med	+7,1	+3,4	-3,8	-0,2	-23,1	+12,9	+3,6	*27,0*
	Bio_med	+0,7	+0,4	+0,7	+0,4	-2,1	-0,1	+0,1	*2,3*

Veränderung der Baumartenanteile bis 2070: (1) In allen Regionen weist der Klimaschutzpfad mit seinen geringeren Zielstärken bzw. kürzeren Produktionszeiträumen die höchsten Veränderungsraten zwischen 26 und 45% auf. Das Biodiversitätsszenario erzielt mit seinen höheren Zielstärken bzw. längeren Produktionszeiträumen hingegen die geringsten Werte zwischen 2 und 9%. (2) Im Regionsvergleich hat Uelzen die höchsten Raten in allen Szenarien, während in Diepholz der Referenzpfad den geringsten Wert aufweist und in Oder-Spree die Biodiversitätsvariante kaum zu einem Baumartenwechsel führt.

Eine baumartspezifische Betrachtung zeigt die Förderung der Douglasie unter dem Klimaschutz- aber auch dem Referenzpfad. Die Buche und in geringerem Ausmaß auch die Eiche werden in allen waldbaulichen Varianten in allen Regionen, mit Ausnahme der Eiche in Uelzen unter Klimaschutz, gefördert. Der Flächenanteil der Kiefer geht in allen Projektionen deutlich zurück außer in Diepholz, wo unter Klimaschutz und Biodiversität eine Zunahme erfolgt.

In der folgenden Analyse des Vorrats, der Nutzungsmasse, des Zuwachses und des Hiebssatzweisers wird die klimatische Unsicherheit, resultierend aus den Simulationen Ref_min, Ref_med und Ref_max, durch die durchschnittliche Differenz des jeweils größten und kleinsten Parameterwertes in den 5-Jahresperioden beschrieben. Analog wird die waldbauliche Variabilität zwischen den Simulationen Ref_med, Kl_med und Bio_med quantifiziert.

Nach der ersten Vorratsreduktion durch Entnahme und Mortalität in 2011 weisen die Regionen Oder-Spree mit 275 m^3/ha, Fläming mit 263 m^3/ha und Uelzen mit 261 m^3/ha ähnliche Durchschnittsvorräte zu Beginn der Waldentwicklungsprojektion auf. Nur die Region Diepholz hat auf Grund des hohen Anteils junger Bestände einen deutlich geringeren mittleren Vorrat von 175 m^3/ha (*Abb. 4*). Für alle Regionen weist die Vorratsentwicklung unter dem Biodiversitätsszenario die größten Werte auf, während die Klimaschutzvariante zu jeweils geringsten Vorratswerten führt. Die Vorratsentwicklung im Entwicklungspfad Referenz verläuft dazwi-

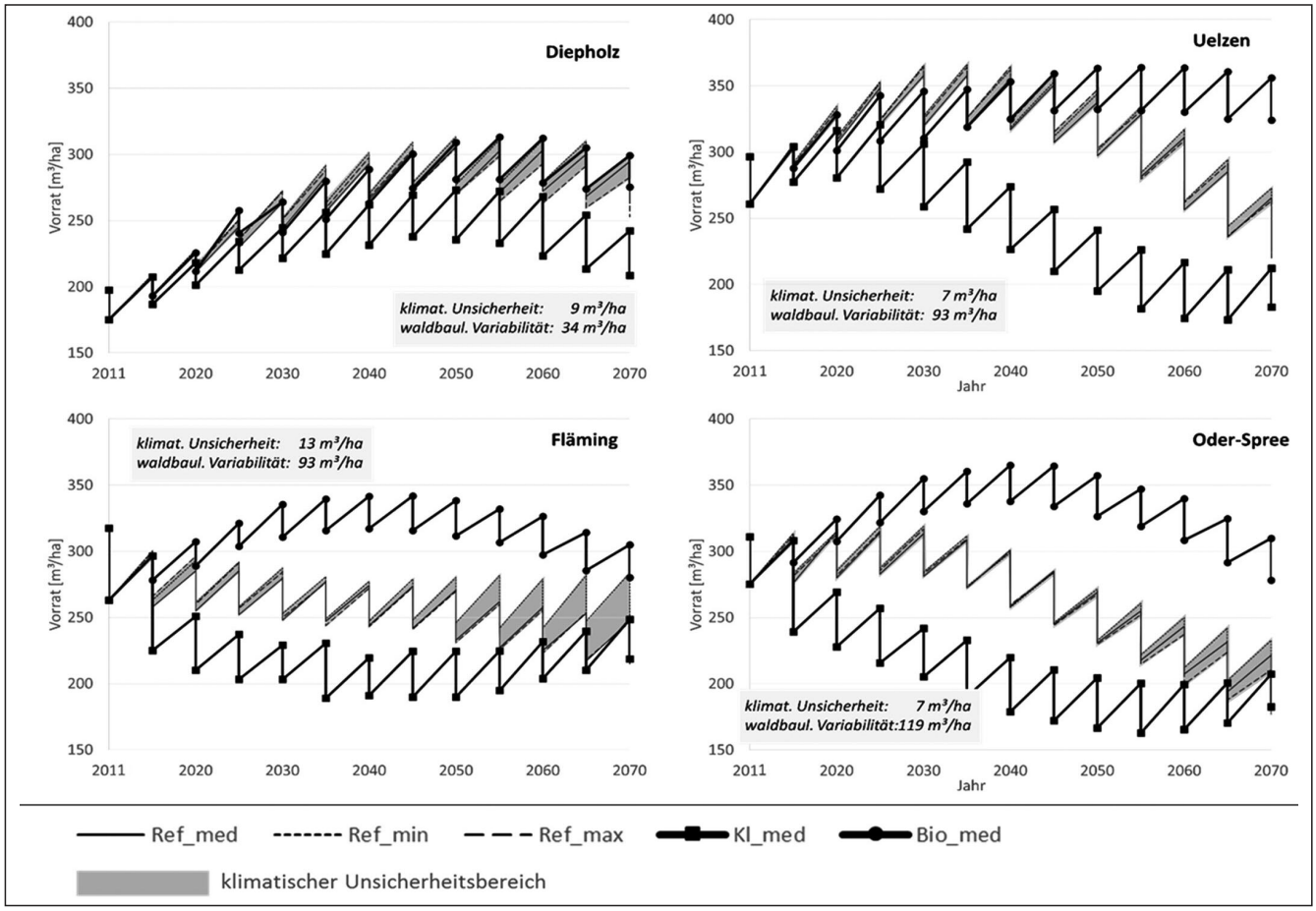


Abb. 4

Vorratsentwicklung (stehender Vorrat sowie durch Entnahme und Mortalität ausscheidende Masse) in den vier Regionen unter den drei waldbaulichen Entwicklungspfaden Referenz (Ref), Klimaschutz (Kl) und Biodiversität (Bio), wobei Kl und Bio unter dem Median-Klimalauf und Ref unter den drei Läufen Minimum (min), Median (med) und Maximum (max) simuliert wurden.

Development of standing volume and removed volume (harvest and density induced mortality) in the four regions under the five scenarios Ref_min, Ref_med, Ref_max, Kl_med and Bio_med.

schen, nur in Diepholz und zu Beginn der Projektion in Uelzen liegt die Vorratsentwicklung bei oder über dem Biodiversität-Verlauf. Der klimatische Unsicherheitsbereich in der Vorratsentwicklung, charakterisiert durch die Simulation des Referenzszenarios unter den drei Klimaläufen, weist einen über der Zeit zunehmenden Trend auf. Diese tendenzielle Zunahme resultiert aus den sich in den Projektionsperioden vergrößernden Differenzen der Temperaturentwicklungen und die Ariditätsindexwerte zwischen dem Minimum-, Median- und Maximum-Lauf. Allein in Uelzen scheint dieser Trend im Unsicherheitsbereich nicht ausgeprägt. Je nach Region schwankt der mittlere klimatische Unsicherheitsbereich zwischen 7 m³/ha in Uelzen und Oder-Spree, 9 m³/ha in Diepholz und 13 m³/ha im Fläming. Die mittlere waldbauliche Variabilität zwischen den drei Entwicklungspfaden ist deutlich größer mit Werten zwischen 34 m³/ha in Diepholz, 93 m³/ha in Uelzen und im Fläming sowie 119 m³/ha in Oder-Spree.

In der Region Diepholz resultieren alle waldbaulichen Entwicklungspfade in einer Vorratszunahme bis 2070, wobei der klimatische Unsicherheitsbereich den Biodiversitätsverlauf weitestgehend einschließt. Die Vorratsentwicklung unter den Bedingungen des Klimaschutzpfades verläuft deutlich niedriger. Im Vergleich mit den anderen Regionen weisen die verschiedenen Vorratsentwicklungen in Diepholz die geringsten Unterschiede auf.

In Uelzen kommt es unter der Biodiversitätsstrategie zu einem kontinuierlichen Vorratsanstieg. Der Referenzpfad weist ebenfalls einen Vorratsanstieg bis 2040 auf und der Unsicherheitsbereich liegt in diesem Zeitraum oberhalb der Biodiversitätswerte. Danach kommt es bis 2070 zu einem Vorratsabbau. Im Rahmen des Klimaschutzpfades erfolgt nach anfänglich eher konstantem Vorratsverlauf ab 2030 eine drastische Vorratsreduktion.

Im Fläming ergibt sich unter dem Biodiversitätspfad ein Vorratsaufbau mit einem Maximum um 2045. Im Klimaschutzszenario beginnt die starke Vorratsreduktion gleich zu Beginn der Projektionsperiode und die Vorräte steigen dann ab 2050 wieder leicht an. Das Refe-

Tab. 6

Erntevolumen als Mittelwert der Projektionsperiode 2011 bis 2070 in den vier Regionen unter den drei waldbaulichen Entwicklungspfaden Referenz (Ref), Klimaschutz (Kl) und Biodiversität (Bio), wobei Kl und Bio unter dem Median-Klimalauf und Ref unter den drei Läufen Minimum (min), Median (med) und Maximum (max) simuliert wurden.

Harvested volume as mean value of the projection period 2011 to 2070 in the four regions under the five scenarios Ref_min, Ref_med, Ref_max, Kl_med and Bio_med.

	Erntevolumen [m³/ha/a]				
	Ref_min	Ref_med	Ref_max	Kl_med	Bio_med
Diepholz	4,2	3,9	4,0	4,7	2,9
Uelzen	6,1	5,9	6,1	6,5	4,1
Fläming	5,5	5,1	5,3	5,6	2,5
Oder-Spree	5,7	5,7	5,5	6,2	3,2

renzszenario weist eine kontinuierliche Vorratsabnahme auf. Gegen Ende der Projektionsperiode nimmt die klimatische Unsicherheit deutlich zu und liegt 2070 bei ca. 38 m³/ha. Damit wird sogar das niedrige Vorratsniveau des Klimaschutzpfades erreicht.

Die Vorratsentwicklung unter den verschiedenen Szenarien in Oder-Spree ähnelt den Verläufen im Fläming, wobei die Unterschiede zwischen den waldbaulichen Varianten hier am größten sind. Auch in Oder-Spree schließt der klimatische Unsicherheitsbereich in 2070 (ca. 22 m³/ha) die Klimaschutzvariante mit ein.

Im Durchschnitt über die gesamte Projektionsperiode 2011 bis 2070 werden unter dem Klimaschutzpfad die höchsten Erntevolumina realisiert. Die Biodiversitäts-

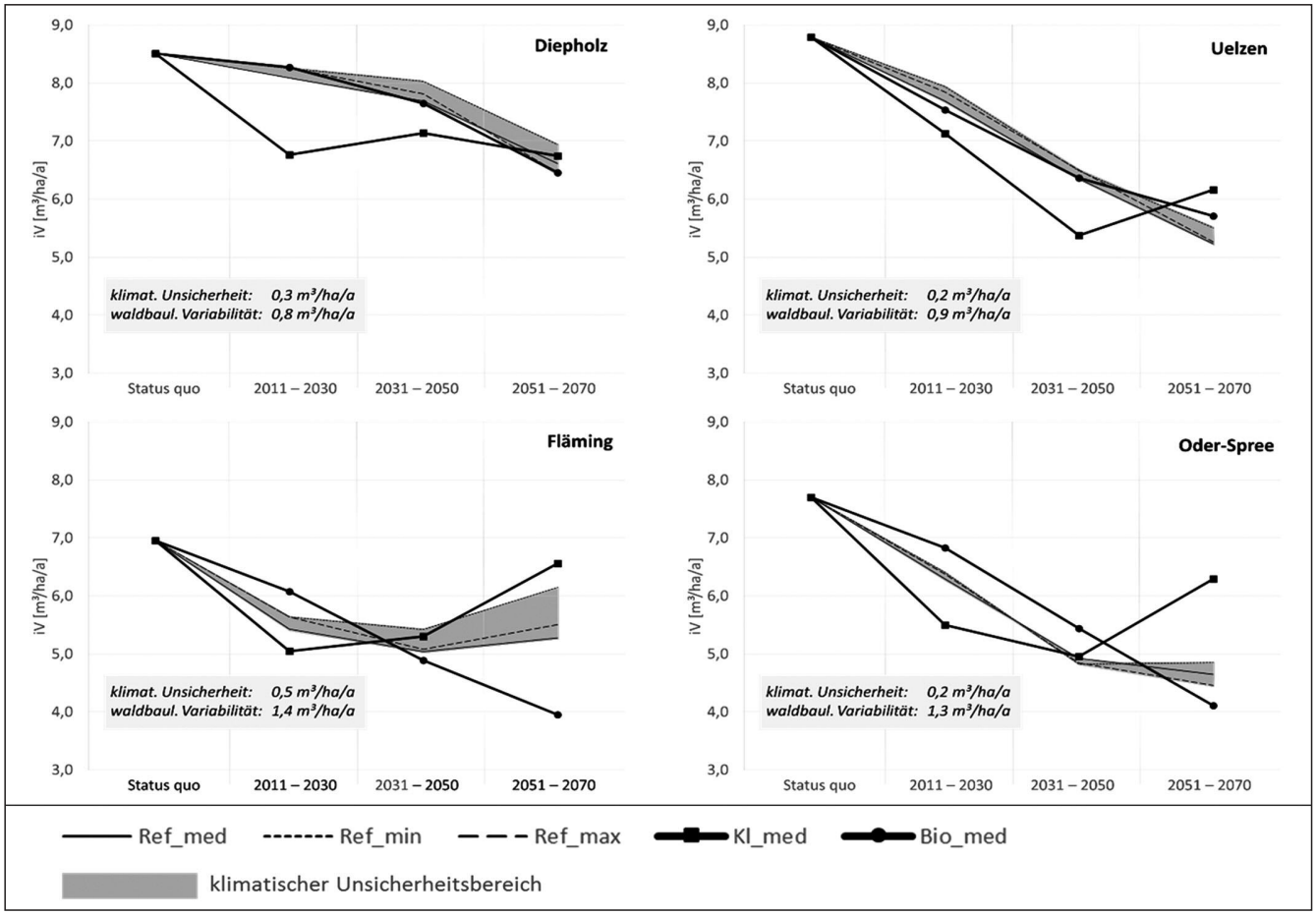


Abb. 5

Laufender Zuwachs als Mittelwert der 20-jährigen Perioden unter den drei waldbaulichen Entwicklungspfaden Referenz (Ref), Klimaschutz (Kl) und Biodiversität (Bio), wobei Kl und Bio unter dem Median-Klimalauf und Ref unter den drei Läufen Minimum (min), Median (med) und Maximum (max) simuliert wurden.

Periodic annual increment (PAI) for 20-year projection periods under the five scenarios Ref_min, Ref_med, Ref_max, Kl_med and Bio_med.

variante hingegen weist die geringsten Entnahmen auf und das Referenzszenario liegt dazwischen (*Tab. 6*). Über alle Entwicklungspfade sind die Erntemassen in Diepholz am geringsten, nur unter der Biodiversitätsvariante im Fläming wird mit 2,5 m³/ha/a noch weniger Masse entnommen. Die höchsten Entnahmemengen werden für alle waldbaulichen Varianten für die Region Uelzen projiziert.

Die klimatische Unsicherheit auf Basis der durchschnittlichen Erntemassen rangiert zwischen 0,2 m³/ha/a in Diepholz, 0,3 m³/ha/a in Uelzen und Oder-Spree sowie 0,4 m³/ha/a im Fläming. Die waldbauliche Variabilität ist deutlich höher mit Werten zwischen 1,8 m³/ha/a in Diepholz und 3,1 m³/ha/a im Fläming.

Die zeitlichen Entwicklungen des Zuwachses und des Hiebssatzweisers werden für 20-jährige Perioden analysiert. Dies ermöglicht klarere Trendaussagen und für die Ableitung von Handlungsempfehlungen die Unterscheidung in eine nahe (Periode 2011 bis 2030), eine mittlere (Periode 2031 bis 2050) und eine ferne Zukunft (Periode 2051 bis 2070). Der Status quo umfasst hier die Periode 1991 bis 2010.

Der laufende Zuwachs sinkt in allen Regionen unter allen Entwicklungspfaden zu Beginn der Projektionsperiode (*Abb. 5*). Die Projektion unter Klimaschutz führt dabei zu dem stärksten Einbruch, gefolgt von einem späteren Anstieg. Diese Trendwende wird für Diepholz und Fläming bereits nach der ersten Projektionsperiode vorher gesagt. In Uelzen und Oder-Spree findet dies erst nach der zweiten Periode statt. Unter dem Referenzszenario wird ebenfalls ein Abfall projiziert, der jedoch im Vergleich zum Klimaschutzpfad weniger steil verläuft. Eine Trendwende ist hier nur in der Region Fläming mit dem am besten ausgeglichenen Altersklassenaufbau zu verzeichnen. Der Biodiversitätspfad weist durchweg einen negativen zeitlichen Trend beim laufenden Zuwachs auf.

Die klimatische Unsicherheit nimmt prinzipiell mit der Zeit zu, besonders ausgeprägt vor allem im Fläming auf 0,9 m³/ha/a am Ende der Projektionsperiode. In der Region Oder-Spree ist die klimatische Unsicherheit bis zur zweiten Projektionsperiode kaum ausgeprägt und nimmt dann aber auf 0,3 m³/ha/a bis 2070 zu. In Uelzen liegt die klimatische Unsicherheit im laufenden Zuwachs eher gleichbleibend über der Zeit bei 0,2 bis 0,3 m³/ha/a. Die waldbauliche Variabilität ist beim laufenden Zuwachs ebenfalls größer als die klimatische Unsicherheit, jedoch im Verhältnis deutlich weniger stark ausgeprägt als bei der Vorratsentwicklung und der Erntemasse. In Diepholz beträgt die waldbauliche Variabilität ca. das Dreifache und in Uelzen das Vierfache der klimatischen Unsicherheit. In Diepholz schließt der klimatische Unsicherheitsbereich den Verlauf des laufenden Zuwachses unter Biodiversität sogar fast komplett ein.

Die periodische Nachhaltigkeit der Holznutzung wird für Forstplanungszwecke mit Hiebsatzweisern, deren Fundament das Normalwaldmodell ist, geprüft. In dieser Untersuchung wird der Hiebsatzweiser nach GEHRHARDT (1923, vgl. SPEIDEL, 1972, S. 171) verwendet:

$$Hi = \frac{lZ + dGZ_u}{2} + \frac{V_w - V_n}{a} \quad [3]$$

wobei

lZ: laufender jährlicher Gesamtderbholzzuwachs [m³/ha/a]

dGZ_u: durchschnittlich jährlicher Gesamtderbholzzuwachs in der Umtriebszeit u [m³/ha/a] (u in *Tabelle 7*)

V_w: wirklicher Vorrat [m³/ha]

V_n: Normalvorrat [m³/ha]

a: Ausgleichszeitraum (hier 20 Jahre)

Die periodische Realisation des nach GEHRHARDT (1923) ermittelten Hiebsatzes verschiebt die Waldstruktur einer Region im Sinne des Normalwaldmodells in Richtung eines vollkommen ausgeglichenen Altersklassenverhältnisses. Dieser modellhafte Idealzustand kann in der Realität nicht erreicht werden. Die Interpretation des Hiebsatzweisers ermöglicht dennoch Erkenntnisse über die nachhaltige Holznutzung.

Die Staffelung zum Status quo ist in den entwicklungspfadspezifischen Umtriebszeiten der Baumarten begründet, d. h. bei gleichen Vorräten und Bonitäten weist die Klimaschutzvariante immer den höchsten Nachhaltshiebsatz auf, gefolgt vom Referenzpfad und dem Biodiversitätsszenario mit dem niedrigsten Hiebsatzweiser (*Abb. 6*). Unter dem Klimaschutzpfad nimmt der Nachhaltigkeitshiebsatz tendenziell ab, in Diepholz leicht und in den übrigen drei Regionen stark. Im Fläming und Oder-Spree wird nach der zweiten Projektionsperiode eine Trendwende vorher gesagt. Der Hiebsatzweiser unter Biodiversitätsstrategie nimmt prinzipiell mit einem Maximum in der zweiten Periode zu, was im Fläming und Oder-Spree im Variantenvergleich zu absolut höchsten Werten für den gesamten Projektionszeitraum von 2011 bis 2070 führt. Der Hiebsatzweiser im Referenzpfad weist über alle vier Regionen keine ein-

Tab. 7

Für den Hiebsatzweiser definierte baumart- und entwicklungspfadspezifische Umtriebszeiten (Jahre).

Rotation age (years) according to species and management strategy defined for prescribed yield index.

	Eiche	Buche	Fichte	Douglasie	Kiefer
Referenz	180	140	80	100	120
Klimaschutz	160	120	60	80	100
Biodiversität	200	140	60	80	140

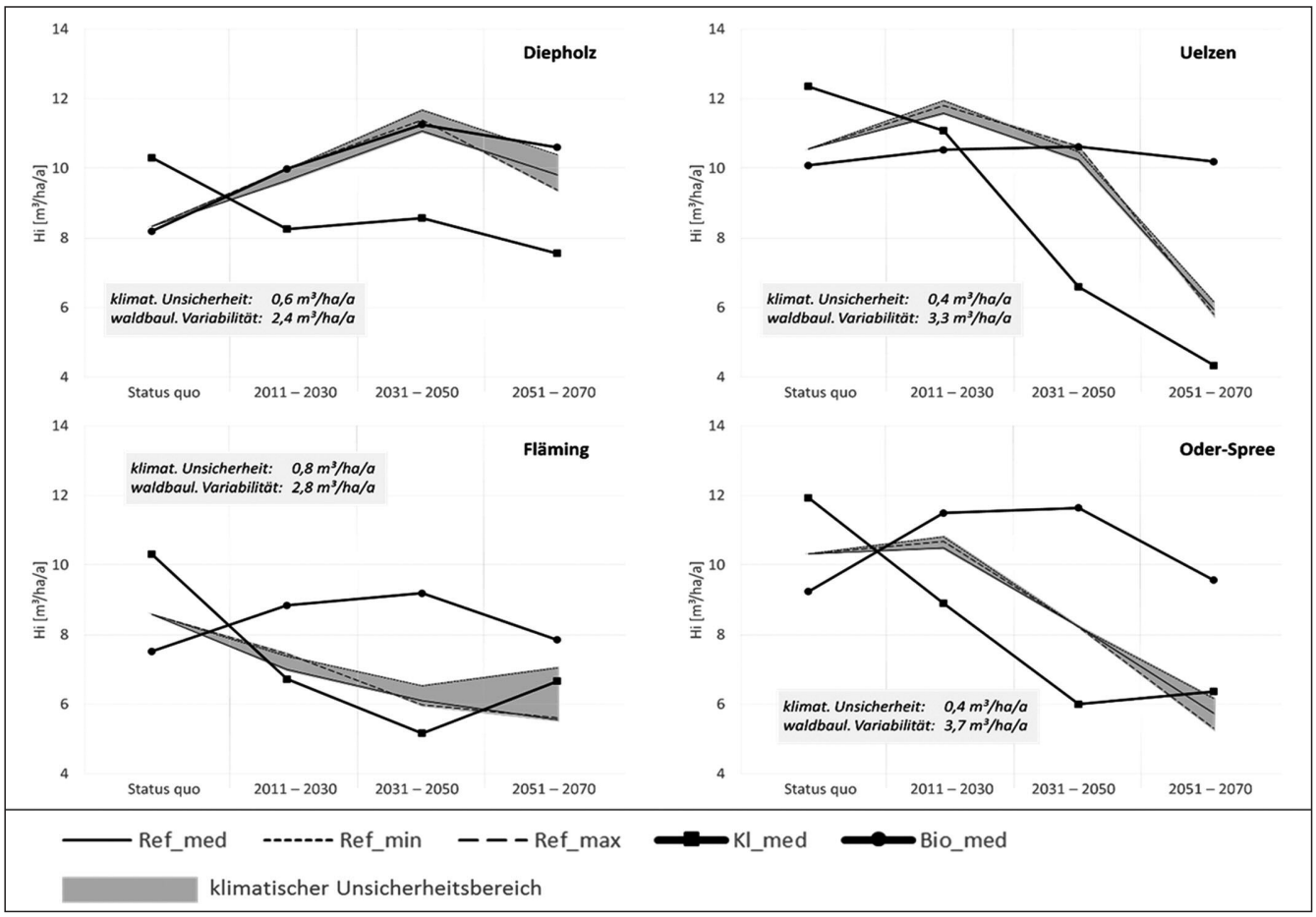


Abb. 6

Hiebsatzweiser nach GEHRHARDT (1923) als Mittelwert der 20-jährigen Perioden unter den drei waldbaulichen Entwicklungspfaden Referenz (Ref), Klimaschutz (Kl) und Biodiversität (Bio), wobei Kl und Bio unter dem Median-Klimalauf und Ref unter den drei Läufen Minimum (min), Median (med) und Maximum (max) simuliert wurden.

Mean values of prescribed yield index by GEHRHARDT (1923) for 20-yar periods under the five scenarios Ref_min, Ref_med, Ref_max, Kl_med and Bio_med.

heitliche Tendenz auf. In Diepholz gleicht der Verlauf dem unter Biodiversität, so dass der klimatische Unsicherheitsbereich diesen fast vollständig einschließt. In Uelzen kommt es unter Referenz zuerst zu einem Anstieg des Nachhaltshiebsatzes, der nach der ersten Periode immer stärker abnimmt. Im Fläming ist eine kontinuierliche Abnahme zu verzeichnen. In Oder-Spree kommt es nach anfänglich leichter Zunahme zu einem starken Abfall des Hiebsatzweisers.

Die klimatische Unsicherheit ist in Diepholz mit 0,6 m³/ha/a und im Fläming mit 0,8 m³/ha/a besonders ausgeprägt und nimmt hier deutlich mit der Zeit zu, im Fläming sogar auf 1,4 m³/ha/a in 2070. Die waldbaulichen Variabilität beträgt hier ungefähr das Vierfache der klimatischen Unsicherheit. In Uelzen und in Oder-Spree ist die klimatische Unsicherheit mit 0,4 m³/ha/a deutlich schwächer ausgeprägt und eher konstant über der Zeit. Die waldbauliche Variabilität ist mit 3,3 m³/ha/a in Uelzen und 3,7 m³/ha/a in Oder-Spree mehr als 8-fach so groß wie die klimatische Unsicherheit.

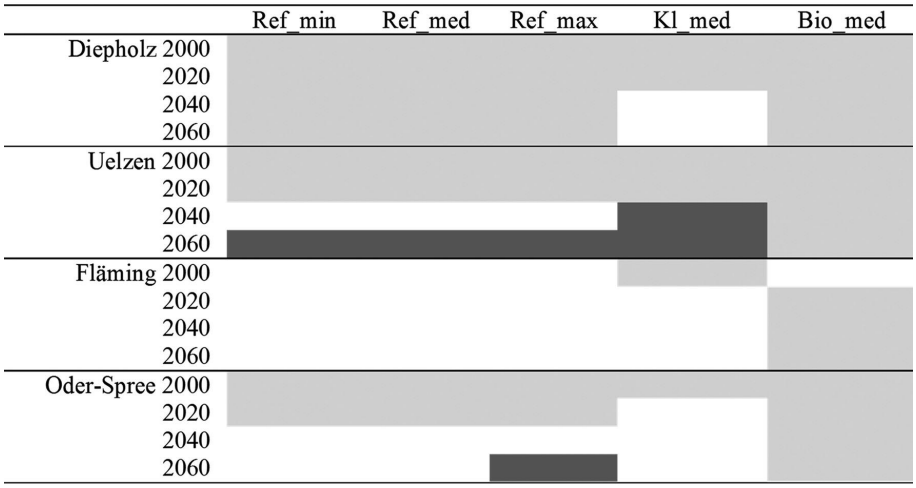
Der Hiebsatzweiser weist ein theoretisch nachhaltig zu nutzendes Potenzial aus, welches z. B. unter dem Biodiversitätspfad speziell in der Region Oder-Spree in der ersten und zweiten Projektionsperiode mit knapp 12 m³/ha/a recht hoch ausfällt. Aufschlussreich ist daher der Vergleich des Nachhaltshiebsatzes mit dem projizierten tatsächlichen Entnahmevolumen (*Tab. 6*). Der waldbauliche Hiebsatz, das ist hier der simulierte ausscheidende Vorrat, gilt bei einer nicht zu stark unausgeglichenen Altersklassenausstattung in einem Bereich von +/– 30 % des Hiebsatzweisers als nachhaltig (PENCZ, 2003).

Die Nachhaltigkeitsbeurteilung in *Tabelle 8* weist unter dem Biodiversitätspfad in allen Regionen und allen Zeitperioden, Ausnahme Status quo im Fläming, eine Mindernutzung aus, d. h. das nachhaltige Nutzungspotenzial wird nicht ausgeschöpft. Auch unter dem Referenzszenario sowie dem Klimaschutzpfad in den beiden ersten Perioden werden für die Region Diepholz Mindernutzungen projiziert. Im Fläming wird in den Simulationen unter Referenz und Klimaschutz, hier mit

Tab. 8

Bewertung der Nachhaltigkeit des waldbaulichen Hiebsatzes mithilfe des Hiebsatzweisers nach GEHRHARDT (hellgrau = Mindernutzung; weiß = nachhaltige Nutzung; dunkelgrau = Übernutzung).

Sustainability of the silvicultural yield evaluated using the prescribed yield index by GEHRHARDT (light gray = less than sustainable cutting; white = sustainable cutting; dark gray = overcutting).



Ausnahme in der Status quo-Periode, nachhaltig genutzt. In Uelzen und Oder-Spree deutet sich unter Referenz und Klimaschutz ein zeitlicher Trend von Mindernutzung zu nachhaltiger Nutzung und in Uelzen sogar zu Übernutzung in der letzten Projektionsperiode an. Unterschiede zwischen den drei Klimaläufen ergeben sich nur in Oder-Spree, wo statt einer nachhaltigen Nutzung unter dem Maximumlauf eine Übernutzung projiziert wird.

3.2 Vulnerabilitätsanalyse am Beispiel des Trockenstresses

Die Projektion der Waldentwicklung in den vier Regionen geschieht ohne Berücksichtigung von Risikofaktoren, d. h. es werden keine Ausfälle durch abiotische und biotische Risiken simuliert und es erfolgen auch keine waldbaulichen Anpassungen an veränderte Risikostrukturen. Am Beispiel einer Trockenstressanalyse wird gezeigt, wie die Vulnerabilität der einzelnen Entwicklungspfade nachträglich bewertet werden kann.

Die Beurteilung des Trockenstresses in den Regionen ist abhängig vom örtlichen Speicherpotenzial des Bodens (nFK), der aktuellen Baumartenzusammensetzung, dem entwicklungspfadspezifischen Waldumbau sowie den sich verändernden klimatischen Bedingungen. Mit Hilfe der Klassifizierung der Trockenstressvulnerabilität (vgl. *Tab. 4*) werden die Flächenanteile in den Vulnerabilitätsklassen je Region zum Status quo (2011) und am Ende der Projektionsperiode (2070) ermittelt (*Abb. 7*).

Die klimatische Unsicherheit und die waldbauliche Variabilität werden, abweichend vom Vorgehen bei den ertragskundlichen Größen, für die Häufigkeitsverteilungen der Flächen in den Trockenstressklassen im Anhalt an die relative Diskrepanz (vgl. GREGORIUS, 1974; POMMERENING, 1997; STAUPENDAHL, 1999) berechnet:

$$y_m = \frac{1}{2}\sum_{i=1}^{k}(x_{max_i} - x_{min_i}) \quad [4]$$

wobei y_m die klimatische Unsicherheit in Modellregion m ist und x_{min} und x_{max} die jeweiligen minimalen und maximalen Flächenanteile in den Risikoklassen k aus einem paarweisen Vergleich der Simulationen Ref_min, Ref_med und Ref_max sind. Analog berechnet sich die waldbauliche Variabilität aus den Simulationen Ref_med, Kl_med und Bio_med. Der größte Wert der jeweiligen drei paarweisen Vergleiche ergibt die klimatische Unsicherheit und die waldbauliche Variabilität.

Die Analyse der Trockenstressvulnerabilität zum Status quo (2011) zeigt nur für die Region Fläming nennenswerte Flächenanteile im mittleren (9 %) und hohen (7 %) Vulnerabilitätsbereich (*Abb. 7*). Bis zum Ende der Projektionsperiode (2070) wird eine generelle Zunahme des Trockenstressrisikos projiziert, wobei die beiden westlichen Regionen Diepholz und Uelzen mit je nach Simulationsvariante schwankenden nennenswerten Anteilen in der geringen Vulnerabilitätsklasse im Gegensatz zu den beiden östlichen Regionen mit fast ausschließlich Anteilen in der mittleren und hohen Vulnerabilitätsklasse begünstigt sind. Zwischen den drei waldbaulichen Entwicklungspfaden ergeben sich nur geringe Unterschiede, hervorgerufen durch die unterschiedlichen Baumartenzusammensetzungen. Die waldbauliche Variabilität schwankt zwischen kaum merklichen 0,01 im Fläming, 0,06 in Oder-Spree, 0,07 in Diepholz und immerhin 0,12 in Uelzen. Die sehr hohen Werte der klimatischen Unsicherheit zwischen 0,24 in Oder-Spree bis 0,74 in Uelzen zeigen jedoch auf, dass der Klimaeffekt in allen Entwicklungspfaden zu erheblichen Veränderungen führen kann. Im Falle der Region Uelzen bedeutet dies, dass in 2070 der Flächenanteil von 74 % im geringen Vulnerabilitätsbereich unter dem

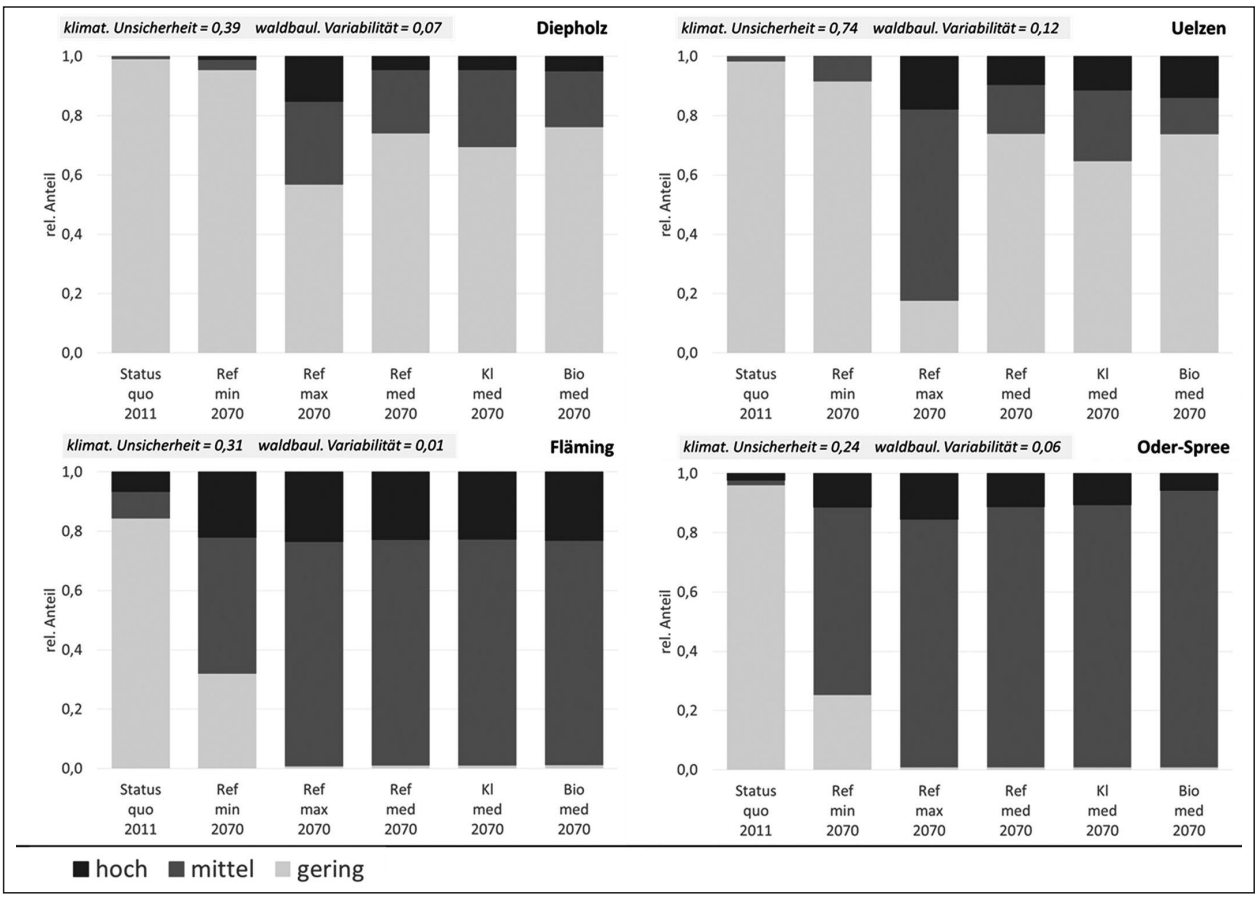


Abb. 7

Flächenanteile aller Baumarten kombiniert in den Trockenstressklassen gering, mittel, hoch in den vier Regionen zum Status quo (2011) und am Ende der Projektion 2070.

Area proportions of all species combined for the drought vulnerability classes low (light gray), medium (gray) and high (dark gray) in the four regions in 2011 and 2070.

Referenzpfad im Medianklimalauf auf 18 % unter dem Maximumklimaszenario absinken kann. Im günstigsten Fall unter Minimumklimabedingungen könnte der Anteil jedoch auch bei 92 % liegen.

Bei Betrachtung des Trockenstressrisikos ist das Verhältnis zwischen der geringen waldbaulichen Variabilität und der großen klimatischen Unsicherheit demnach konträr zu den Auswirkungen auf die ertragskundlichen Parameter mit einem großen Einfluss der waldbaulichen Entwicklungspfade und den eher geringen Schwankungen auf Grund des Klimaeffektes. Dennoch wird das stark klimagetriebene Trockenstressrisiko einen großen Einfluss auf die zukünftige Baumartenzusammensetzung (vgl. *Tab. 5*) und damit die waldbaulichen Entwicklungspfade haben.

4. DISKUSSION

Szenariostudien unterstützen die Ableitung von Handlungsempfehlungen für die Forstplanung (Mendoza und Sprouse, 1989; Gadow und Puumalainen, 2000; Gadow, 2005). Clark et al. (2001) betonen, dass Szenarien für Entscheidungsträger Möglichkeiten aufzeigen, die aber mit Unsicherheiten behaftet sind. Nach Clark et al. (2001) verhält sich der Informationsgehalt einer Szenariosimulation für die Entscheidungsfindung ferner invers proportional zu der in der Simulation enthaltenen Unsicherheit. Anschaulich illustrieren Wilby und Dessai (2010), wie sich die Unsicherheit am Beispiel der Klimafolgenforschung kaskadenartig vergrößert, beginnend mit einer Annahme über die zukünftige Gesellschaft, dem darauf aufbauenden Emissionsszenario, dem globalen Klimamodell über die Regionalisierung des Klimaszenarios, dem Wirkmodell bis hin zu den Anpassungsmaßnahmen.

4.1 Kritische Bewertung der Wirkungsanalyse

Prinzipiell wird für Wirkungsanalysen ein Ensemble-Ansatz empfohlen, also eine Kombination verschiedener Klimamodelle und mehrerer Emissionsszenarien (vgl. Knutti, 2010). Das Projekt ReKliEs-De erstellt derzeit diesbezügliche Empfehlungen für die Impakt-Forschung (Hessisches Landesamt für Naturschutz, Umwelt und Geologie, 2016). Im Rahmen des ReKliES-De-Projektes werden auch verschiedene regionale Klimamodelle, u. a. STARS, evaluiert. Die hier vorgestellte Wirkungsanalyse wird ganz wesentlich von den Klimaprojektionen des

regionalen Klimamodells STARS (ORLOWSKY et al., 2008) getrieben. Das statistische Modell STARS erstellt Klimaprojektionen auf Grundlage eines temperaturgetriebenen Resampling-Algorithmus'. Der Temperaturantrieb wird als periodischer Trend durch globale Klimamodelle (in dieser Untersuchung: INM-CM4, ECHAM6 und ACCESS1.0) vorgegeben. Das Resampling wird in einem ersten Schritt durch neu geordnete Jahresklimawerte und in einem zweiten Schritt durch eine Neuordnung von 12-Tages-Wettersequenzen durchgeführt. WECHSUNG und WECHSUNG (2014a und b) setzen sich kritisch mit der Annahme von GERSTENGABE et al. (2013) auseinander, dass die Validität von STARS durch die Ähnlichkeit zwischen den mittleren statistischen Schätzern (Mittelwert, Standardfehler, Perzentile etc.) der Beobachtungsperiode 1951 bis 1975 und der Validierungsperiode mit durch den TCR-Algorithmus neu geordneten Werten untermauert werden kann. Des Weiteren weisen WECHSUNG und WECHSUNG (2014a und b) einen negativen Bias in der Projektion der Niederschlags von ca. 5% je 1°C-Temperaturerhöhung nach. Trotz der Modelllimitationen empfehlen WECHSUNG und WECHSUNG (2014a) STARS-basierte Klimaprojektionen für Wirkungsanalysen. So modellieren beispielsweise BLOCH et al. (2014) die regionalen Auswirkungen von Trockenheit auf den Ertrag von Klee und Luzerne unter STARS-Klimaprojektionen für die Periode 2062 bis 2092 und ziehen Schlussfolgerungen für eine zukünftige Bewirtschaftung.

Somit müssen auch die hier dargestellten Ergebnisse der auf STARS basierenden Wirkungsanalyse als Vulnerabilität der Wälder unter dem projizierten Klimaänderungstyp, trockenere Sommer und nassere Winter, interpretiert werden. Generell muss betont werden, dass Szenariostudien und Wirkungsanalysen immer nur Projektionen auf Basis des derzeitigen Wissensstandes sind. Allein die sich in den letzten Jahren als Antrieb der Globalmodelle verändernden Emissionsszenarien verdeutlichen, wie unsicher langfristige Aussagen sind (vgl. MOSS et al., 2010).

Ein weiteres wesentliches Merkmal der vorgestellten Wirkungsanalyse ist die Simulation ohne simultane Rückkopplung des Waldwachstums mit abiotischen und biotischen Störungen sowie keine Berücksichtigung eventueller Ausfälle durch Mortalität. Wie eingangs dargestellt, ist es Ziel dieser Untersuchung, die klimatischen und waldbaulichen Effekte auf die Waldentwicklung abzubilden. Dies ist nur möglich, wenn Störgrößen, die zu einer Anpassung des Systems führen, explizit in den Simulationen unberücksichtigt bleiben. Störgrößen sind in diesem Zusammenhang z. B. Vitalitätsverlust und Minderwachstum durch Insektenfraß und Ausfälle durch Sturmereignisse. Auch eine angepasste Baumartenwahl, die durch Klimawandel veränderte Standortsverhältnisse berücksichtigt, wäre in diesem Zusammenhang eine die Wirkungsanalyse störende Größe. A posteriori werden die Waldentwicklungsvarianten hinsichtlich der einzelnen Risikofaktoren untersucht und im Sinne einer Vulnerabilitätsanalyse bewertet. Am Beispiel des Trockenstresses wird dies hier verdeutlicht.

Allgemein stellen die hier präsentierten Ergebnisse die über Baumarten, Altersklassen, Besitzverhältnisse, Standortsunterschiede u. a. aggregierten mittleren Verhältnisse in den vier Regionen Diepholz, Uelzen, Fläming und Oder-Spree dar. Schlussfolgerungen aus dem Variantenstudium der drei waldbaulichen Entwicklungspfade und der drei Klimaprojektionen sind somit unter Beachtung einer nachgeschalteten Vulnerabilitätsanalyse im Sinne einer regionalen Waldbauplanung und Nachhaltigkeitsprüfung eines größeren Forstbetriebes möglich. Mehr noch, sie sind angesichts der Langfristigkeit der forstlichen Produktion auf der einen Seite und dem Ausmaß, der Geschwindigkeit sowie der räumlichen wie zeitlichen Verteilung der projizierten Klimaänderungen auf der anderen Seite notwendig. Im konkreten Fall sind zudem die Unterschiede zwischen den entlang eines Niederschlagsgradienten aufgereihten Regionen ebenfalls interpretierbar.

4.2 Variabilität der ertragskundlichen und forstplanerischen Kenngrößen

Das Variantenstudium zeigt auf, dass die abgebildete klimatische Unsicherheit für die Bewirtschaftung der aktuellen Bestockung der vier Modellregionen im Hinblick auf die ertragskundlichen Größen Vorrat, Nutzung und Zuwachs sowie den Nachhaltshiebsatz zur Zeit nur eine geringe Relevanz hat, da die Unterschiede zwischen den Waldbaustrategien wesentlich größer sind als zwischen den Klimaszenarien. Forstplanerische Entscheidungen sollten jedoch den Klimatrend berücksichtigen (BOLTE et al., 2009; DAY und PÉREZ, 2013; SCHELHAAS et al., 2015). Die aus unterschiedlichen Projektionen erwachsende klimatische Unsicherheit spielt jedoch in den untersuchten Modellregionen bei einer Vernachlässigung der sich ebenfalls ändernden Risiken eine untergeordnete Rolle. Ein wesentlich größerer Handlungsspielraum erwächst der Forstplanung durch alternative Bewirtschaftungskonzepte, wie den hier vorgestellten drei waldbaulichen Szenarien Referenz, Klimaschutz und Biodiversität.

Der Hiebsatzweiser nach GEHRHARDT (1923) fasst das Wechselspiel von Vorräten, Nutzungen und Zuwachs zusammen. Die waldbauliche Behandlung unter dem Klimaschutzpfad, insbesondere die höheren Nutzungsvolumina und der frühere Erntezeitpunkt durch geringere Zielstärken, führen zu Beginn der Projektionsperiode beim Zuwachs und auch bei dem nachhaltig nutzbaren Holzvolumen gemäß des Hiebsatzweisers zu einem drastischen Rückgang in allen Regionen. Durch den Anbau ertragsstarker Nadelbaumarten wird in den Regionen Fläming und Oder-Spree bereits innerhalb des Projektionszeitraumes ein wieder ansteigender Nachhaltshiebsatz erreicht. Die bezüglich Nutzungsmassen und Zielstärken etwas moderatere Referenzvariante führt im Vergleich zum Klimaschutzpfad zu einer ähnlichen jedoch zeitverzögerten und abgeschwächten Entwicklung in Uelzen, Fläming und Oder-Spree. Lediglich für den Fläming mit seinem relativ ausgeglichenen Altersklassenaufbau zeigen die Projektionsergebnisse, dass der Waldumbau mit vornehmlich führendem Laubholz ebenfalls den Rückgang im Zuwachs und Nachhaltshieb-

satz verlangsamen und unter dem Minimumklimalauf sogar umkehren kann. Hier wird auch deutlich, dass die klimatische Unsicherheit bei der Festsetzung des Nachhaltshiebsatzes für die Forstplanung bedeutsam ist. Im Fläming beträgt die klimatische Unsicherheit im Mittel 0,8 m^3/ha/a, sodass ein mittlerer projizierter Nutzungsansatz von ca. 5,5 m^3/ha/a um ca. 7 % im günstigsten Fall nach oben bzw. im ungünstigsten Fall nach unten korrigiert werden müsste.

Neben der Variabilität der ertragskundlichen und forstplanerischen Kenngrößen durch die Unsicherheit in der Entwicklung der Umweltbedingungen und durch den waldbaulichen Handlungsraum beeinflussen weitere Unsicherheitsfaktoren die reale Waldentwicklung. Einen großen Einfluss auf das Nutzungsvolumen hat z. B. direkt die Entwicklung der Holzpreise (Leskinen und Kangas, 1998) bzw. indirekt die Preisentwicklung von Substituten wie Rohöl (Härtl und Knoke, 2014) oder der Umfang naturschutzrechtlicher Restriktionen (Rüther et al., 2007; Seintsch et al., 2012). Abweichungen der durch die Forstplanung vorgesehenen Waldentwicklung können jedoch auch durch Unzulänglichkeiten in der Umsetzung der Bewirtschaftungskonzepte entstehen. So konnte bereits auf der untersten Umsetzungsebene, beim Auszeichnen eines Bestandes, gezeigt werden, dass bei gleicher Durchforstungsanweisung zum Teil erhebliche Abweichungen in der Entnahmemasse zwischen Förstern bzw. Förster und Harvesterfahrer und sogar bei mehrfacher Auszeichnung durch einen Förster auftreten (Albert, 2006). Das Wissen um die einzelnen Unsicherheitsfaktoren und ihren Wirkamplituden auf die Zielgrößen ist essentiell, wenn Handlungsempfehlungen erfolgreich in die Forstplanung integriert und diese dann in der Praxis umgesetzt werden sollen.

4.3 Bewertung der Trockenstressanalyse

Häufig verwendete Indikatoren zur Charakterisierung von Trockenstress sind der relative Transpirationsindex *RTI* (Müller, 2006; Wellpott, 2005) oder der relative Bodenwassergehalt *REW* (Garnier et al., 2007; García-Santos et al., 2009). Letztgenannter Indikator deutet entsprechend der Ergebnisse von Choat et al. (2012) darauf hin, dass Abweichung von den langjährigen Witterungsbedingungen eine zentrale Bedeutung für das bestandesspezifische Trockenstressrisiko aufweisen. Gegenwärtig ist das Wissen noch zu lückenhaft, um zuverlässig die Wirkung von Trockenstress baumart- und standortspezifisch abzuschätzen (Choat et al., 2012; Anderegg et al., 2013). Ein Indikator, der stärker die absolute Wasserverfügbarkeit berücksichtigt, ist der RTI. Müller (2006) beschreibt die Möglichkeiten, diesen für praktische Anwendungen durch die Verknüpfung von klimatischer Wasserbilanz und nFK abzuleiten. Entsprechend wurde auch in dieser Untersuchung auf einen vergleichbar einfachen Trockenstressindikator zurückgegriffen. Dies geschieht mit dem Ziel, anhand der langfristigen Standortswasserbilanz das trockenstressbedingte Anbaurisiko für Baumarten flächendeckend einzuschätzen (vgl. Albert et al., 2015). Ein langfristiger Klimatrend der Standortswasserbilanz erscheint als unscharfes Entscheidungskriterium für die Forstplanung geeignet, wohl wissend, dass singuläre kurzzeitige Trockenperioden dennoch der vermeintlich sicheren Baumartenwahl widersprechen können. Im Sinne einer Entscheidungsunterstützung sind auch die angenommenen Grenzwerte der Vulnerabilitätsklassen (vgl. *Tab. 4*) zu verstehen. Die Rangreihung der Baumarten hinsichtlich ihrer Trockenstressvulnerabilität wird durch zahlreiche Untersuchungen unterstützt (Otto, 1994; Bredemeier et al., 2001; Roloff und Grundmann, 2008; Zang et al., 2011b; Kätzel et al., 2015). Dennoch sollten die Klassengrenzen in der Forstplanung nicht zu starr angewendet werden. Vielmehr ergeben sich im Einzelfall Interpretationsspielräume, z. B. hinsichtlich der Mischungsanteile bei einer Empfehlung, eine Baumart auf einem Standort nur noch als Mischbaumart zu planen.

Auf der Grundlage der in dieser Untersuchung analysierten Trockenstressvulnerabilitäten ergibt sich im Vergleich zu den ertragskundlichen Ergebnissen eine gänzlich gegensätzliche Einschätzung der Wirkung von klimatischer Unsicherheit und waldbaulichen Varianten. Am Beispiel der hier verwendeten Trockenstressvulnerabilität zeigt sich, dass die Risikobewertung erheblich durch die klimatische Unsicherheit geprägt ist. Die Einschätzung, wie groß der mittel bis stark trockenstressgefährdete Flächenanteil ist, hängt direkt mit der projizierten Trockenheit zusammen, die je nach unterstellter Klimaentwicklung große Unterschiede aufweisen kann. Eine detaillierte baumartspezifische Analyse am Beispiel der Region Uelzen offenbart die gravierenden Unterschiede in der Trockenstressbeurteilung zwischen den drei Klimaläufen. So wird unter dem Minimumlauf nur für geringe Flächenanteile von Buche und anderem Laubholz sowie bereits für 66 % der Fichtenfläche eine mittlere Trockenstressgefährdung projiziert. Unter dem Medianklimalauf befindet sich die gesamte Fichtenfläche in der mittleren (33 %) bzw. starken (66 %) Gefährdungsklasse. Nur noch geringe Flächenanteile der Buche (8 %) aber immerhin noch über 50 % der Fläche des anderen Laubholzes werden als gering gefährdet angesehen. Es werden ebenfalls bereits einige Flächenanteile der Eiche (12,5 %) und der Douglasie (17 %) im mittleren Trockenstressrisiko eingestuft. Die komplette Kiefernfläche wird wie auch unter dem Minimumszenario als gering trockenstressgefährdet klassifiziert. Das Maximumklimaszenario projiziert für fast die gesamte Fichtenfläche eine starke Trockenstressvulnerabilität, ebenso für 78 % der Buchen- und 56 % der anderen Laubholzflächen. Fast die komplette Douglasienfläche (94 %) wird als mittel trockenstressgefährdet klassifiziert. Die Einstufung von 81 % der Kiefernfläche im mittleren Vulnerabilitätsbereich unter dem Maximumszenario ist dabei mit der Einschränkung einzuordnen, dass sich die eingeschätzten Standortswasserbilanzen im unteren Bereich des bei dieser im Allgemeinen als besonders trockenstresstolerant geltenden Baumart ohnehin am weitesten aufgespannten mittleren Vulnerabilitätsbereiches befinden.

Während die Quantifizierung der klimatischen Unsicherheit die möglichen Auswirkungen des Klimawandels auf die potenzielle Trockenstressvulnerabilität und

je nach Risikopräferenz des Entscheidungsträgers den notwendigen Handlungsbedarf aufzeigt, weisen die Unterschiede in der Trockenstressanalyse zwischen den waldbaulichen Entwicklungspfaden die tatsächlich durch Bestandesbehandlung und Waldumbau möglichen Anpassungen auf. Es ist dabei zu beachten, dass in den vorgestellten Simulationen zukünftige Risiken in der Formulierung der waldbaulichen Szenarien nicht berücksichtigt wurden. Bei Waldumbau wird die Baumartenwahl auf der Grundlage der Standortsbedingungen zum Status quo (2011) getroffen. Eine Anpassungsstrategie z. B. an sich verschärfende Trockenheit wird nicht simuliert. Auf dieser Grundlage verschieben sich die Flächen- und Vorratsanteile der Baumarten durch Wachstum, Durchforstung und Ernte sowie Waldumbau (vgl. *Tab. 5*). Dabei fällt die waldbauliche Variabilität zwischen den Entwicklungspfaden Referenz, Klimaschutz und Biodiversität in den vier Regionen im Vergleich zur klimatischen Unsicherheit bezogen auf die Trockenstressvulnerabilität sehr gering aus. Eine eingehende Betrachtung der Region Uelzen, die mit 0,12 die höchste waldbauliche Variabilität der vier Regionen aufweist, verdeutlicht die Ursachen. Unter dem Klimaschutzpfad wird bis 2070 eine Flächenreduktion der als trockenstresstolerant eingestuften Kiefer um 34 %-Punkte projiziert, während die Fläche der deutlich gefährdeteren Buche um 15 %-Punkte sowie der Douglasie um 27 %-Punkte zunimmt (vgl. *Tab. 5*). Dabei ist zu beachten, dass die Buche im Rahmen des Waldumbaus größtenteils als zweite Baumart in Mischung mit den trockenstresstoleranteren Arten Kiefer oder Douglasie vorgesehen ist (vgl. WET-Matrizen; Albert et al., 2016). Untersuchungen von Pretzsch et al. (2015) an überwiegend 60–80-jährigen Beständen entlang eines Produktivitätsgradienten durch Europa zeigen, dass Mischbestände aus Buche und Kiefer in dieser Entwicklungsphase auf geeigneten Standorten in der Trockenmassenleistung produktiver sein können als Reinbestände. Anhand von Durchmesserzuwachsdaten aus Süddeutschland konnte ebenfalls für die Buche in Mischung mit anderen Baumarten auch eine höhere Toleranz gegenüber Trockenheit festgestellt werden (Pretzsch et al., 2013, Metz et al., 2016). Eine projizierte Zunahme der Buchenfläche in den trockenen Gebieten des Fläming, hier speziell im Niederen Fläming, und in Oder-Spree ist vor diesem Hintergrund dennoch wenig wahrscheinlich. Auch unter dem Referenzszenario kommt es in Uelzen zu einer Flächenveränderung von Kiefer (–18 %-Punkte) hin zu Buche (+7 %-Punkte) und Douglasie (+13 %-Punkte). Nur unter dem Biodiversitätspfad mit der insgesamt geringsten Veränderungsrate nimmt die Buchenfläche (+8 %-Punkte) im Wesentlichen auf Kosten der durch Trockenheit am stärksten gefährdeten Fichte (–6 %-Punkte) und zu einem deutlich geringen Teil durch Flächenreduktion der Kiefer (–3 %-Punkte) zu. In der Analyse der Trockenstressvulnerabilität schneidet die Klimaschutzvariante mit einem Flächenanteil von 35 % in der mittleren und starken Gefährdungsklasse am schlechtesten ab. Dies ist auf den größeren Fortschritt des Waldumbaus auf Grund der geringeren Zielstärken bzw. kürzeren Produktionszeiträume zurückzuführen und nicht auf die bevorzugte Begründung von Waldentwicklungstypen mit führendem Nadelholz. Bei dem Referenz- und dem Biodiversitätspfad, für die mit jeweils 26 % deutlich weniger trockenstressgefährdete Flächenanteile in 2070 projiziert werden, kommen dementsprechend die höheren Zielstärken bzw. längeren Produktionszeiträume zum Tragen. Langfristig ist jedoch beim Biodiversitätspfad mit seiner Orientierung an der potenziellen natürlichen Vegetation mit den höchsten Flächenanteilen in der mittleren und vor allem in der hohen Gefährdungsklasse zu rechen. Dem hier aufgezeigten Trockenstressrisiko kann durch eine angepasste Baumartenwahl, die Nutzung des positiven Effektes von Mischbeständen und eventuell durch eine frühzeitige Abnutzung besonders gefährdeter Bestände im Rahmen einer expliziten Anpassungsstrategie begegnet werden.

4.4 Waldbauliche Schlussfolgerungen

Die Standortsbedingungen verändern sich mit dem Klimawandel, was sich direkt auf die Ertragsaussichten und Produktionsrisiken der Forstbetriebe auswirkt. Nachhaltig wirksame Anpassungsstrategien müssen daher sich verschärfende Risikofaktoren sowie neu entstehende Bedrohungen antizipieren (Gadow, 2000; Buongiorno und Zhou, 2015). Entscheidungen der Forstplanung wurden allerdings schon immer unter Unsicherheit getroffen. Neu ist die Geschwindigkeit, mit der einige Umweltveränderungen auf die Risikostrukturen und Wachstumstrends wirken. Daher müssen bereits heute bestehende Bestände und Waldbehandlungskonzepte den neuen Rahmenbedingungen angepasst werden. Dies sollte nach Bolte et al. (2011) flexibel mit Hilfe einer Mischung aus aktiver Förderung, passiver Duldung und aktiven Gegenmaßnahmen geschehen. Unter aktiver Förderung werden dabei u. a. angepasste Bestandesbehandlungskonzepte und ein zielgerichteter Waldumbau verstanden. Passive Duldung umfasst z. B. die Erhaltung und Förderung standortsgemäßer Naturverjüngung, während ein Baumartenwechsel bei nicht standortsgemäßer Verjüngung als aktive Gegenmaßnahme gesehen wird. Auf Grund der langen Produktionszeiträume hat letzteres ohne Aktionismus und mit Augenmaß zu erfolgen (Spellmann et al., 2011). Dies gilt insbesondere auch angesichts des hohen investiven Charakters eines aktiven Waldumbaus.

Als Anpassungsstrategien bieten sich drei zeitlich differenzierende Maßnahmenkataloge an (Spellmann, 2010). Kurzfristig ist die Stabilisierung der vorhandenen Wälder vorrangig. Dies kann u. a. durch eine Förderung der Einzelbaumvitalität, durch den Erhalt und begünstigende Pflege von Mischbaumarten und ggf. durch eine Verkürzung der Produktionszeiten und somit kürzeren Gefährdungszeiträumen gewährleistet werden. Mittelfristig ist eine aktive Risikominderung von Bedeutung. Diese umfasst Elemente wie die Förderung standortsgemäßer Naturverjüngung, eine ausreichende Anzahl von Z-Bäumen mit Reserve, eine angepasste Vorratshöhe, eine differenzierte Zielstärkennutzung und ein konsequenter Waldschutz inklusive angepasster Wildbestände. Schließlich trägt langfristig der Waldumbau

mit standortsgemäßen und anbauwürdigen eingeführten Baumarten (vgl. VOR et al., 2015) dazu bei, Totalausfälle von Beständen zu vermeiden und die Anpassung an die Auswirkungen der sich wandelnden Umweltbedingungen zu verbessern. Eine geeignete Mischung vom Baumarten kann einen zusätzlichen positiven Effekt aufweisen.

Für die hier analysierten Wälder in den vier Regionen können hinsichtlich der Auswirkungen des Klimawandels auf die ertragskundlichen und forstplanerischen Kenngrößen und der Analyse der Trockenstressvulnerabilität folgende Empfehlungen gegeben werden:

(1) In der Region Diepholz werden die Auswirkungen des Klimawandels insbesondere auf das Trockenstressrisiko als moderat eingestuft, d. h. auch zukünftig steht in dieser Region der Forstwirtschaft ein breites Spektrum an standortsgemäßen Baumarten zur Verfügung. Es besteht somit wenig Anpassungsbedarf hinsichtlich des Klimawandels. Aber es gibt deutliche Optimierungsmöglichkeiten bezüglich anderer Ziele. Der hohe Anteil von Weichlaubhölzern mit relativ geringer flächenbezogener Volumenleistung sollte ebenso wie Anteile der Kiefernfläche zu Gunsten ertragsstärkerer Baumarten reduziert werden, was sich positiv auf die CO_2-Bindung, die Rohstoffversorgung sowie die Ertragslage der örtlichen Forstbetriebe auswirken würde.

(2) In Uelzen sollten weiterhin Mischbestände gefördert werden. Bei der Nutzung von Altbeständen sollte verstärkt auf die Klimaanpassung der Baumarten in der neuen Waldgeneration geachtet werden. Ggf. muss ein aktiver Waldumbau stattfinden, z. B. ist der hohe Fichtenanteil kritisch auf Standortseignung und Trockenstressvulnerabilität zu prüfen. Die hohe klimatische Unsicherheit in Bezug auf die Trockenstressvulnerabilität verdeutlicht für die Region Uelzen, dass die Forstplanung eine große Verantwortung trägt und der Waldumbau nicht schablonenhaft, sondern einzelfallweise gestaltet werden sollte. Ein schrittweiser Umbau mit einer fortwährenden Rückkopplung der Anpassungsstrategie mit den Fortschritten der Klimafolgenforschung kann durch den ungleichen Altersklassenaufbau und die jährlich anstehenden Verjüngungsflächen stattfinden.

(3) In den Regionen Fläming, hier speziell im Bereich des trockeneren Niederen Fläming im Gegensatz zu dem etwas feuchteren Hohen Fläming, und Oder-Spree wird sich die bereits heute bestehende Trockenstressproblematik zukünftig weiter verschärfen. Selbst für die als trockenstresstolerant einzustufende Kiefer wird zunehmend eine mittlere Gefährdung projiziert. Auch die vorhandene klimatische Unsicherheit in den Projektionen zeigt selbst bei optimistischer Interpretation nur geringe Handlungsspielräume bei der Baumartenwahl auf, was für eine stärkere Beteiligung anbauwürdiger und ökologisch zuträglicher eingeführter Baumarten wie Douglasie, Küstentanne und Roteiche spricht. Eine Diversifizierung des Baumartenspektrums ist durch Mischbestände notwendig, z. B. durch Laubholz in Mischung mit führender Kiefer oder Douglasie. Hierbei sollte auch die Buche zumindest als Begleitbaumart nicht ausgeschlossen werden, obwohl die Untersuchungen von PAUL et al. (2013) im Fläming zeigen, dass der Wasserbedarf von Buchenvoranbauten hoch ist und es zweifelhaft erscheint, ob der Wasserstress in der Jugendphase künftig eine stärkere Beteiligung der Buche überhaupt zulässt. Aber auch hier müssen einzelfallweise die klimatischen Unterschiede, z. B. zwischen dem Hohen und dem Niederen Fläming, beachtet werden. Des Weiteren erscheint auch eine Förderung der Eiche/Roteiche auf geeigneten Standorten als sinnvoll. Die Kiefer wird jedoch weiterhin in den beiden Regionen die dominierende Hauptbaumart bleiben, auch wenn andere Risiken wie z. B. die weiterhin ansteigende Waldbrandgefahr oder Kahlfraß durch Kieferngroßschädlinge existent sind (vgl. FLECK et al., 2015).

Abschließend ist festzustellen, dass die vorliegende Szenariostudie die Effekte der Klimaänderung und insbesondere der klimatischen Unsicherheit sowie die Wirkung alternativer Waldbaukonzepte auf die Waldentwicklung aufzeigen kann. Indem die Projektion der Waldentwicklung ohne Berücksichtigung von Risikofaktoren durchgeführt wurde, können die klimatischen und waldbaulichen Effekte direkt miteinander verglichen werden. Die nachträgliche Risikoanalyse, hier am Beispiel des Trockenstresses dargestellt, ist integraler Bestandteil bei der Bewertung der einzelnen waldbaulichen Entwicklungspfade. Die Interpretation der Projektionsergebnisse dient der Forstplanung u. a. bei der Formulierung notwendiger Anpassungsstrategien. Ein Vergleich der vier Regionen unterstreicht die eingangs erwähnte Forderung nach einem adaptiven Anpassungskonzept, welches in Anbetracht der langfristigen Bindung maßvoll umgesetzt werden sollte.

5. ZUSAMMENFASSUNG

Die vorgestellte Untersuchung zeigt die Auswirkungen der Unsicherheit in den sich verändernden klimatischen Standortsbedingungen, hier quantifiziert durch die Verwendung von drei unterschiedlichen Klimaprojektionen, auf ertragskundliche Größen am Beispiel von vier Regionen im norddeutschen Tiefland auf (*Tab. 1*). Es wird der Frage nachgegangen, ob aus der klimatischen Unsicherheit Konsequenzen für die Forstplanung erwachsen oder ob unterschiedliche Waldbaukonzepte die klimatischen Effekte in der Waldentwicklung überlagern. Der waldbauliche Handlungsraum wird in dieser Untersuchung durch drei Entwicklungspfade charakterisiert: dem *Referenzszenario* mit einem naturnahen Waldbau in Anlehnung an das LÖWE-Programm, dem *Biodiversitätspfad* im Anhalt an die Biodiversitätsstrategie des Bundes und der *Klimaschutzstrategie*, die eine Maximierung der Kohlenstoffspeicherung anstrebt (*Tab. 3*).

Die Waldentwicklung in den vier Regionen wird unter den verschiedenen waldbaulichen Entwicklungspfaden und Klimaprojektionen mit Hilfe des Simulationssystems *WaldPlaner*, dessen Wachstumsmodell sensitiv auf Bodenparameter und Klimagrößen reagiert, von 2011 bis 2070 fortgeschrieben (*Abb. 1*). Indem die Projektion der Waldentwicklung ohne Berücksichtigung von Risikofaktoren durchgeführt wird, können die klimatischen und waldbaulichen Effekte direkt miteinander verglichen werden.

Die naturalen Ausstattungen in den vier Regionen, insbesondere die Standortseigenschaften (*Tab. 2*), die

klimatischen Bedingungen (*Abb. 2*), die Altersklassensausstattung (*Abb. 3*) und Baumartenverteilung (*Tab. 5*), beeinflussen die projizierte Waldentwicklung maßgeblich. Die Szenariostudie zeigt, dass in der Vorratsentwicklung (*Abb. 4*), im Erntevolumen (*Tab. 6*), beim laufenden Zuwachs (*Abb. 5*) und beim Hiebsatzweiser (*Abb. 6*, *Tab. 8*) die klimatische Unsicherheit deutliche Auswirkungen hat, die mit fortschreitender Projektionsdauer zunehmen. Die Steuerungsmöglichkeiten durch waldbauliche Konzepte können jedoch einen weitaus größeren Effekt haben.

Zur Ableitung von Handlungsempfehlungen und Entwicklung von Anpassungsstrategien ist eine nachgeschaltete Risikoanalyse unumgänglich. In dieser Untersuchung werden die klimatischen und waldbaulichen Effekte auf Risikofaktoren am Beispiel der Trockenstressvulnerabilität aufgezeigt (*Tab. 4*, *Abb. 7*). Es ergibt sich, dass bei Betrachtung des Trockenstressrisikos der waldbauliche Effekt gering und der klimatische Einfluss groß ist, d. h. die Auswirkungen auf den Trockenstress sind konträr zu denen auf die ertragskundlichen Größen.

Auf Grund dieses starken Effektes der klimatischen Unsicherheit auf klimasensitive Risikofaktoren muss die Forstplanung verantwortungsbewusst agieren und einen Waldumbau nicht schablonenhaft umsetzen. Eine flexible Gestaltung der Anpassungsstrategien mit einer fortwährenden Rückkopplung mit den Fortschritten der Klimafolgenforschung ist notwendig. Die Ergebnisse dieser Szenariostudie dienen dazu, die Effekte des Klimawandels, das Ausmaß der Unsicherheit und die waldbaulichen Handlungsmöglichkeiten gegeneinander abzuwägen und bei der Formulierung von Handlungsempfehlungen und Anpassungsstrategien zu berücksichtigen.

6. SUMMARY

Title of the paper: *Effects of climatic uncertainty on forest management – a case study in four regions in the north German lowlands.*

The presented study shows the effects of climate uncertainty, characterized using three different climate projections, on growth and yield in four regions of the north German lowlands (*tab. 1*). We examine whether climate uncertainty affects forest management or whether different silvicultural concepts might eviscerate the climatic effects in forest development. Three silvicultural concepts are applied: the *reference scenario* defined by the principles of close-to-nature silviculture, the *biodiversity strategy* indending to increase the area of natural vegetation, and the *climate protection* path trying to maximize CO_2 sequestration (*tab. 3*).

The simulation system *WaldPlaner* with site- and climate-sensitive growth functions projects forest development in the four regions from 2011 to 2070 applying the three silvicultural concepts as well as three climate projections (*fig. 1*). Climatic and silvicultural effects are directly comparable as the projection excludes any tree or forest losses due to risk factors, i.e. no interaction of mortality and forest development is simulated.

The starting conditions in the four regions, i.e. site and climate characteristics (*tab. 2*, *fig. 2*), age class distribution (*fig. 3*) and species proportions (*tab. 5*) heavily influence the projected forest development. The scenario study shows the clear effects of climatic uncertainty on standing and harvested volume (*fig. 4*, *tab. 6*), on periodic annual increment (*fig. 5*) and on the prescribed yield index (*fig. 6*, *tab. 8*). Climatic uncertainty increases with time. Nevertheless, we show that silvicultural measures are capable to control forest development to a much stronger degree.

A subsequent risk analysis is indispensable to recommend management options or to derive adaptation strategies. Here, we show the effect of climate uncertainty and silvicultural practices on risk factors using drought vulnerability as an example (*tab. 5*, *fig. 6*). Obviously the climate effect is much stronger on drought vulnerability than the silvicultural effect. This result is contrary to the effects on growth and yield.

Keeping in mind the strong influence of climatic uncertainty on climate-sensitive risk factors forest management needs to plan responsibly and forest conversion must not be in stereotypes. A flexible formulation of adaptation strategies continuously acknowledging progress in climate change research is necessary. The results of the presented scenario study help to evaluate the climate effects, the degree of uncertainty and silvicultural alternatives on forest development in order to recommend management options and to derive adaptation strategies.

7. RÉSUMÉ

Titre de l'article: *Impact de l'incertitude climatique sur la planification forestière avec l'exemple de quatre régions du bas pays du Nord de l'Allemagne.*

La présente recherche montre les impacts que cause l'incertitude sur les conditions climatiques locales en cours de changement, qui sont ici quantifiées au moyen de trois projections climatiques différentes, sur la base de valeurs de production prises en exemple dans quatre régions du bas pays du Nord de l'Allemagne (*Tabl. 1*). La question suivante a été examinée, à savoir si, en raison de l'incertitude climatique, il y a eu des répercussions dans la planification forestière ou bien si différents concepts sylvicoles incluent les effets climatiques dans le développement forestier. Le terrain d'intervention sylvicole est caractérisé ici au travers de trois chemins de développement: le *scenario de référence* avec une sylviculture proche de la nature sur le modèle du Programme-LÖWE; le *chemin de la biodiversité* avec l'appui de la stratégie fédérale de biodiversité; la *stratégie de protection du climat* qui vise une économie maximale de carbone (*Tabl. 3*).

Le développement forestier dans les quatre régions a été actualisé de 2011 à 2070 au travers des trois différents chemins de développement sylvicole et des prévisions climatiques, à l'aide du système de simulation *WaldPlaner* dont le modèle de croissance réagit avec finesse aux paramètres du sol et aux valeurs climatiques (*Fig. 1*). Du fait que la prévision du développement forestier a été réalisée sans tenir compte des

facteurs de risques, les effets climatiques et sylvicoles peuvent être directement comparés les uns avec les autres.

Les composantes naturelles des quatre régions, en particulier les propriétés stationnelles (*Tabl. 2*), les conditions climatiques (*Fig. 2*), la distribution des classes d'âges (*Fig. 3*) et la répartition des espèces ligneuses (*Tabl. 5*), influencent le développement forestier prévu de manière prépondérante. L'étude des scenarii fait apparaître que dans le développement du volume sur pied (*Fig. 4*), dans les volumes de récolte (*Tabl. 6*), dans l'accroissement courant (*Fig. 5*) et dans l'indice de rendement prescrit (*Fig. 6*, *Tabl. 8*), l'incertitude climatique a des impacts notoires qui augmentent avec la progression de la durée de prévision. Les possibilités de pilotage par des concepts sylvicoles peuvent cependant avoir un effet nettement plus fort.

Pour revenir aux conseils de gestion et au développement de stratégies d'aménagement, une analyse de risques est incontournable *a posteriori*. Dans cette recherche, les effets climatiques et sylvicoles sont identifiés par rapport à la vulnérabilité au stress hydrique (*Tabl. 4*, *Fig. 7*). Il apparaît qu'à l'examen des risques de stress hydriques, l'effet sylvicole est moindre et l'influence climatique grande, c'est-à-dire que les effets du stress hydrique viennent contrer la croissance et la production.

En raison de cet impact important de l'incertitude climatique sur les facteurs de risques des aléas climatiques, la planification forestière doit agir de manière responsable et ne pas mettre en œuvre une conversion sylvicole de manière stéréotypée. Une élaboration flexible des stratégies d'adaptation avec une capacité de rétroaction permanente de concert avec les progrès de la recherche sur les conséquences climatiques, s'avère nécessaire. Les résultats de cette étude de *scenarii* servent à évaluer les effets du changement climatique, la mesure de l'incertitude et les possibilités d'interventions sylvicoles afin de les contrer, et à tenir compte, dans la formulation, des conseils d'interventions et des stratégies d'adaptation.

8. DANKSAGUNG

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"Forest Tweets" – Informal Digital Coverage of the *Oak Processionary Moth* or Why Foresters should care about Social Media

(With 6 Figures and 2 Tables)

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Waldschutzmonitoring; soziale Medien; eingebürgerte invasive Arten; Eichenprozessionsspinner; Textanalyse; soziale Netzwerkanalyse; Bürgerwissenschaft.

1. INTRODUCTION

Ecological drivers like climate change and invasive alien species (IAS) represent new challenges for foresters and demand effective responses in order to ensure planned and relied upon forest functions and services. Given limited monitoring resources and the need for an ever broader consideration of the large numbers of forest functions in different contexts, alternative information sources and routes for monitoring deserve consideration (DAUME, ALBERT and VON GADOW, 2014). One such example is the increased involvement of the general public in the form of so-called citizen science initiatives (DICKINSON et al., 2012; SILVERTOWN, 2009). However, given the resources required to facilitate even such volunteer efforts, it has been suggested that informal online information sources such as social media (e.g. blogs, Twitter, Facebook) may play a similar role in the acquisition of environmental information and early warnings as already demonstrated in the domain of public health monitoring (GALAZ et al., 2010).

An exploration of this idea established that social media can indeed deliver primary biodiversity observations (DAUME, 2016; BARVE, 2014), and in addition may act as a source of public communities that could potentially be mobilized in the active monitoring of specific threats (DAUME and GALAZ, 2016). A manual evaluation of samples of short messages (so-called "Tweets") send on the micro-blogging platform Twitter showed for example

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RESEARCH ARTICLE Open Access

Assessing risks and uncertainties in forest dynamics under different management scenarios and climate change

Matthias Albert*, Jan Hansen, Jürgen Nagel, Matthias Schmidt and Hermann Spellmann

Abstract

Background: Forest management faces a climate induced shift in growth potential and increasing current and emerging new risks. Vulnerability analysis provides decision support based on projections of natural resources taking risks and uncertainties into account. In this paper we (1) characterize differences in forest dynamics under three management scenarios, (2) analyse the effects of the three scenarios on two risk factors, windthrow and drought stress, and (3) quantify the effects and the amount of uncertainty arising from climate projections on height increment and drought stress.

Methods: In four regions in northern Germany, we apply three contrasting management scenarios and project forest development under climate change until 2070. Three climate runs (minimum, median, maximum) based on the emission scenario RCP 8.5 control the site-sensitive forest growth functions. The minimum and maximum climate run define the range of prospective climate development.

Results: The projections of different management regimes until 2070 show the diverging medium-term effects of thinnings and harvests and long-term effects of species conversion on a regional scale. Examples of windthrow vulnerability and drought stress reveal how adaptation measures depend on the applied management path and the decision-maker's risk attitude. Uncertainty analysis shows the increasing variability of drought risk projections with time. The effect of climate projections on height growth are quantified and uncertainty analysis reveals that height growth of young trees is dominated by the age-trend whereas the climate signal in height increment of older trees is decisive.

Conclusions: Drought risk is a serious issue in the eastern regions independent of the applied silvicultural scenario, but adaptation measures are limited as the proportion of the most drought tolerant species *Scots pine* is already high. Windthrow risk is no serious overall threat in any region, but adequate counter-measures such as species conversion, species mixture or reduction of target diameter can be taken. This simulation study of three silvicultural scenarios and three climate runs spans a decision space of potential forest development to be used for decision making. Which adaptation measures to counteract climate induced risks and uncertainty are to be taken is, however, a matter of individual risk attitude.

Keywords: Climate change; Silvicultural management strategies; Site-sensitive growth model; Scenario simulation; Vulnerability analysis; Drought stress; Windthrow risk; Uncertainty

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Background

Vulnerability (see Table 1 for definition) analysis has played an important role in forestry since Carlowitz (1713) introduced the *principle of sustainability* provoked by the exploitation of forests. Even more today, multi-functional forest management in central Europe faces new threats as climate change induces shifts in forest growth potential as well as increasing current and emerging new abiotic and biotic risks (Lindner et al. 2010; Seidl et al. 2010; see Table 1 for definition). Consequently, Millar et al. (2007) promote adaptive forest management strategies because knowledge about past forest conditions, forest dynamics and the corresponding suitable management options is not sufficient in an environment of new threats with yet relatively unknown forces and multiple factors of uncertainty (see Table 1 for definition). Bolte et al. (2009) concretize adaptive forest management strategies for central Europe proposing conservation of forest structures, active adaptation and passive adaptation as three possible concepts. A first step towards adaptation measures is a vulnerability assessment which in itself is no easy task. Turner et al. (2003) state that the complexity of factors, processes and various requirements by society and stakeholders complicate a comprehensive vulnerability assessment. Nevertheless, it is essential to provide profound support for decision-makers in land-use management based on feasible projections of natural resources taking risks and uncertainties into account.

Generally, the current state of a forest region can be characterized by different sustainability indicators including also measures to describe the forests' stability and resilience towards multiple abiotic and biotic hazards (see Table 1 for definition). Different planning strategies within the range of ecologically and socio-economically sound developments lead to diverging future states. The interdisciplinary research project "Sustainable land-use management in the North German lowlands" investigates the opportunities, challenges and potential conflicts in the fields of agriculture, forestry and water management by analysing the effect of silvicultural and agricultural management alternatives on natural resources, their economical evaluation and the ecological value. Special emphasis is given to vulnerability analysis taking climate change into account. In particular, the analysis of diverging effects on forest dynamics due to silvicultural management alternatives can be used to identify adaptation measures.

Table 1 Definition of terms

Term	Definition
Hazard	Threatening event within a given time period and area (United Nations Department of Humanitarian Affairs 1992)
Vulnerability	Degree to which natural resources are susceptible to loss or damage on being exposed to a certain hazard (Adger 2006)
Risk	Probability of expected loss or damage due to a particular hazard for a given area and reference period; mathematically the product of hazard and vulnerability (United Nations Department of Humanitarian Affairs 1992)
Uncertainty	Situation where the current state of knowledge is incomplete due to (1) lack of information, (2) imprecision in model projections, and (3) unknown preferences in decision making (cf. Ascough et al. 2008)

The overall goal of this study is to deduce forest management options in the face of climate change by comparing forest dynamics in four regions in northern Germany. The four regions display different current species compositions and age class distributions. Already nowadays, regional vulnerability seems to increase from west to east on the grounds of climatic conditions and soil properties. Under climate change, vulnerability will possibly increase even more but not necessarily equally in every region. Thus, this comparative simulation study might depict regionally specific risks and consequently adaptation measures. We use two simulation approaches to deal with our research goals. Simulation approach 1 applies three silvicultural scenarios and one climate projection. Simulation approach 2 contains only one silvicultural scenario but three climate projections. In the presented analysis we pursue three specific objectives: (1) to characterize differences in forest dynamics under three contrasting silvicultural management strategies as a prerequisite to analyse risks and uncertainties (approach 1), (2) to quantify the effects of different silvicultural practices on the vulnerability to drought stress and windthrow hazard (approach 1), and (3) to quantify the effects and the amount of uncertainty on forest growth and drought stress due to climate change (approach 2).

Methods

The core of the forest simulation framework *WaldPlaner 2.1* (Hansen and Nagel 2014) is a site-sensitive single tree growth model. The growth model consists of statistical functions basically describing tree height development, diameter growth and changes in crown dimensions. Soil and climate parameters directly affect tree height development which is predicted using the longitudinal height-diameter model by Schmidt (2010). However, tree diameter and crown dimensions are indirectly projected site-sensitively as tree height is an important predictor to estimate crown dimensions and these in turn have a major impact on diameter growth.

Forest data

The presented research is conducted in four regions *Diepholz*, *Uelzen*, *Fläming* and *Oder-Spree* all located in the north German lowlands (Figure 1 and Table 2).

Total forest area, forest proportion and mean stand size increase from west to east in the four regions. The

climatic water balance indicates a higher aridity in the two eastern regions *Fläming* and *Oder-Spree* compared to the two western regions.

As the starting basis for the projection of forest development, approximately 1000 stands are sampled on a regular grid from the population of all stands with available yield data in every region. The sampling universe, though, does not cover every forested area since for certain stands yield data is missing or incomplete. Thus, the sampling points do not exhibit a constant representative factor of the area. We assume that the data availability is not correlated to the value of major site and stand parameters, thus the samples suffice to estimate the distribution of these site and stand parameters. The results from the samples are extrapolated to the entire regions using strata specific weights, calculated as follows:

$$g_{ij} = F_{ij}/f_{ij}$$

where F_{ij}: by stand type j and age class i stratified area proportion of the sampling universe of all stands in a region with known tree species and age, f_{ij}: by stand type j and age class i stratified proportion of the sample.

Each sample stand thus represents an area of $1/n \times g_{ij}$ of the total forest area of a region, with n = 874 stands in *Diepholz*, n = 999 in *Uelzen*, n = 1011 in *Fläming* and n = 1003 in *Oder-Spree*. Based on the information at each sampling point, i.e. for each occurring species age, mean diameter, mean height, site index, species proportion, stocking degree and volume per hectare, model stands of 0.2 ha in size with single trees are generated using the stand generation algorithm implemented in the *WaldPlaner* software (Hansen and Nagel 2014).

Soil data

Soil parameters as input variables for the site-sensitive forest growth projection are provided at each sampling point using a soil map of scale 1:1 Mio (Richter et al. 2007). To assign soil nutrient classes from 1 (poor) to 5 (rich) to each sampling point, the information of the soil map and model functions by Ahrends (2010a) are applied. Accordingly, the available soil moisture as defined by Overbeck et al. (2011) is estimated. Three groundwater classes are assigned, based on the long-term mean depth to water table (MDWT) using groundwater contours and digital terrain models. MDWT is further statistically transferred into the long-term lowest depth to water table which is regarded as the depth to water table during growing season. Table 3 presents characteristics of the three parameters soil nutrient class, groundwater class and available soil moisture based on 1.4 m soil depth.

The soil parameters in Table 3 are assumed constant over the projection period. This can be justified in the case of available soil moisture which is used as a substitute for soil water storage. And as we consider the site conditions during the growing season, winter precipitation will most likely fill the soil water storage. A change in soil nutrients is a rather long-term and quite complex process of temperature-driven mineralization and alteration. Niklińska et al. (1999) state that it is difficult to make reasonable predictions on changes of nitrogen turnover under climate change. Thus, we assume the effect of soil nutrient change as being negligible during the 60-year projection period. The assessment of groundwater classes is rather coarse, thus it does not seem advisable to regard this parameter dynamically.

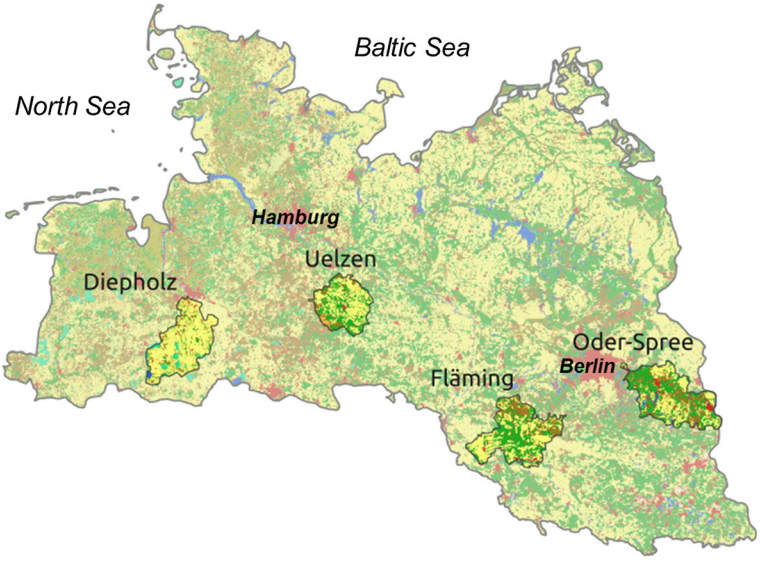


Figure 1 Location of the four research areas Diepholz, Uelzen, Fläming and Oder-Spree in northern Germany.

Table 2 Characteristic numbers of research areas

	Diepholz	*Uelzen*	*Fläming*	*Oder-Spree*
Forest area (ha)	15.042	45.712	51.368	76.714
Forest proportion (%)	6.7	34.7	41.5	48.7
Mean stand size (ha)	1.05	1.51	2.98	2.93
Mean summer temp. (°C)	22.9	22.8	24.2	24.0
Summer precipitation (mm)	210	215	180	188
Climatic water balance (mm)	−90.5	−82.0	−157.8	−147.2

Climatic water balance is the difference of precipitation and evapotranspiration for grass.

Climatic data

We choose the emission scenario *representative concentration pathway 8.5 (RCP 8.5)* by IPCC to initialize climate projections (Moss et al. 2008). Although being the most fierce emission scenario among the proposed ones by IPCC (2013), today's observed emissions already surpass RCP 8.5 (Peters et al. 2013). A total of 21 median climate projections all driven by RCP 8.5 and generated by different global climate models were further transferred to the region of Germany using the regional climate model *STARS II* (Orlowsky et al. 2008). Based on the anomaly in 2100 to today's temperature we select three climate projections to account for the variability in climate change. The climate scenarios are a minimum climate run resulting in a 2°C increase projected by the global model *INM-CM4* of the *Institute of Numerical Mathematics Russian Academy of Science*, a median run with a temperature increase of about 3.5°C projected by the *ECHAM6* model of *Max-Planck-Institute Hamburg*, Germany, and a maximum run with the highest temperature increase of more than 5°C projected by *ACCESS1.0* of the *Commonwealth Scientific and Industrial Research Organisation* and the *Bureau of Meteorology (CSIRO-BOM)*.

Table 3 Characteristics of soil parameters on forest land in the four regions

	Diepholz	*Uelzen*	*Fläming*	*Oder-Spree*
NC	Proportion (%)			
2	6	–	25	49
3	47	75	49	21
4	24	7	23	29
5	23	18	1	1
GWC	Proportion (%)			
0	60	92	91	80
1	17	5	7	15
2	23	4	2	5
asm (mm)	196	110	123	116

NC: soil nutrient class with 2 = poor, 3 = medium, 4 = good, 5 = rich; *GWC*: ground water class with 0 = no groundwater access, 1 = low groundwater access, 2 = moderate to strong groundwater access; *asm*: available soil moisture.

The *Potsdam Institut für Klimafolgenforschung* (PIK) provided homogenised daily climate observations for the time period 1951 to 2010 originating from the *German Weather Service* and the corresponding three sets of scenario data (minimum, median, maximum) for the time period 2011 to 2070. For consistent climate parameters, the *STARS II* model was driven by the climate observations for the period 1951 to 2010 resulting in simulated climate parameters from 1951 to 2070. Based on these climate projections for Germany the temperature sum (*temp*) in the species-specific growing season and the aridity index (*ari*) are predicted annually for each meteorological station in Germany until 2070. In order to assign climate parameters to each sampling point, the hydrological model *WaSIM-ETH* which is driven by meteorological and physical site parameters, is applied by downscaling the projected values of all meteorological stations within a 20-km radius around the sampling point with a distance-weighted regression model (Schulla 1997; Schulla and Jasper 2007). Thus, regionalized climate parameters are available on a 100 m × 100 m grid.

The temperature sum in the growing season and the aridity index are climatic predictors in the longitudinal height-diameter model. Based on the statistical model *LNVAR* by Menzel (1997, p 52 ff) the beginning of the growing season is species-specifically estimated. The end of the growing season is determined species-independently, modifying the approach by Wilpert (1990) and Walther and Linderholm (2006). Thus, either the temperature criterion defined as a 7-day-period with mean temperature below 5°C between July and October or the short day criterion, whichever is met first, terminates the growing season. Aridity index is defined as the ratio of annual precipitation (mm) and mean annual temperature (°C) +10 (de Martonne 1926).

Figure 2 illustrates the development of both climate parameters, temperature sum in the growing season and aridity index, over time in the four regions for the simulation period 2011 to 2070. The values are derived based on projections of *STARS II* using RCP 8.5.

The curves of temperature sum in growing season reveal increasing trends over time for all regions as well as

a spatial trend with increasing values from west to east (Figure 2A). The aridity index displays a clear spatial trend with drier conditions in the east while the temporal trend is less obvious (Figure 2C). Comparing the development of climate parameters under the three climate runs, minimum, median and maximum, using *Diepholz* as an example, it is noticeable that the amplitude over time within a run is stronger than between the runs. Nevertheless, the minimum and maximum run seem to project more extreme values around the median run (Figure 2B and D).

Longitudinal height-diameter model

The basic model for a site sensitive prediction of the single-tree height to diameter relation originates from a reparameterized version of the Korf function (Lappi 1991). Schmidt (2010) applies a multi-stage approach to fit height-diameter models for *Norway spruce*, *Scots pine*, *Douglas-fir*, *European beech* and sessile and pedunculate oak in Germany. In the first stage dbh, tree age, relative dbh, year of germination, temperature sum in the growing season, aridity index, height a.s.l. and spatial coordinates are used as predictors in a generalized additive model (*gam*) to predict tree height. The *gam* formulation allows the incorporation of nonlinear effects. Furthermore, the model is longitudinal and can be used for height prediction because tree age is a major explanatory variable. To further enhance the sensitivity of predictions to soil parameters a second model stage is applied. Again, a generalized additive model is formulated, using the transformed tree height estimate of the first stage, available soil moisture, soil nutrient class and groundwater class as predictors (see Table 3 for parameter definitions). Separate modelling steps are necessary as soil information is not available nationwide but the wide range of climate values over Germany is beneficial to identify climatic effects. Finally, the longitudinal height-diameter model is sensitive to spatially and temporal changing climatic conditions and to different soil properties.

In our simulation framework, the climate parameters vary according to climate projections whereas the soil parameters are assumed constant over time. Nevertheless, climate change affects tree height predictions differently depending on soil properties because of the multiplicative combination of both soil and climate parameters. Therefore, the longitudinal height-diameter model is soil and climate sensitive.

Simulation framework *WaldPlaner 2.1*

The simulation framework *WaldPlaner 2.1* projects forest development by applying different silvicultural management regimes and accounting for changing climatic conditions. Figure 3 displays the major components of the *WaldPlaner* system.

The system needs three main data categories as input, i.e. data on forest stands, soil properties and climate conditions, all as described above.

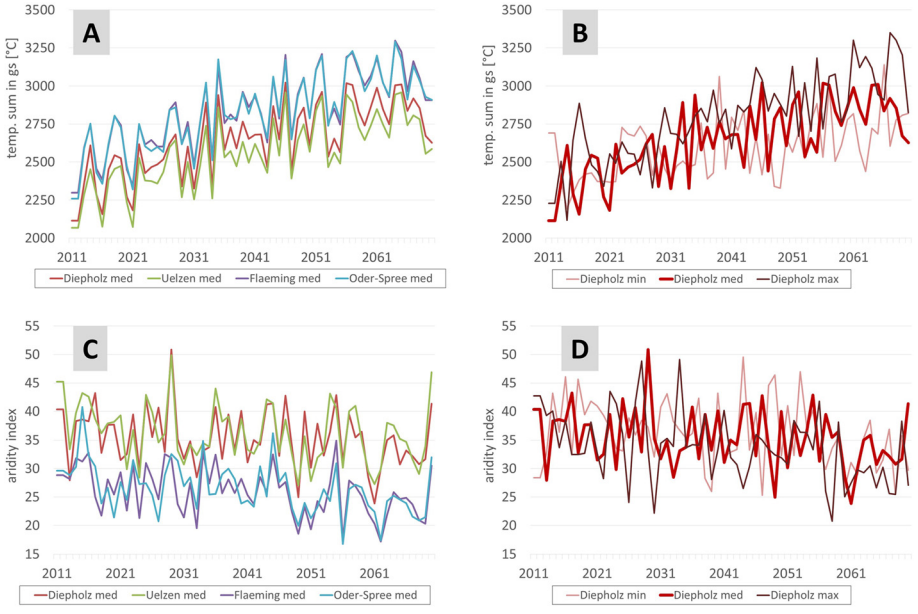


Figure 2 Climate parameters over time for the simulation period 2011 to 2070 projected with STARS II using RCP 8.5 (**A**: temperature sum in the growing season of the median climate run as mean regional values, **B**: temperature sum in the growing season of the minimum, median and maximum climate run as mean values in Diepholz, **C**: aridity index of the median climate run as mean regional values, **D**: aridity index of the minimum, median and maximum climate run as mean values in Diepholz).

A list of control variables is used to define silvicultural management strategies and nature conservation rule sets. We apply three contrasting management scenarios, i.e. a reference scenario reproducing today's close-to-nature silvicultural practices in Germany, a biodiversity run aiming at increasing the area of potential natural vegetation, and a climate protection run with the goal to maximize CO_2 sequestration in standing volume and wood products. Table 4 lists the main characteristics of the control variables to reproduce the three management scenarios.

The nature conservation rule sets differ in the three management strategies according to the proportion of unmanaged area, the proportion of forest area managed in low intensive silviculture to conform to the flora-fauna-habitat (FFH) directive, the amount of deadwood and the number of habitat trees. The biodiversity path's objective can clearly be identified as a higher proportion of forest land will be totally unmanaged and the entire FFH-area will be developed towards the natural habitat type. The reference path and climate protection path are equal in matters of nature conservation taking these control variables into account.

An important indicator to differentiate between the management strategies is species conversion. For all management paths, the selection of future tree species always has to be in line with species suitability to site conditions. In the reference scenario, deciduous tree species are preferred as is defined by the principles of close-to-nature silviculture. In the biodiversity strategy, silvicultural practices intend to increase the area of natural vegetation, thus, tree species of potential natural vegetation are chosen. In the climate protection strategy a high CO_2 sequestration can best be realized by high increment resulting in high standing volume and simultaneously harvesting a considerable mass of timber being used in long-lasting products such as construction wood. Therefore, fast growing conifer species are preferred. It is important to note that species conversion is only realized in the simulations when the existing stand is mature and harvested.

The control variables in the thinning and harvesting section all determine the speed of conversion. While harvesting of stands is delayed under the biodiversity run because of lower thinning intensity, a lower limit of thinning and harvesting volume per cut and higher target diameter for favored species it is the opposite under the climate protection path and the reference path taking an intermediate position.

In the simulation framework *WaldPlaner* with all input data and determining factors set forest development is projected starting with density induced mortality in every stand where occurrence is predicted (Hansen and Nagel 2014, p 138 ff.). Single tree growth is then predicted for a 5-year period from 2011 to 2015, taking site and period specific climate conditions as well as specific soil properties into account. Thinnings and harvests complete the first projection cycle. These 5-year cycles of mortality, growth and fellings are repeated until 2070 (Figure 3).

We analyze the effects of different management scenarios and climate projections on forest development excluding any risk induced impacts such as mortality or loss of vitality. After the undisturbed simulation, the management paths are evaluated taking risks into account. In particular, we conduct a risk analysis looking

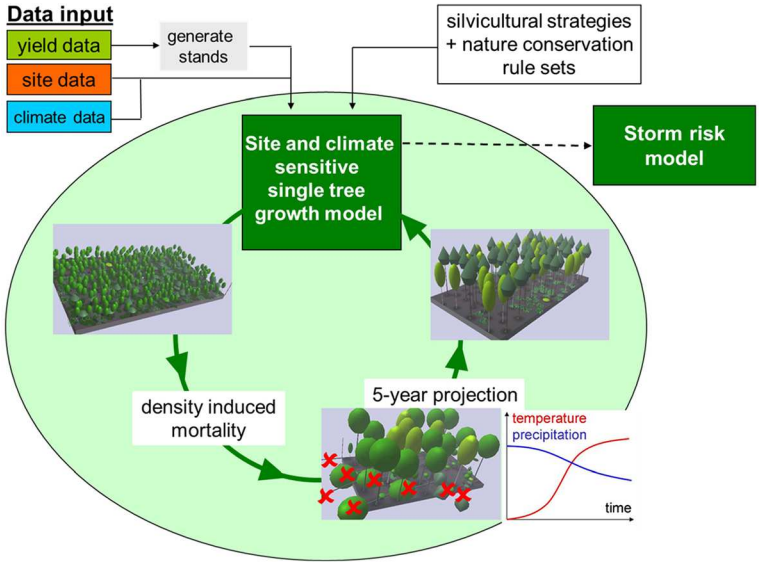


Figure 3 Representation of the major components of the *Waldplaner* simulation framework.

Table 4 Characteristics of selected control variables defining the three silvicultural management strategies reference, biodiversity and climate protection and the according nature conservation rule sets

	Control variable	Reference	Biodiversity	Climate protection
Nature conservation	Unmanaged area	Status quo	5% of forest area	Status quo
	Area under flora-fauna-habitat (FFH) directive	45% of the FFH-area as natural habitat type	100% of the FFH-area as natural habitat type	45% of the FFH-area as natural habitat type
	Deadwood ($m^3 \cdot ha^{-1}$)	20	40	20
	Habitat tress ($N \cdot ha^{-1}$)	3	10	3
Species conversion	Selection of future stand type	Dominating deciduous species	Tree species of potential natural vegetation (pnv)	Dominating conifer species
Thinning	Thinning intensity	Variable over time: high, moderate, low	Moderate	Variable over time: high, moderate, low
	Thinning type	Thinning from above	Thinning from above	Thinning from above
	Start of thinning (defined by stand height)	12–16 m	12–16 m	11–15 m
	Limit of thinned volume per cut ($m^3 \cdot ha^{-1}$)	Max 70 (Douglas-fir max 100)	Max 50 (Douglas-fir max 100)	Max 70 (Douglas-fir max 100)
Harvest	Target diameter (cm)	Oak 70, beech 60, spruce 45, pine 45, Douglas-fir 70	All species +5 cm, in FFH-areas +10 cm except spruce −5 cm, Douglas-fir −10 cm	All species −5 cm
	Limit of harvested volume per cut ($m^3 \cdot ha^{-1}$)	Max 100 (Douglas-fir max 120)	Max 70 (max 100 for all species not included in pnv)	Max 100 (Douglas-fir max 120)

at the effects of management paths and climate projections on windthrow probability and drought stress. To evaluate windthrow probability, a storm risk model is linked to the simulation framework. After each 5-year cycle the single-tree windthrow probability can be predicted based on the current stand and constant site conditions.

Storm risk model

The risk of windthrow is predicted using the binary additive regression model with explicit spatial component by Schmidt et al. (2010). The storm risk model predicts the probability of windthrow for single trees based on the tree-specific variables species, height and dbh, on the topographic variable Topex-to-distance index with a marginal distance of 1000 m in a modified version to the original by Scott and Mitchell (2005), on site conditions characterized by three waterlogging classes and on a spatial proxy for flow field information (wind speed). The storm risk model is parameterized for the species groups *European beech* – oaks, other deciduous species, *Norway spruce*, *Scots pine* – larches, *Silver fir* – *Douglas-fir*.

The model proves most sensitive to tree height, while height-diameter ratio has a much lower effect on windthrow probability. With all other factors constant *Norway spruce* is most prone to windthrow followed by the *Silver fir* – *Douglas-fir* group and the *Scots pine* – larches group. Deciduous species are generally less susceptible to windthrow than conifers.

Furthermore, the model is highly sensitive to terrain exposure interacting with cardinal direction. In our four model regions, the terrain merely shows distinctive relief. Therefore, in our predictions of windthrow probability Topex-to-distance index and the accompanying cardinal direction play an inferior role.

The model is initialized for predictions using the current and future stocking, the specific terrain exposure and cardinal direction of the sample point centre and a constant spatial proxy representing gale wind speed. Furthermore, we simulate a winter storm with south-western direction.

Drought stress

Drought stress is seen as an important hazard impinging on tree vitality, growth potential and ultimately even mortality (Hanson and Weltzin 2000; Allen et al. 2010). Different definitions and assessment methods for drought stress exist (Farooq et al. 2009; Anderegg et al. 2013). Considering the data available to us we define drought stress using the water available to plants in the growing season as an indicator (Spellmann et al. 2007). For this purpose, water available to plants (*wap*) is estimated as the sum of climatic water balance (*cwb*) in the growing season and the available soil moisture (*asm*). Climatic water balance, furthermore, is the difference between the precipitation and the potential evapotranspiration of grass. As an advantage the variable *wap* can easily be derived spatially comprehensive. Based on the mean *wap*-values of a 20-year period (1991 to 2010 as

status quo, and the three projection periods 2011 to 2030, 2031 to 2050 and 2051 to 2070) it is possible to assess a drought stress indicator at each site in the study regions over time under the three climate projections.

The continuous variable *wap* is further transformed into risk classes (Spellmann et al. 2011). The derivation of the species-specific *wap*-range is crucial for the drought stress assessment. The ranges and drought stress classes are assessed based on (1) the correlation between growth potential and water regime, (2) an analysis of observed species distribution ranges depending on water availability as well as (3) expert knowledge on the cultivation of species under different water regimes in northern Germany (Table 5).

This drought stress classification is used in strategic planning when evaluating species suitability for cultivation. The interpretation of the three classes is straightforward. No restrictions apply when low drought risk is assigned. On sites with a medium drought risk the respective species should not be planned as leading species but possibly as associated species. Where high drought risk is predicted, the respective species should not be planned at all or at the most as secondary species.

The values in Table 5 indicate *Norway spruce* as most prone to drought stress, followed by *European beech*, oak and *Douglas-fir* and *Scots pine* as most resistant. For a complete drought risk assessment in the study regions, other tree species are assigned to one of the four species classifications.

Results

The risk profile of a forest region, in particular windthrow risk and drought stress, is determined by site parameters, climate conditions and forest characteristics in terms of e.g. species composition, age class distribution, standing volume, growth potential. Silvicultural management strategies are the only direct option to control forest dynamics and thus impact future risks. Therefore, the analysis of forest dynamics in the silvicultural decision space defined by the three applied management strategies *reference*, *climate protection* and *biodiversity* is a prerequisite to interpret and understand risk analysis and to develop adaptation strategies. All following reported results of forest dynamics and risk analysis are projected under the median climate scenario.

Table 5 Definition of risk classes on drought stress based on water available to plants in the growing season for Norway spruce, European beech, sessile and pedunculate oak and Douglas-fir and Scots pine

Drought stress	Water available to plants in growing season (mm)			
	Spruce	Beech	Oak/Douglas-fir	Pine
Low	>0	> −25	> −150	> −180
Medium	0 to −80	−25 to −100	−150 to −400	−180 to −450
High	< −80	< −100	< −400	< −450

Simulation approach 1: Forest dynamics

Silvicultural operations like thinnings and harvests have an immediate impact on forest dynamics whereas conversion in species composition is a rather long-term process because only mature stands are harvested and potentially converted.

The age class structure defines the potential speed of forest conversion. The initial state of the proportion of crown cover for all species combined over age classes illustrates differences between the four regions in 2010 (Figure 4).

The age class distributions indicate a majority of young stands in *Diepholz* (Figure 4A), a peak at the mid-age stands in *Uelzen* and *Oder-Spree* (Figure 4B and D) and a rather balanced distribution in the *Fläming* region (Figure 4C). The status quo of the age class distribution is one important determinate when starting the simulation of forest development under the three silvicultural management strategies.

The development of standing volume and the corresponding harvested volume reflect medium-term forest dynamics (Figure 5 and Table 6).

The *Oder-Spree* region has the highest initial standing volume with an average of 275 $m^3 \cdot ha^{-1}$ in 2010 followed by *Fläming* with 263 $m^3 \cdot ha^{-1}$ and *Uelzen* with 261 $m^3 \cdot ha^{-1}$. *Diepholz* has the lowest value with 175 $m^3 \cdot ha^{-1}$ due to the bulge of young stands. The volume trends displayed in Figure 5 indicate for all regions that under the biodiversity management regime standing volume is highest, under the climate protection path the lowest and the volume development under the reference strategy in an intermediate position. In *Diepholz*, coming from a low level, all management paths result in an increase of standing volume over time with the reference and biodiversity runs almost identical. In *Uelzen*, the biodiversity strategy yields a steady increase in standing volume. Under the reference path, volume increases until 2030 and afterwards shows a reduction below the initial value in 2070. Standing volume under the climate protection strategy drops continuously to an overall minimum of 173 $m^3 \cdot ha^{-1}$ in 2055. In the *Oder-Spree* region under the reference management strategy, the standing volume is almost constant until 2030 and decreases steadily afterwards. The climate protection path reduces standing volume considerably at the beginning and volume accumulates from 2055 on to reach almost the same value as under the reference path in 2070. The biodiversity run leads to an overall maximum of 338 $m^3 \cdot ha^{-1}$ in 2040 followed by a volume reduction again. The standing volume trends in *Fläming* resemble the development in *Oder-Spree* being just on a lower level.

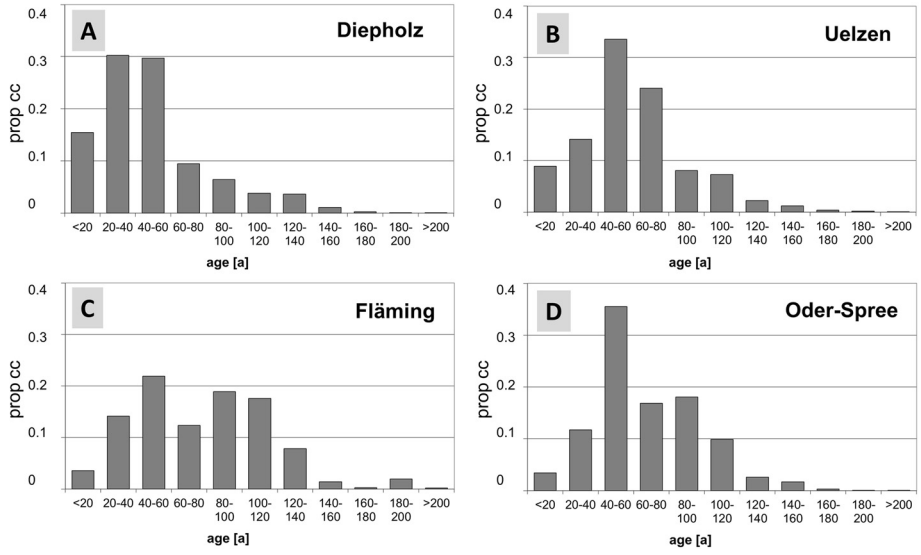


Figure 4 Proportion of crown cover (prop cc) for all species combined over age classes for the four regions Diepholz **(A)**, Uelzen **(B)**, Fläming **(C)** and Oder-Spree **(D)** in 2010.

The analysis of mean harvested volume in the four regions under the three silvicultural management strategies is complementary to standing volume development (Table 6). For all regions, the highest mean annually harvested volume is realized under the climate protection path, followed by the amount taken under the reference strategy and low intensity silviculture of the biodiversity run consequently yields the lowest mean harvested volume. Comparing the four regions, the most intense cuttings for all three management strategies are projected in the *Uelzen* region. Thinnings and harvests in *Fläming* and *Oder-Spree* yield almost the same mean annually harvested volume. The low values of harvested volume per cut in *Diepholz* reflect the projected volume accumulation.

Tree species composition of existing stands can gradually be changed by natural ingrowth or advance planting

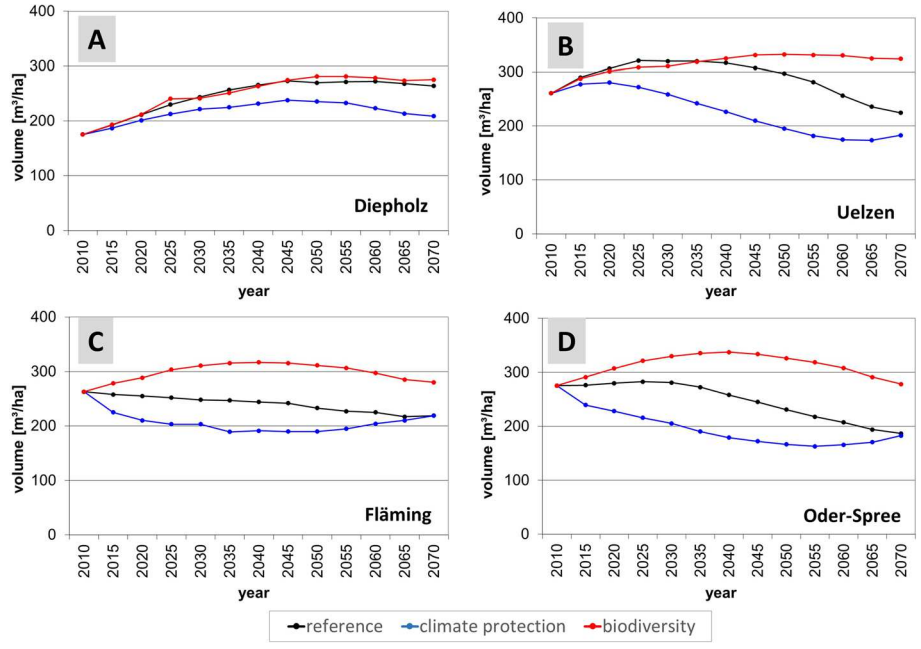


Figure 5 Development of standing volume ($m^3 \cdot ha^{-1}$) in the four regions Diepholz **(A)**, Uelzen **(B)**, Fläming **(C)** and Oder-Spree **(D)** under three silvicultural management regimes (black: reference, blue: climate protection, red: biodiversity) from 2010 until the end of the projection period in 2070 applying the median climate scenario.

Table 6 Mean harvested volume (m^3 under bark·ha^{-1}·a^{-1}) for the four regions under the three silvicultural management strategies from 2010 until 2070 applying the median climate scenario

	Diepholz	*Uelzen*	*Fläming*	*Oder-Spree*
Reference	4.2	6.3	5.9	6.0
Climate protection	5.0	7.0	6.3	6.6
Biodiversity	4.0	5.1	4.4	4.5

and abruptly after harvesting the mature stand. The need for conversion arises mainly in regard to changing growth conditions due to climate change and because of the contrasting intentions of the three silvicultural management regimes. Generally, changes in species composition on the regional scale are a rather long-term process as shown in Table 7.

The current species composition in the four regions specified in Table 7 reveals a striking trend of increasing dominance of *Scots pine* in terms of crown cover proportion from west to east. While species composition in *Diepholz* is quite diverse with almost 50% of crown cover made up by other deciduous tree species, mostly birch, alder, poplar, the proportion of *Scots pine* in *Uelzen* already reaches 61%. *Uelzen* nowadays has the highest proportion of *Norway spruce* (13%) in comparison to the other regions. Both *Diepholz* and *Uelzen* have a considerable share of *Douglas-fir* which is almost entirely absent in the two eastern regions. In the *Fläming* region *Scots pine* dominates with almost 75% and only beech (13%) and oak (6%) have notable percentages. In *Oder-Spree* 81% of the crown cover derives from *Scots pine*, far behind are other deciduous species with 9% and oak with 6%.

The changes in species proportions until 2070 in Table 7 show two overall findings: (1) comparing the three silvicultural scenarios the climate protection path has the highest conversion rate of species proportions and the biodiversity path the lowest in all regions and (2) comparing the four regions *Uelzen* has the highest conversion rates for all scenarios, *Diepholz* has the lowest rate under the reference path and *Oder-Spree* under the biodiversity path.

General tendencies for species are a preferential treatment of *Douglas-fir* under the climate protection and reference scenario. Beech and, to a lesser extent, oak are favoured by all silvicultural regimes in all regions, except oak in *Uelzen* under the climate protection path. The proportion of *Scots pine* is projected to decrease under all silvicultural scenarios in all regions except *Diepholz* where the crown cover proportion of *Scots pine* displays a considerable increase under the climate protection and even under the biodiversity path.

Analysing regional features in *Diepholz* under the climate protection regime, a strong reduction of other deciduous species' proportion is projected towards the more productive species beech, oak, spruce, pine and *Douglas-fir*. The reference settings simulate a similar

Table 7 Proportion of species crown cover based on the area of the respective region for European beech, sessile and pedunculate oak, all other deciduous species, Norway spruce, Scots pine, Douglas-fir and all other conifer species in 2010 and change in percentage points and the conversion rate in percent under the three silvicultural management strategies reference (ref), climate protection (cp) and biodiversity (bio) until 2070 applying the median climate scenario

		Beech	Oak	Other deciduous	Spruce	Pine	Doug-fir	Other conifers	Conversion rate
Diepholz	2010	8.9%	11.2%	45.2%	6.0%	19.3%	4.1%	5.4%	
	ref 2070	+5.1	+2.1	−4.7	−0.8	−0.9	+1.1	−2.0	8.3
	cp 2070	+7.8	+3.0	−25.0	+2.1	+7.4	+5.9	−1.4	26.2
	bio 2070	+0.2	+4.6	−2.5	−2.2	+2.8	−1.5	−1.5	7.6
Uelzen	2010	4.8%	6.1%	8.7%	13.3%	61.3%	3.9%	1.9%	
	ref 2070	+7.0	+1.6	+2.3	−6.7	−17.7	+13.3	−0.1	24.2
	cp 2070	+14.7	−0.9	−1.5	−8.9	−34.1	+26.8	+4.0	45.5
	bio 2070	+8.0	+0.2	+0.6	−5.6	−3.2	+0.4	−0.4	9.2
Fläming	2010	12.8%	5.9%	4.3%	1.8%	73.5%	0.4%	1.2%	
	ref 2070	+8.3	+2.5	−0.4	−0.8	−11.2	+1.9	−0.2	12.7
	cp 2070	+8.4	+1.9	−1.2	−1.1	−30.2	+18.5	+3.8	32.6
	bio 2070	+5.9	+0.7	+1.1	+1.6	−9.2	+/−0	+/−0	9.3
Oder-Spree	2010	2.0%	5.7%	8.8%	1.1%	80.9%	0.5%	1.0%	
	ref 2070	+7.1	+2.9	−1.8	−0.1	−8.3	+0.3	−0.1	10.3
	cp 2070	+7.1	+3.4	−3.8	−0.2	−23.1	+12.9	+3.6	27.0
	bio 2070	+0.7	+0.4	+0.7	+0.4	−2.1	−0.1	+0.1	2.3

trend on a lower level without favouring spruce, pine and *Douglas-fir*. The biodiversity run projects only small changes mainly preferring oak. In *Uelzen*, all silvicultural management regimes simulate a reduction of spruce and pine proportions in favour of beech and *Douglas-fir* which is especially privileged under the climate protection (+27 percentage points) and reference run (+13 percentage points). In the *Fläming* region the proportion of *Scots pine* decreases under all silvicultural regimes especially preferring beech, oak and *Douglas-fir* and additionally under the biodiversity path also increasing the proportions of deciduous species and *Norway spruce*. The somewhat unexpected increase of *Norway spruce* results mainly from a conversion towards mixed stands with 90% beech and 10% spruce. In *Oder-Spree*, under the biodiversity strategy, almost no changes in species composition are projected. The climate protection and reference paths result in increasing proportions of beech, oak and *Douglas-fir* at the expense of *Scots pine* and other deciduous species.

Simulation approach 1: vulnerability analysis

Risk assessment on a regional scale aims at determining the need for adaptation measures and identification of the causes for high risk. Thus, after quantifying windthrow and drought risk, we focus on the effects of the three management strategies on both risk factors, as silvicultural treatments in general offer a direct and immediate access to reduce risks.

Windthrow risk

Species composition and age class structure, i.e. tree heights, significantly influence the windthrow risk on a regional scale. For forest management, in order to anticipate adaptation measures, it is more meaningful to investigate the windthrow probability of the most vulnerable stands or cohort of trees than looking at the mean risk value. Thus, in a first analysis, the mean windthrow probability of the 20% volume quantile of trees with the highest predicted single-tree windthrow probabilities are calculated for each region under the three silvicultural management strategies in 2010, 2030, 2050 and 2070 (Figure 6).

Figure 6 reveals some variability between the management paths over time for the *Diepholz* and *Uelzen* regions (Figure 6A and B), whereas no significant differences between the silvicultural regimes are noticeable for the *Fläming* and *Oder-Spree* regions (Figure 6C and D). Currently, the highest mean windthrow probability of the 20% volume quantile exists in *Uelzen* followed by *Diepholz* and both eastern regions on the same level. Over time in *Diepholz* the reference strategy displays the highest probabilities followed by the climate protection path and the biodiversity strategy. While in *Diepholz* the probabilities decrease in the second and third projection period, there is a steady increase in *Uelzen* with similar values under the reference and climate protection path in 2070 and under the biodiversity strategy with considerably lower probability. In the *Fläming* and *Oder-Spree* regions all management

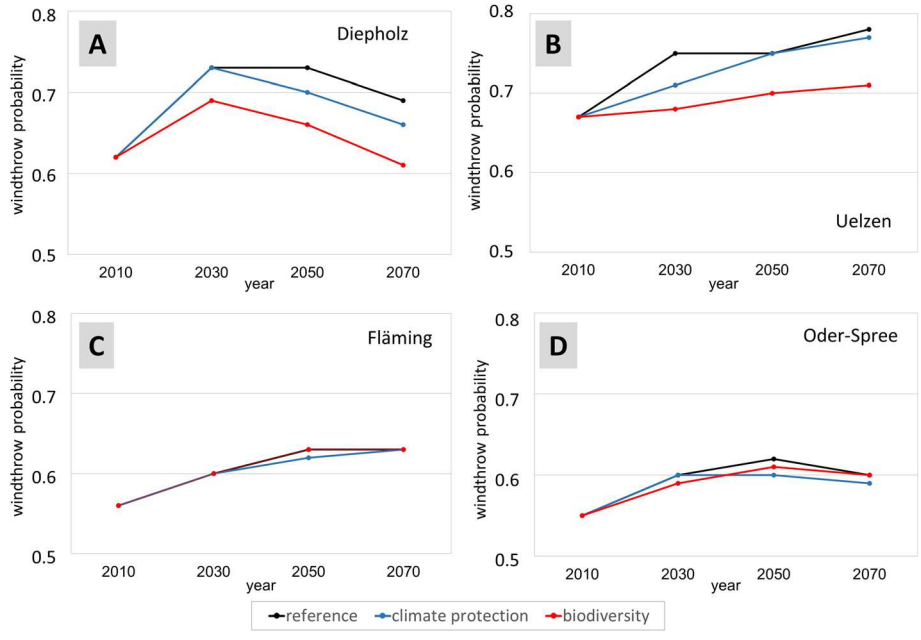


Figure 6 Mean volume-weighted windthrow probability over time in the four regions Diepholz **(A)**, Uelzen **(B)**, Fläming **(C)** and Oder-Spree **(D)** under the three silvicultural management scenarios (black: reference, blue: climate protection, red: biodiversity) applying the median climate scenario.

scenarios result in quite similar probability values which slightly increase over time.

A closer species-specific analysis of windthrow risk in *Uelzen* reveals more detailed differences among the management paths than the mean windthrow probability of the 20% volume quantiles (Figure 7).

Figure 7 shows species-specific volume proportions over windthrow probability classes in *Uelzen*. Thus, each species' contribution to windthrow risk can be quantified directly. *Scots pine* dominates the current distributions in probability classes 0.4 to 0.6 (Figure 7A). Also considerable peaks in higher probability classes 0.7 to 0.9 exist for *Norway spruce*. A shift in distributions from 2010 to 2070 reflects changes in species composition due to the different silvicultural management paths as well as tree height growth. Under the reference path (Figure 7A) *Douglas-fir* shows a peak in a high probability class and a considerable volume proportion is made up by *Scots pine* in medium to increased probability classes in 2070. Under the climate protection regime, however, the volume at risk is distributed over many probability classes from 0.5 to 0.9 for pine and *Douglas-fir* (Figure 7C). Contrary, windthrow risk under the biodiversity strategy is solely dominated by *Scots pine* in the probability classes 0.6 and 0.7 (Figure 7D).

Drought risk

Changing climatic conditions heavily impact drought stress as reduced precipitation and higher temperatures intensify the risk of growth depressions, loss of vitality or even dieback. Therefore, keeping the climatic factor constant in order to better analyse the effect of silvicultural management regimes on drought risk, all reported results are generated under the median climate scenario. Also, species' susceptibility to drought stress varies significantly. Consequently, shifts in species composition due to different silvicultural management regimes and changing climate conditions affect the regional drought risk over time. Furthermore, regionally different soil properties, namely available soil moisture, contribute to different drought risks in the four regions. A first overview of drought risk is given in Figure 8.

As a general trend, in all regions and under every management strategy, a shift towards higher drought risk classes in the future is projected. However, obviously for all four regions, there are no significant differences between the risk class distributions of the three different silvicultural management strategies in 2070. Rating the four regions, *Diepholz* (Figure 8A) currently and in 2070 has the least overall drought risk closely followed by *Uelzen* (Figure 8B), although here already noticeable volume proportion are classified as high drought risk prone in all three silvicultural regimes. In both regions there seems to be no strong need for extensive adaptation measures regarding only drought risk under the assumed forest dynamics and climate projection. In the *Oder-Spree* region (Figure 8D) and even more in *Fläming* (Figure 8C) a considerable volume proportion is projected to be at risk in 2070. To ensure future forest productivity in the two eastern regions measures to counter drought stress seem advisable.

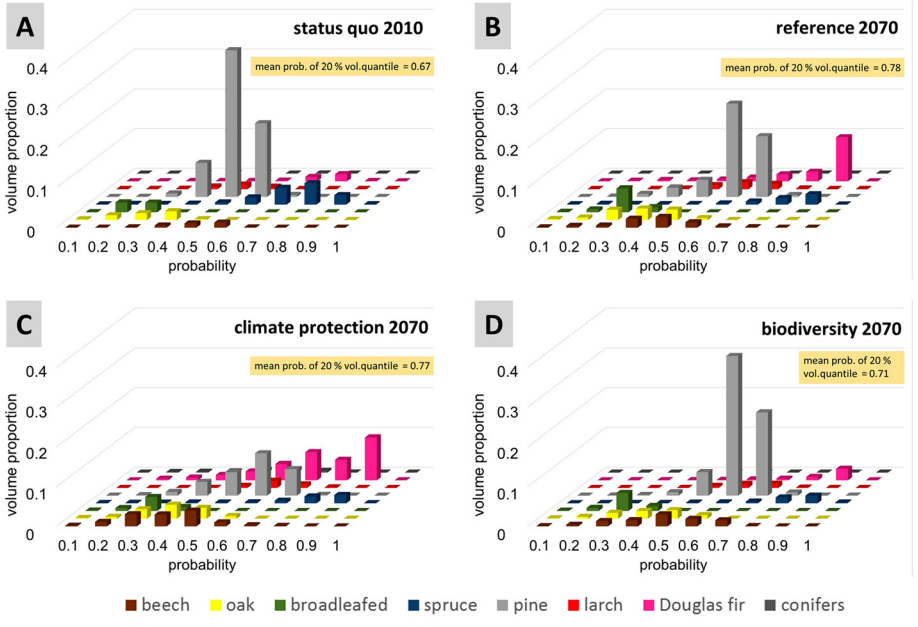


Figure 7 Distribution of species-specific volume proportions over windthrow risk classes in Uelzen for status quo conditions **(A)** and under the three silvicultural management strategies in 2070 **(B, C and D)** applying the median climate scenario.

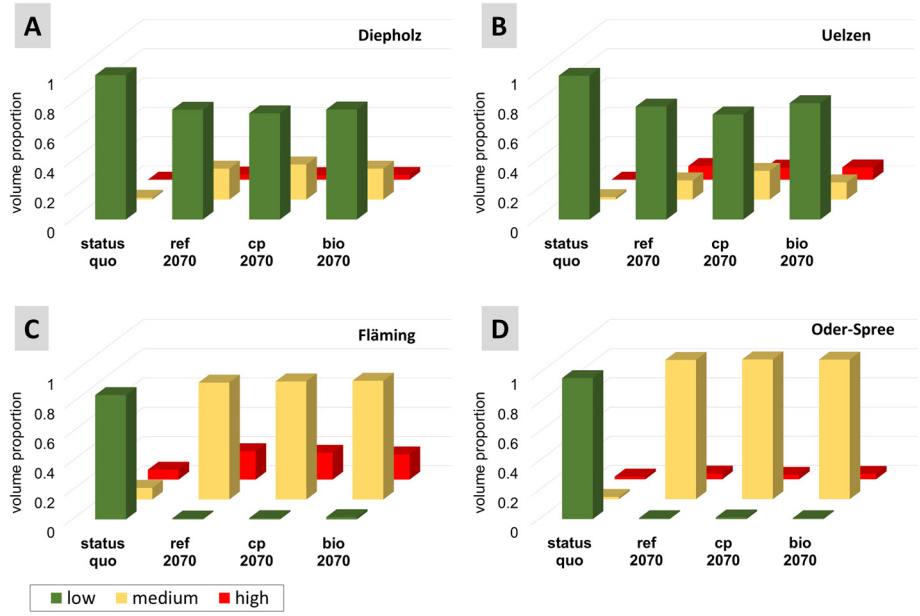


Figure 8 Distribution of volume proportions (all species combined) over drought risk classes in the four regions Diepholz **(A)**, Uelzen **(B)**, Fläming **(C)** and Oder-Spree **(D)** for status quo conditions and under the three silvicultural management strategies reference (ref), climate protection (cp) and biodiversity (bio) in 2070 applying the median climate scenario.

A species-specific analysis of drought risk development over time is essential to fathom adaptation options to reduce drought risk on a regional scale (Figure 9).

The example illustrates how regional drought risk is distributed between species in *Fläming* over time (Figure 9). This detailed drought risk assessment helps to better identify starting-points for adaptation measures. The distribution of species-specific volume proportions over drought risk classes for status quo conditions (Figure 9A) reveals that nowadays drought stress is no contemporary issue in the region, only beech with a total volume proportion of 12% contributes to the medium and high risk classes. In 2030 (Figure 9B), the drought risk assessment is unchanged but in 2050 (Figure 9C) there is a major shift in the classification of *Scots pine* and oak to the medium risk class and beech is entirely classified as highly drought risk prone. In 2070 (Figure 9D), virtually no volume proportion displays low risk but 80% made up by oak, pine, *Douglas-fir* and larch are under medium drought risk. Beech, accounting for the remaining 20%, is highly threatened by drought stress.

Simulation approach 2: uncertainty analysis

Forest dynamics can be controlled by silvicultural management scenarios to a certain extent. Other factors outside the scope of forestry's area of influence can also affect forest dynamics heavily. For example, changing climatic conditions impact various abiotic and biotic risk factors and account for shifts in growth potential. Climate projections, in turn, differ tremendously depending on the assumed emission scenario, the applied global climate model and even when downscaling climate projections using different regional climate models. Therefore, climatic conditions are a considerable source of uncertainty in the projection of forest development.

We investigate the effect of the different climate projections on the risk factor drought stress and on height growth applying the minimum, median and maximum climate run.

Drought risk

The climate parameters precipitation and temperature vary significantly depending on the climate scenario applied (see Figure 2). This consequently affects drought stress to a great extent, and the arising uncertainty in a regional drought risk assessment resulting from different climate projections can be quantified (Figure 10).

The interpretation of Figure 10 is straightforward. A square is displayed if the three climate projections minimum, median and maximum do not generate different volume proportions in one risk class at a time. For example, 3% of the volume is classified in the high risk class under all three climate scenarios in 2050. But for the medium risk class in 2050, for example, the lowest volume proportion observed is 51% and the highest value is 96%. Thus, the uncertainty in this risk class is 45 percentage points.

Assuming the future climate values will be in the range defined by the three climate projections, then the future drought risk in the *Oder-Spree* region will be

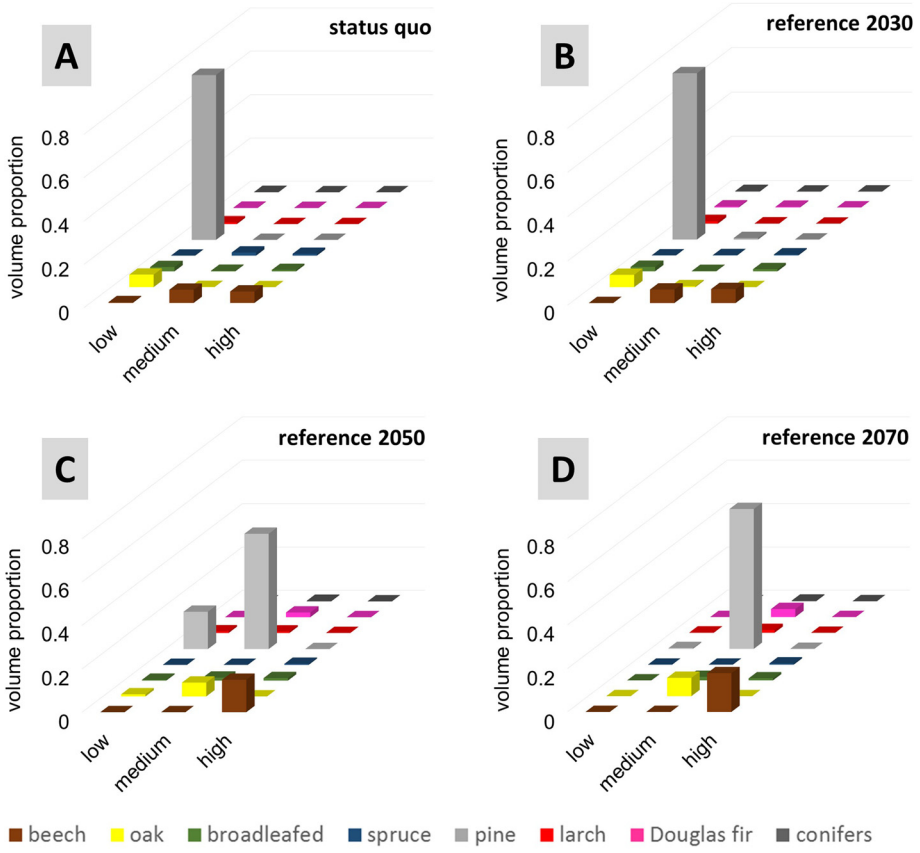


Figure 9 Distribution of species-specific volume proportions over drought risk classes in Fläming for status quo conditions **(A)** and under the reference scenario in 2030, 2050 and 2070 **(B, C and D)** applying the median climate scenario.

within the variability shown in Figure 10 when refraining from other sources of uncertainty.

Height development

Tree growth responds differently to changing climatic conditions. Depending on species, location, and site a moderate rise in temperature might enhance tree growth while decreasing precipitation will eventually result in reduced growth (Albert and Schmidt 2010; Pretzsch et al. 2014). Thus, it is important to evaluate the uncertainties in tree growth reaction to different climate projections (Figure 11).

Figure 11 illustrates the effects of different climate runs on periodic height increment of all trees remaining

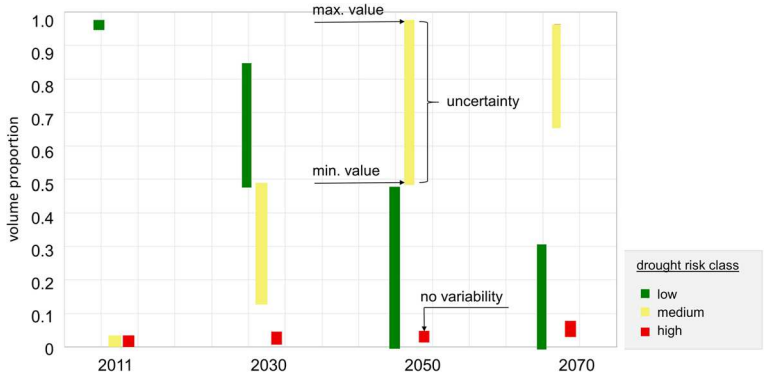


Figure 10 Variability in the distribution of volume proportions in drought risk classes over time for the Oder-Spree region applying the minimum, median and maximum climate run under the reference management scenario.

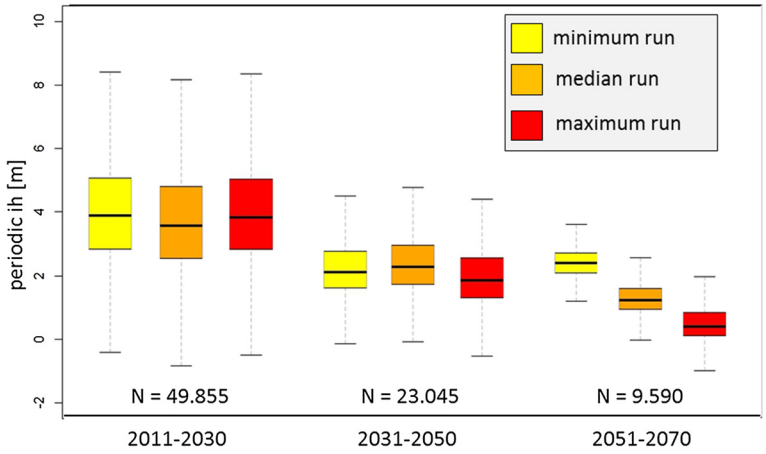


Figure 11 Boxplots of the 20 year periodic height increment of all trees remaining at the end of each projection period in the Oder-Spree region under the reference management scenario and applying the three climate runs.

at the end of each 20-year projection period under the reference management scenario in the *Oder-Spree* region. The analysis does not take ingrowth into account, thus, the collective of trees starting with almost 50,000 individuals shrinks to less than 10,000 at the end of the third projection period. Hence, differences between boxplots in one projection period are climatic effects, differences between periods are climatic and age effects. In the first two projection periods no trend in the climate effects on tree height growth can be observed. However, looking at the median value in the last projection period height increment under the minimum climate scenario is projected as 12 cm per year, under the median run as 6 cm per year and under the maximum run as 3 cm per year. Thus, the uncertainty on height growth in this case amounts to 9 cm per year for the median value.

When comparing the results between periods changing climate and proceeding age of the trees both contribute to the overall reduced level of height growth throughout the entire projection period until 2070 (Figure 11). A separate analysis distinguishes between both effects (Figure 12).

The analysis of periodic height increment clearly states the overwhelming influence of tree age on height growth (Figure 12). The decrease in height growth comparing the first three age classes outnumbers the climate induced effect. Trees older than 100 years, however, seem to react stronger on differences in the climatic conditions than on the aging effect.

Discussion

Various empirical and ecophysiological models exist to predict future hazards on forest ecosystems (e.g. Gadow 2001; Lindner et al. 2010). Thus, it is possible to detect potential hazards and to identify the most vulnerable areas in forest regions. The hazards can be further transformed into risks using probabilities. Risk is defined as the expected loss due to a particular hazard in a region during a defined time span (United Nations 1992). It is a major challenge to quantify the expected loss, for example assigning occurrence probabilities using quantitative approaches such as the applied storm risk model. However, such models are not always available. In that case Hirshleifer and Riley (1992) emphasize that risk is a situation in which subjective probabilities to hazard events are assigned depending on the stakeholder's expectation. The expectation reflects the stakeholder's risk attitude.

Applying scenario simulation, diverging effects of different silvicultural strategies on risks can be quantified (Clark et al. 2001). In forest planning models, risk factors can be considered as constraints to restrict the total risk level to a certain limit or to exclude certain risky management alternatives (Gadow 2000). Altogether, a comprehensive vulnerability analysis is of great importance to forest management in order to answer following questions according to the respective silvicultural management regime applied: (1) what are the major risk factors, (2) how will risk affect different forest functions, (3) is action needed for adaptation measures, and (4) what adaptation measures can be applied?

The presented risk assessment delivers insight into the effects of three silvicultural management strategies on two abiotic risk factors, windthrow and drought stress. To quantify these effects, we project forest development excluding interaction by mortality due to windthrow, loss of vitality or even mortality due to drought stress. In reality forest dynamics can substantially depart from this idealized projection.

Windthrow risk

The applied storm risk model (Schmidt et al. 2010) is a statistical approach utilizing variables which are generally

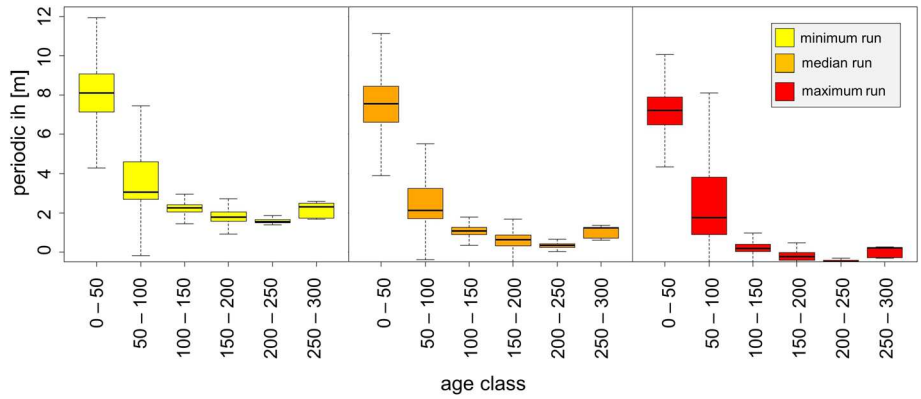


Figure 12 Boxplots of the 20 year periodic height increment over age classes in the Oder-Spree region in the projection period 2031 to 2050 under the reference management scenario and applying the three climate runs.

available in forestry for large areas. The information about single trees, stands and sites to predict windthrow probability is crucial to many different statistical model approaches such as the binary additive regression model used in this study, a discriminant model by Valinger et al. (1993), a logistic regression model by Kellomäki and Peltola (1998), and a neural network approach by Hanewinkel et al. (2004). In order to explain the causal relationship of wind damage to trees, most mechanistic model formulations require detailed information about physical as well as meteorological parameters (e.g. Peltola et al. 2013). Especially data characterizing wind fields and flow dynamics are not commonly available for risk projections in large forest areas, at least in our case. Therefore, the statistical storm risk model by Schmidt et al. (2010) is used in this study albeit knowing about the limitations when predicting windthrow probabilities in the north German lowlands while the model was parameterized using data from mainly southwestern German medium mountain ranges. Although the storm risk model does not predict windthrow probability climate-sensitively, assumptions on the frequency and intensity of storm events under climate scenarios alter the interpretation when transferring vulnerability probabilities into damages and losses. Further shortcomings of the model formulation are the lack of sensitivity to important factors such as species mixture, stand structure (c.f. Lüpke and Spellmann 1997; Griess et al. 2012) and also interaction with neighboring stands (c.f. Olofsson and Blennow 2005). Nevertheless, the projected ranking of species' sensitivity to windthrow vulnerability is mainly in accordance with other findings (Peltola et al. 1999; Bredemeier et al. 2001; Kohnle and Gauckler 2003; Schütz et al. 2006). The species effect on windthrow clearly shows that *Norway spruce* is most prone, followed by *Scots pine*, *European beech* and oak as well as other deciduous species. The susceptibility of *Douglas-fir* towards windthrow vulnerability is discussed controversially. Albrecht et al. (2012) conclude from their storm damage analysis that no differences between *Norway spruce* and *Douglas-fir* exist, while Schütz et al. (2006) argue in favor of *Douglas-fir* in mixed stands which is often the case in central Europe.

The implications from our windthrow vulnerability analysis for the four regions strongly depend on the individual risk attitude. Yet, no projections on storm frequencies and intensities are available. Thus, we can interpret the calculated windthrow probabilities by anticipating how many storm incidents will occur during the period regarded. Furthermore, a storm event will hardly hit an entire region equally. Whether or not a windthrow probability of 69% for the 20% volume quantile for the entire region of *Diepholz* under the reference path in 2070 calls for adaptation measures lies in the valuation of the decision maker. Nevertheless, the results of our analysis can contribute to depict windthrow vulnerabilities and possible counter-measures in the regions. Generally, the ranking of windthrow risk for the 20% volume quantile in the regions under the three silvicultural management scenarios is a result of conversion of different species as well as the different harvesting dimensions (c.f Tables 4 and 7).

The detailed example of the windthrow vulnerability analysis in the *Uelzen* region indicates that the climate protection management strategy is superior to the reference path as the volume at risk is divided more evenly between species, namely *Douglas-fir* and *Scots pine*, and also distributed over a broader range of probability classes (Figure 7). In terms of diversification of windthrow risk, the conversion from *Scots pine* to *Douglas-fir* in combination with a reduced target diameter harvest for all species is favorably on a regional level. Furthermore, species change to *Douglas-fir* will usually not result in pure stands but in mixtures mainly with *European beech* or *Scots pine* depending on soil nutrient supply. Species mixture will further enhance stand stability (Schütz et al.

2006; Griess et al. 2012). Compared to the vulnerability assessment of the other two paths the biodiversity management strategy features only low volume proportions in the high probability classes. This is a clear advantage when only the most windthrow prone stands shall be converted.

If stakeholders nevertheless opt for the reference silvicultural management strategy in *Uelzen* because it might be preferable when considering other risk factors or management objectives windthrow risk reduction or prevention seems necessary. A substantial volume proportion of *Douglas-fir* and *Norway spruce* is predicted in high probability classes under the reference scenario in 2070 (Figure 7B). Considering only the most vulnerable species in the region the stakeholders have to decide whether or not action is necessary if about 10% of the total volume in the region has an 80% to 90% chance of windthrow in the case of a winter storm with gale wind speed. One possible adaptation measure could be species conversion. For example, *Norway spruce* stands could be converted to more stable deciduous species or at least mixed species stands. A second adequate measure could be reducing the target diameter, thus a lower harvesting age and consequently lower tree heights with lower windthrow risks. This is a feasible strategy which resembles an intermediate silvicultural management path between the reference and climate protection scenario. Next to the high windthrow risk of *Norway spruce* and *Douglas-fir, Scots pine* contributes the biggest share of endangered volume with a windthrow probability of 60% to 70% under the reference as well as the biodiversity strategy in 2070. Whether or not adaptation measures are necessary and economically worthwhile looking at the risk level and concerned species depends on the risk attitude of the decision maker. Possible adaptation measures might include conversions to deciduous species where soil conditions are favorable or enriching pine stands with deciduous species.

Drought risk

Modelling drought induced effects on forest ecosystems is a complex task. Anderegg et al. (2013) state that it is still not possible to reliably predict tree mortality triggered by drought based on easily available meteorological parameters. Adams et al. (2009) point out that mortality is a non-linear threshold process and thus being difficult to predict. Generally, trees react to drought incidents by primarily reduced productivity, a loss of vitality and at the same time a higher susceptibility to biotic hazards and even mortality (Hanson and Weltzin 2000). Obviously, species and individual trees experience different thresholds of soil moisture deficits leading to plant water stress and consequently resulting in physiological damage. Niinemets and Valladares (2006) present a drought tolerance classification for temperate northern hemisphere trees. Zang et al. (2011a) prove different stress responses of diameter increment depending on tree size for *Scots pine*, *Norway spruce* and oak. Also stand structure and species mixture plays an important role in species' reaction to drought. Pretzsch et al. (2012) show differences in species' tolerance and growth recovery under drought stress comparing pure and mixed forest stands. Furthermore, the interaction of environmental factors might influence the trees' reaction to drought stress. For example, with increasing temperature, water deficits of only short duration can trigger severe physiological damage (Adams et al. 2009).

The purpose of our drought risk assessment is to provide decision support on managing existing stands under climate change and to give recommendations for potential species conversions considering drought stress. Volume proportions in risk classes are quantified instead of predicting mortality or growth reduction. Hence, an adequately precise classification of drought risk should suffice to derive silvicultural adaptation measures and for strategic planning of species cultivation.

So, albeit far from being comprehensive, still lessons can be learnt from the results. The *Diepholz* region is climatically favored by enough precipitation and extensive areas with sufficient soil moisture. The forest area can best be characterized as a diverse species composition with a high proportion in young age classes. Thus, current vulnerability looking at drought stress is low. Also, under climate change no adaptation measures need to be considered in *Diepholz* as drought stress will be negligible until 2070. In *Uelzen*, today's site conditions are characterized by sufficient water for most species and a high proportion of fertile soils. Species distribution in *Uelzen* seems to be well adapted to the current situation. Under climate change *Norway spruce*, representing 13% of the area today, will be the most vulnerable species considering both drought risk and windthrow probability. Bredemeier et al. (2001), Hanewinkel et al. (2009), Spellmann et al. (2011) confirm the critical vulnerability rating of *Norway spruce* in Germany. The two eastern regions *Fläming* and *Oder-Spree* both are highly vulnerable to drought stress as, already today, the deficit in climatic water balance is substantial (see Table 2). Limitations on available water in combination with a high proportion of poor soil nutrient supply leaves a narrow margin of management alternatives for the future especially when considering the already overwhelming proportion of the most drought tolerant *Scots pine*.

Our evaluation of drought stress strongly relies on the derived risk class limits. Although evidence from observed species distribution ranges depending on water available to plants and conclusions from physiological drought experiments as well as drought assessments

from literature are considered (e.g. Otto 1994; Roloff and Grundmann 2008; Kätzel et al. 2008) there is still the subjective element of setting the class boundaries in our classification. Considering the applied parameter *water available to plants* to evaluate drought stress there is just not sufficient knowledge from experiments or evidence from forest monitoring to warrant a more detailed drought risk classification by, for example, tree age or region. Nevertheless, other findings support our ranking from *Norway spruce* as most drought prone, followed by *European beech*, the group oak and *Douglas-fir* to *Scots pine* as most drought tolerant (Otto 1994; Bredemeier et al. 2001; Roloff and Grundmann 2008; Zang et al. 2011b). On the other hand, there is a controversial debate on drought tolerance of certain species, in central Europe especially *European beech*. For example, Rennenberg et al. (2004) regard *European beech* as highly vulnerable under climate change in central Europe whereas Ammer et al. (2005) conclude that beech will be competitive enough to dominate the potential natural vegetation in the future. Bolte et al. (2007) augment the debate with the argument that the high phenotypic plasticity and evolutionary adaptability of beech towards drought stress will be another competitive advantage. Eichhorn et al. (2008) analyzed the extreme dry and hot weather conditions in Germany in 2003 and conclude that European beech meets drought stress in the following year by shifting the carbon allocation towards pronounced fruit development and natural regeneration in order to secure species survival rather than individual biomass production. They conclude that adaptation of carbon allocation is an important indicator for drought stress tolerance.

Our drought risk analysis based on mean values (Figure 8) reveals whether or not action needs to be considered. The detailed species-specific analysis points to possible adaptation measures (Figure 9).

The example on drought risk analysis (Figure 8) uncovers a predicament in the results of the vulnerability analysis. Currently, in *Diepholz* and *Uelzen* no extensive adaptive measures seem necessary. In *Fläming* and *Oder-Spree*, a large volume proportion is predicted to be highly drought stress prone. Unfortunately, the more drought tolerant species *Scots pine* and oak already make up 70% of species area in *Fläming* and 85% in *Oder-Spree* leaving few potential for further increases. Furthermore, the high proportion of pine in the eastern regions might also bear intrinsic risks as other findings hint at a close relationship between climate change induced drought stress and *Scots pine* mortality as high summer temperatures along with drought may negatively shift the balance between trees and pathogens (Rebetez and Dobbertin 2004; Dobbertin et al. 2007). Also, simulation results by Lindner (2000) indicate that beech, due to its drought sensitivity, is not the best choice to transform pure Scots pine stands into mixed pine-deciduous species stands. Thus, although drought risk is an issue in the two eastern regions adaptation measures seem limited.

Uncertainty

Various definitions of uncertainty exist depending on discipline and also on context (Ascough et al. 2008). Furthermore, no unambiguous consensus on the characteristics, relative magnitude, and possible countermeasures exist, although many sources of uncertainty are identified. A more universal definition of uncertainty by Rowe (1994) is straightforward: the major attribute of uncertainty is the lack of information which may or may not be obtainable. Thus, every projection of forest dynamics and each decision process in natural resource management is connected to multiple uncertainties. Borchers (2005) calls for accepting uncertainty as it is better to identify factors of uncertainty and to include the effects on, for example, forest resources in the decision process rather than to strive for putative certainty. Such false certainty might be pretended by selecting, for example, one silvicultural strategy as irrevocably established and ignoring the multitude of possible management paths.

Generally, in the forestry domain three major sources of uncertainty are to be considered. Uncertainty may arise from sampling errors, measurement errors and prediction errors (Kangas and Kangas 2004). In our analysis we focus on the latter as we compare the effects of three climate projections on drought risk and height growth. The purpose of our uncertainty analysis is to quantify a range of possible outcomes. Especially in the case of climate projections, Jones (2000) precisely distinguishes between scenarios, forecasts and projected ranges of outcomes. In his definition a scenario is one possible projection with no probability assigned to it. A forecast, on the other hand, is the most likely projection with high probability and little uncertainty left. And eventually, a projected range of outcomes, as is the case in our analysis, includes uncertainties due to different probabilities. Of course, the probabilities of climate projections are unknown also in our analysis. The range of results simply illustrates the potential effects on, for example, drought risk or height growth. Using this information in the course of the decision process the forest manager might define his risk attitude and thus, consequently, assigns probabilities to the climate projections.

The uncertainty analysis in *Oder-Spree* (Figure 10) shows a high variability of drought risk on climate projections. In order to draw conclusions on the results and to opt for management alternatives, the quantified amount of uncertainty can be regarded as probabilities of future states. The stakeholders, thus, might look at

the different climate projections as hazards. A risk-averse attitude assigns the climate run with the most negative impact on the forest ecosystem a high probability.

The second example on uncertainty concerns the variability of height growth due to climate projections (Figures 11 and 12). The uncertainty on height growth and thus forest productivity might have major implications for timber yield predictions affecting timber supply and income of forest enterprises (c.f. Hanewinkel et al. 2009) as well as ecological parameters, for example carbon sequestration and carbon offsets (c.f. Galik and Jackson 2009) or shifts in volume increment to mean tree volume allometry and number of trees to mean tree volume allometry (Pretzsch et al. 2014).

Conclusions

Simulation studies on forest dynamics applying the introduced simulation framework *WaldPlaner* are useful to evaluate the impact of different silvicultural management strategies and to analyse the effects of different climate projection on a regional level. We characterize the variation in forest development and assess the effects on drought and windthrow risk due to different silvicultural practices in four regions in the North German lowlands.

Drought risk is a serious issue in the eastern regions *Fläming* and *Oder-Spree* independently from the applied silvicultural scenario, but adaptation measures are limited as the proportion of the most drought tolerant species *Scots pine* is already high. Whether or not there will be a significant drought induced die-back even of pine is debatable (cf. Dobbertin et al. 2007). In any case, the area of less productive forests will increase.

Windthrow risk is no serious overall threat in any region, but adequate counter-measures such as species conversion, species mixture or reduction of target diameter can be taken where endangered stands are identified.

Furthermore, we quantify the amount of uncertainty in drought risk assessment and height growth arising from different climate projections. Taking adaptation measures to counteract climate induced uncertainty on e.g. drought risk or changes in productivity is a matter of individual risk attitude as the three climate runs span a decision space with possible developments.

The investigated projection period until 2070 suffice to detect changes, although being short of the proposed 100-year simulation period as species conversion is a slow process (Lindner 2000). Based on the simulation results it is possible to give decision support for sustainable forest management and adaptation measures can be considered. Risk assessment, of course, is only one important contribution in the decision process on how to manage stands and about conversion strategies. Other factors such as forest productivity, timber supply, non-timber products even recreational value play an important role in a comprehensive decision process.

Obviously, the three contrasting management scenarios and the three climate projections investigated are only a small extract of multiple future paths. Other than in a forest management optimization process the contrasting scenarios define a decision space with quantified effects on forest dynamics, risks and uncertainties. Furthermore, forest management planning is always customised to local conditions. Therefore, none of the introduced silvicultural management paths will actually be assigned to the entire forest land of a region but forest management will strive for the best mixture.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

The first author (MA) conducted the data analysis and wrote the first draft. HS and JN initiated the research project "Sustainable land-use management in the North German lowlands". HS defined the silvicultural management regimes and provided major input to the drought risk analysis. JH provided and adjusted the *WaldPlaner* software. MS provided the longitudinal height diameter model and the storm risk model and had a major input in improving the manuscript. All authors jointly discussed the simulation results. All authors read and approved the final manuscript.

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Matthias Albert, Matthias Schmidt

Standort-Leistungs-Modelle für die Entwicklung von waldbaulichen Anpassungsstrategien unter Klimawandel

Im Rahmen der Klimafolgenfoschung der Nordwestdeutschen Forstlichen Versuchsanstalt (NW-FVA) werden klimasensitive Standort-Leistungs-Modelle und biometrische Ansätze zur Quantifizierung abiotischer und biotischer Risiken entwickelt. Neben klimabedingten Verschiebungen im Wuchspotenzial werden sich verstärkende und neu auftretende abiotische und biotische Risikofaktoren negativ auf die Vitalität der Wälder und die Ertragslage der Forstwirtschaft auswirken. Ziel dieses Beitrages ist es, Modellansätze vorzustellen, die den Standort-Leistungs-Bezug so umfassend beschreiben, dass das gesamte Leistungsspektrum auf einem Standort quantifiziert werden kann. Dies ist zum einen ein verallgemeinertes additives Modell zur Schätzung des Erwartungswertes der Mittelhöhenbonität, welches im Rahmen von Szenariosimulationen eingesetzt werden kann, um z. B. Verjüngungs-, Pflege- und Nutzungskonzepte auf ihre Eignung zu prüfen und Anpassungsmaßnahmen zu planen, Holzaufkommensprognosen zu rechnen und die Möglichkeiten der Kohlenstoffsequestrierung im Bestand einzuschätzen. Der zweite Ansatz zur Modellierung der Standort-Leistungs-Beziehung beruht auf der Methode der Quantilsregression. Zur Beurteilung der Anbauwürdigkeit von Baumarten wird es als erforderlich erachtet, dass nicht nur die mittlere Leistungsfähigkeit eines Standortes sondern dass ein Quantil der Höhenbonitätsverteilung geschätzt wird. Somit können Anteile der Bestände geschätzt werden, die auf einer Standortseinheit eine bestimmte Wuchsleistung erreichen. Auf das Quantilsregressionsmodell aufbauend dienen mehrdimensionale Ökogramme als Entscheidungsunterstützungsinstrumente für die Baumartenwahl unter sich verändernden Klimabedingungen.

Stichworte: Standort-Leistungs-Bezug, Klimawandel, verallgemeinertes additives Modell, Quantilsregression, Produktivitätsveränderung, Baumartenwahl

Site-productivity models for developing silvicultural adaptation strategies under climate change

Climate-sensitive site-productivity models and biometric approaches to quantify abiotic and biotic risks are the core of the Northwest German Forest Research Institute's (NW-FVA) climate impact research. A climate induced shift in forest growth potential as well as increasing current and emerging new abiotic and biotic risks will impact forest ecosystem's vitality and the forest enterprises' economic condition. The presented research introduces two statistical models which comprehensively describe the site-productivity relationship of beech (*Fagus sylvatica*, L.), oak (*Quercus* spec.), spruce (*Picea abies*, [L.] KARST), pine (*Pinus sylvestris*, L.) and Douglas-fir (*Pseudotsuga menziesii* [MIRB.] FRANCO). Firstly, species-specific generalized additive models predict the expected site index value. Based on scenario simulations silvicultural concepts for regeneration, tending and harvesting under a changing climate can be checked and adaptation measures can be applied in case of need. Furthermore, climate-sensitive predictions of future timber stocks and carbon sequestration calculations are possible fields of model application. Secondly, the site-productivity relationship is modelled using a quantile regression approach. In order to evaluate the tree species' worthiness of cultivation a predicted mean site productivity is considered not sufficient but additionally certain quantiles of the site index distribution need to be predicted. Thus, proportions of forest stands stocking on a specific site and reaching a certain productivity level can be predicted. Based on the species-specific quantile regression models multidimensional ecograms are developped as decision support instruments for selecting tree species for cultivation under a changing climate.
Keywords: Site-productivity relationship, climate change, generalized additive model, quantile regression, changes in productivity, choice of tree species

1 Einleitung

Forsteinrichtung und Waldbauplanung müssen durch den rapiden Wandel der ökologischen Rahmenbedingungen und ökonomischen Produktionsgrundlagen Entscheidungen in einem Umfeld treffen, das durch ein hohes Maß an Unsicherheit geprägt ist. Allein die projizierten Klimaveränderungen werden zu einer Zunahme abiotischer und biotischer Risiken und zu wuchsleistungsbeeinflussenden Standortveränderungen führen, deren räumliches und zeitliches Muster nur schwer quantifiziert werden kann. Instrumente zur waldbaulichen Entscheidungsunterstützung, die diese Veränderungen unter Berücksichtigung der Unsicherheit beschreiben und einen Handlungskorridor aufzeigen, können daher eine wertvolle Hilfestellung bieten.

Auch in Mitteleuropa beeinflusst der Klimawandel bereits heute die Wälder. Die Klimaprojektionen lassen zukünftig für Deutschland deutlich höhere Temperaturen bei gleichzeitig veränderten jährlichen Niederschlagsverteilungen erwarten (UBA 2006, IPCC 2007, GERSTENGARBE 2008). Insbesondere die projizierte Zunahme extremer Witterungsereignisse wie lang anhaltende Trockenperioden und Stürme werden sich negativ auf den Gesundheitszustand der Wälder und die Ertragslage der Forstwirtschaft auswirken. Angemessene Anpassungsmaßnahmen der mittel- bis langfristigen Waldbauplanung können die Risiken jedoch abschwächen (MILLAR et al. 2007; SPELLMANN et al. 2007; BOLTE et al. 2009).

Die klimasensitive Modellierung des Waldwachstums ist neben der Quantifizierung von abiotischen und biotischen Risiken einer der Schwerpunkte in der Klimafolgenforschung der Nordwestdeutschen Forstlichen Versuchsanstalt (NW-FVA). Es ist das Ziel, den Standort-Leistungs-Bezug so umfassend zu beschreiben, dass die Variabilität des Leistungsspektrums auf einem Standort quantifiziert werden kann. Für viele waldwachstumskundliche Fragestellungen sind Schätzungen des Erwartungswertes einer Bonitätsverteilung aussagekräftig.

Für eine spezifische Kombination von Standortseigenschaften sind die beobachteten Höhenbonitäten approximativ normalverteilt, so dass ihr Erwartungswert mit einem Standardregressionsmodell geschätzt werden kann. Jedoch werden viele waldbauliche Entscheidungen wie z. B. die Baumartenwahl nicht ausschließlich an Erwartungswerten ausgerichtet. Die Anbauempfehlung für eine Baumart muss vielmehr die Variabilität der Bonitäten eines Standortes berücksichtigen. Ein mögliches Entscheidungskriterium ist daher der Anteil der Bestände (z. B. 70, 80 oder 90 %) einer Standortseinheit, der eine bestimmte Mindestbonität erreicht. Für die Entscheidungsunterstützung bei der Baumartenwahl muss folglich ein Quantil der Verteilung der Standortleistungsfähigkeit geschätzt werden. Die Anforderungen der forstlichen Praxis an die Leistungsfähigkeit von Waldbeständen bestimmen dabei, welches konkrete Quantil als ausreichend angesehen wird.

In diesem Beitrag werden sowohl verallgemeinerte additive Modelle zur Schätzung des Erwartungswertes als auch Schätzmodelle für Quantile des Standort-Leistungs-Bezuges für die Baumarten Buche (*Fagus sylvatica*, L.), Eiche (*Quercus* spec.), Fichte (*Picea abies*, [L.] Karst), Kiefer (*Pinus sylvestris*, L.) und Douglasie (*Pseudotsuga menziesii* [Mirb.] Franco) vorgestellt. Ziel ist es (1) die unterschiedlichen Anwendungsbereiche der beiden Modellansätze aufzuzeigen und (2) den Beitrag der beiden Modellansätze für die Entwicklung von waldbaulichen Anpassungsstrategien an den Klimawandel vorzustellen.

2 Material und Methoden

Zur klimasensitiven Modellierung des Standort-Leistungs-Bezuges müssen Standortsvariablen räumlich hoch aufgelöst vorliegen. Viele Variablen stehen in adäquater Qualität jedoch entweder nicht flächendeckend für alle Besitzarten, wie z. B. bodenkundliche Informationen aus der Forstlichen Standortskartierung, oder sogar nur als Stationsmesswerte, wie z. B. die Klimaparameter auf Basis der DWD-Stationen, zur Verfügung. Somit müssen die Standortsvariablen über kombinierte geostatistische und regressionsanalytische Verfahren regionalisiert werden. Diese Regionalisierungen sind zum einen für die Modellentwicklung notwendig, weil ertragskundliche Erhebungen auf Versuchsflächen und in Waldinventuren nicht deckungsgleich mit z. B. bodenkundlichen Erhebungen wie der BZE sind. Zum anderen ist die flächendeckende Verfügbarkeit von Standortsvariablen für die spätere Initialisierung bzw. Anwendung der Modelle in der forstlichen Praxis notwendig.

2.1 Datenmaterial

Die Datengrundlage für die Modellierung des Standort-Leistungs-Bezuges sind Inventurpunkte der Bundeswaldinventuren 1 und 2 (BWI) sowie der Betriebsinventuren der Niedersächsischen Landesforsten (BI). Für die baumartenspezifischen Modelle wurden jeweils die Inventurpunkte selektiert, an denen die Baumart mit mindestens einer Baumhöhenmessung erfasst wurde (Tab. 1). Aufgrund der repräsentativen Stichprobenmethoden ergeben sich umfangreiche baumartspezifische Datengrundlagen, die das gesamte Alters- und Bonitätsspektrum abdecken.

Tabelle 1: *Charakteristika der Parametrisierungsgrundlage (N – Anzahl der Beobachtungen; $\bar{x}$ – Mittelwert; sd – Standardabweichung; 5-%- und 95-%-Quantil; hg_{100} – Mittelhöhenbonität im Alter 100)*

Table 1: *Characteristic values of the parameterization data base (N – number of observations; $\bar{x}$ – mean; sd – standard deviation; 5-%- and 95-%- quantile; hg_{100} – site index at age 100)*

		Buche	Eiche	Fichte	Kiefer	Douglasie
N		35864	20666	57094	35104	4750
Alter	$\bar{x}$	96	100	69	75	44
	5 %	35	29	25	27	18
	sd	40	47	34	36	21
	95 %	161	177	130	140	90
hg_{100}	$\bar{x}$	27,9	24,3	31,8	26,2	47,5
	5 %	20,9	18,0	25,0	20,3	35,5
	sd	4,1	3,7	4,1	3,5	6,6
	95 %	34,5	30,3	38,5	31,7	57,1

Tabelle 2: *Verwendete Modellvariablen und die zu ihrer Herleitung verwendete Methodik ([1] 1 000 eq / ha·a = 14,01 kg / ha·a)*

Table 2: *Selected model variables and method of derivation ([1] 1 000 eq / ha·a = 14.01 kg / ha·a)*

Variable	Einheit	Datenquelle
Bodennährstoffe (Nähr)	nach Berg- und Tiefland klassifizierte und in (max.) je 4 Stufen gruppierte Bodennährstoffversorgung in Anlehnung an die niedersächsische Standortskartierung	abgeleitet aus Leitprofilen entsprechend der Wald-Bodenübersichtskarte (BÜK); modifiziert von Ahrends (2010)
Nutzbare Feldkapazität (nFK)	auf 1,4 m Bodentiefe bilanziert [mm]	abgeleitet aus Leitprofilen entsprechend der Wald-BÜK; modifiziert von Ahrends (2010)
Stickstoffdeposition (Ndep)	über das Bestandesleben gemittelte jährliche Stickstoffdepositionsrate [eq/ha·a] [1)]	modelliert mit einer modifizierten Version von MAKEDEP (Alveteg et al. 1997, Ahrends et al. 2008)
Temperatursumme (Temp)	Summe aller Tagesmitteltemperaturen in der Vegetationszeit [°C], wobei die Vegetationszeit dynamisch und baumartspezifisch berechnet wird (vgl. Menzel 1997, v. Wilpert 1990)	modelliert mit WETTREG für die Klimanormalperiode 1961 bis 1990; regionalisiert auf Einheiten von 200 m×200 m mit WASIM-ETH (vgl. Schulla 1997, Spekat et al. 2006)
Klimatische Wasserbilanz (KWB)	Differenz aus der Niederschlagssumme und der potenziellen Evapotranspiration (vgl. Monteith 1965) in der Vegetationszeit [mm]	modelliert mit WETTREG für die Klimanormalperiode 1961 bis 1990; regionalisiert auf Einheiten von 200 m × 200 m mit WASIM-ETH (vgl. Schulla 1997, Spekat et al. 2006)

An jedem Inventurpunkt wird baumartspezifisch die Mittelhöhenbonität im Alter 100 mit Hilfe des longitudinalen Höhen-Durchmesser-Bonitierungsansatzes von Schmidt (2008, 2009), basierend auf den Arbeiten von Lappi (1997) und Mehtätalo (2004), als Funktion von Bestandesparametern und der Seehöhe sowie der geografischen Lage geschätzt (vgl. auch Albert und Schmidt 2010). Dieser Bonitierungsansatz berücksichtigt die durch Klimawandel und Stoffeinträge hervorgerufenen Wachstumstrends, die bereits für die vergangenen Jahrzehnte beobachtet wurden (vgl. z. B. Röhle 1995, Sterba 1995, Elfing und Nyström 1996, Spieker et al. 1996; Schadauer 1999). Die so hergeleitete Mittelhöhenbonität drückt die Standortleistungsfähigkeit aus und ist die Zielgröße der im folgenden beschriebenen Modellierungsansätze.

		Buche	Eiche	Fichte	Kiefer	Douglasie
Nähr Bergland	schwach	487	1229	1898	6724	781
	mittel	1841		6668		
	gut	24549	12642	22693	15987	1583
	sehr gut			13196		1128
Tiefland	schwach	1346	1965	2145	7223	421
	mittel	101	3239			
	gut	7540		6150	3983	673
	sehr gut		1591	4350	1187	
nFK	$\bar{x}$	157	173	158	187	178
	sd	48	52	43	44	47
Ndep	$\bar{x}$	2163	2202	2635	2728	3622
	sd	862	1149	1043	1351	1701
Temp	$\bar{x}$	2117	2215	2048	2070	2205
	sd	140	92	183	92	107
KWB	$\bar{x}$	–188	–234	–157	–237	–265
	sd	109	69	127	81	87

Tabelle 3: *Wertebereiche der verwendeten Variablen (Nähr – Anzahl der Beobachtungen je Nährstoffstufe; die geschweifte Klammer kennzeichnet Klassen die aufgrund von nicht signifikant unterschiedlichen Modelleffekten bei der Modellselektion zusammengefasst wurden; $\bar{x}$ – Mittelwert; sd – Standardabweichung)*

Table 3: *Range of parameter values (Nähr –* ***number of observations in*** *nutrient class; curly bracket indicates combined classes because of not significantly differing effects during model selection;* ***$\bar{x}$ – mean; sd – standard deviation)***

Die Mittelhöhenbonität der BWI- und BI-Punkte wird über die zugehörigen geografischen Koordinaten mit verschiedenen Standortsvariablen verknüpft, deren Effekte auf die Standortleistungsfähigkeit geprüft werden. Die im Rahmen der Modellbildung als signifikant herausselektierten erklärenden Variablen sind die Bodennährstoffversorgung (Nähr), die nutzbare Feldkapazität (nFK), die Stickstoffdepositionsrate (Ndep) sowie die Temperatursumme (Temp) in der Vegetationszeit und die klimatische Wasserbilanz (KWB) in der Vegetationszeit. Eine räumliche Trendfunktion quantifiziert den Einfluss der geografischen Lage auf die Standortleistungsfähigkeit und subsummiert Effekte, wie z. B. den Windeinfluss, die nicht explizit durch die im Modell integrierten kausalen Variablen beschrieben werden. Tabelle 2 gibt einen Überblick über die verwendeten erklärenden Variablen und die Methodik ihrer Herleitung. Die Niederschlagssumme und Evapotranspiration in der Vegetationszeit sowie die CO_2-Konzentration wurden als weitere erklärende Variablen untersucht, aber im Rahmen der Modellbildung durch Modellvergleiche auf Basis des Bayesian Information Criterion (BIC) ausgeschlossen.

Die große Streuungen in den Beobachtungswerten der erklärenden Variablen und die Klassenbesetzungen in der kategorischen Variablen Nähr, getrennt nach Baumarten, verdeutlicht die weitreichende Abdeckung der forstlichen Standorte (Tabelle 3).

Die Bodenparameter Nähr und nFK werden aus der bundesweit vorliegenden Wald-Bodenübersichtskarte (Wald-BÜK) hergeleitet. In einem ersten Schritt werden die Bodenparameter eines Leitprofils, das dem Stichprobenpunkt zugeordnet wird, übernommen. In einem zweiten Schritt werden diese Parameterwerte des Leitprofils anhand von Transferfunktionen modifiziert (Ahrends 2010). Die Bodennährstoffversorgung wird im Anhalt an die Niedersächsische Standortskartierung klassifiziert (AK Standortskartierung 1996). Das Kartierschema unterscheidet dabei zwischen Bergland und Tiefland, was bei der Modellierung des Standort-Leistungs-Bezuges die Möglichkeit eröffnet, etwaige Unterschiede von Bergland- und Tieflandstandorten gleicher Nährstoffausstattung auf die Wuchsleistung zu identifizieren (vgl. Ahrends 2010). Daher wird die kategorische Variable Bodennährstoffe ebenfalls nach Berg- und Tieflandstandorten klassifiziert. Die nutzbare Feldkapazität wird einheitlich für alle Standorte auf 1,4 m bilanziert, weil die Bäume auf vielen Böden des Tieflandes eine effektive Durchwurzelungstiefe von mindestens 1,4 m aufweisen (Czajkowski et al. 2009). Für Berglandstandorte ist die größere Bezugstiefe abgesehen von Lößstandorten und Gesteinsklüften meist unerheblich, da die effektive Durchwurzelungstiefe durch das anstehende Gestein selten mehr als 1,0 m beträgt.

Die zeitdynamische Stickstoffdeposition (Ndep) wird als die durchschnittliche jährliche Rate bezogen auf das Bestandesleben am Beobachtungspunkt beschrieben. Der Bilanzierungszeitraum ist somit für Ndep dynamisch an den Zeitraum zwischen der Bestandesbegründung und dem jeweiligen Inventurzeitpunkt angepasst. Die jährlichen Stickstoffdepositionsdaten wurden mit einer modifizierten Version des Modells MAKEDEP von Alveteg et al. (1997) geschätzt (Ahrends et al. 2008; Ahrends 2010). Die Mittelwerte der Temperatursumme (Temp) und der klimatischen Wasserbilanz (KWB) in der Vegetationszeit der 30-jährigen Klimanormalperiode 1961 bis 1990 werden mit dem regionalen Klimamodell WETTREG (Spekat et al. 2006) retrospektiv für die geografische Lage der DWD-Messstationen projiziert. Für die zeitdynamischen Klimaparameter wird somit ein fixer Bilanzierungszeitraum verwendet. Diese projizierten Klimaparameter werden danach mit Hilfe des Modells WASIM-ETH (vgl. Schulla 1997; Schulla und Jasper 2007) deutschlandweit auf 200 m × 200 m Teilflächen regionalisiert. Jeder ertragskundliche Inventurpunkt bekommt die Klimaparameterwerte derjenigen Teilfläche zugeordnet, die ihm räumlich entspricht.

2.2 Methodik der verallgemeinerten additiven Modelle (GAM)

Der verwendete statistische Modellierungsansatz zur Beschreibung des Standort-Leistungs-Bezuges der Baumarten Fichte, Buche, Kiefer, Eiche und Douglasie ist ein verallgemeinertes additives Modell (vgl. Hastie und Tibshirani 1990), das im Statistikpaket R 2.10.0 (R Development Core Team 2006) unter Verwendung der Bibliothek mgcv 1.6-0 (Wood 2006) parametrisiert wurde. Additive Modelle erlauben es, nichtlineare Effekte der Prädiktorvariablen auf die Antwortvariable zu identifizieren, ohne dass Annahmen über eine bestimmte Funktionsform vorgegeben werden müssen. In der Methodik von Wood (2006) werden dazu penalisierte Regressionssplines verwendet. Dabei wird die Flexibilität der Anpassung fast ausschließlich über einen Glättungsparameter gesteuert, der über verallgemeinerte Kreuzvalidierung optimiert wird. Die allgemeine Form eines verallgemeinerten additiven Modells (GAM) lautet für normal- und homogenverteilte Beobachtungen wie folgt:

$$Y_i = \alpha + f(X_i) + \varepsilon_i \qquad \varepsilon_i \sim N(0, \sigma^2)$$

Y_i abhängige Variable für Beobachtung i
X_i Vektor von erklärenden Variable für Beobachtung i
f glättende Funktion

Im Gegensatz zum einfachen linearen Regressionsmodell, in dem die Beziehung zwischen Y_i und X_i durch einen konstanten Regressionsparameter beschrieben wird, werden im GAM glättende Funktionen zur Beschreibung potenzieller nichtlinearer Effekte verwendet. Das Schätzergebnis ist der Erwartungswert der Zielvariablen Y_i.

2.3 Methodik der Quantilsmodellierung

Die Modellierung von Quantilen zielt auf eine möglichst exakte Schätzung der bedingten Verteilungen der Zielvariablen y in Abhängigkeit der Prädiktorvariablen x. Quantilsmodellierungsverfahren können in zwei Gruppen eingeteilt werden: (1) nichtparametrische, verteilungsfreie Quantilsregressionsverfahren (vgl. KOENKER und BASSETT 1978; KOENKER 2005) und (2) verteilungsbasierte Verfahren wie z. B. die Generalized Additive Models for Location, Scale and Shape (GAMLSS-Modelle; vgl. RIGBY und STASINOPOULOS 2005, STASINOPOULOS und RIGBY 2007). GAMLSS-Modelle setzen eine bestimmte Verteilungsannahme, analog zur Normalverteilungsannahme im Standardregressionsmodell, für die Zielvariable voraus.

In dieser Untersuchung wird die LMS-Methode nach COLE und GREEN (1992) verwendet, bei der angenommen wird, dass die abhängigen Variablen der Box-Cox-Cole-Green-Wahrscheinlichkeitsverteilung (BCCG) folgen. Die BCCG-Verteilung hat drei Parameter, die die Schiefe λ (L), den Erwartungswert μ (M) und den Variationskoeffizienten σ (S) beschreiben. Die drei Parameter λ, μ und σ können mit Hilfe von verallgemeinerten additiven Modellen als Funktion von Kovariablen u. a. mittels glättender Splines modelliert werden, womit eine sehr hohe Flexibilität bezüglich der Modelleffekte erreicht wird (RIGBY und STASINOPOULOS 2004). Für eine einfache Interpretation additiver Effekte auf den Erwartungswert μ wird die Verknüpfungs-Funktion $g(\mu) = \mu$ verwendet (vgl. RIGBY und STASINOPOULOS 2004, 2005, 2006, FENSKE, 2008). Um positive Werte von σ zu gewährleisten, wird die Verknüpfungs-Funktion $g(\sigma) = log(\sigma)$ gewählt. Die Schiefe λ unterliegt keiner Restriktion und wird wie μ identisch verknüpft. Die Parametrisierung der drei Funktionen erfolgt durch Maximierung der penalized log-likelihood-Funktion. Die BCCG-Verteilung ist wie folgt definiert (RIGBY und STASINOPOULOS 2004, 2006):

$$f(y|\mu,\sigma,\lambda) = \left(\frac{1}{\sqrt{2\cdot\pi}\cdot\sigma}\right)\cdot\left(\frac{y^{\lambda-1}}{\mu^{\lambda}}\right)\cdot\exp\left(\frac{-z^2}{2}\right) \quad [1]$$

$$\text{wenn } \lambda \neq 0 \quad z = \frac{\left[\left(\frac{y}{\mu}\right)^{\lambda}-1\right]}{\mu\cdot\sigma} \quad [1.1]$$

$$\text{sonst} \quad z = \frac{\log\left(\frac{y}{\mu}\right)}{\sigma} \quad [1.2]$$

für $y > 0, \mu > 0, \sigma > 0, \lambda = (-\infty, +\infty)$

Die Box-Cox-transformierten *z*-Werte sind annähernd standard normal verteilt, d. h. durch die geeignete funktionale Beschreibung von λ wird jegliche Schiefe beseitigt, der Parameter μ beschreibt den Median anstelle des Mittelwertes und der Skalenparameter σ entspricht approximativ dem dimensionslosen Variationskoeffizienten (COLE et al. 2009). Kurtosis wird als nicht vorhanden angenommen. Die bedingte Quantilsfunktion im LMS-Modell ist, im Anhalt an VAN BUUREN (2007), wie folgt definiert:

$$Q(\tau\,|\,X_i) = \mu\,(X_i)\,(1+\lambda\,(X_i)\,\sigma\,(X_i)\,\phi{-}1(\tau))^{1/\lambda(X_i)} \quad [2]$$

τ Anteil der Verteilung
X_i Kovariablenvektor i
ϕ^{-1} inverse Verteilungsfunktion der Standardnormalverteilung

Die Modellbildung zur Schätzung von Quantilen des Standort-Leistungs-Bezuges erfolgt mit Hilfe des Statistikpaketes R, Version 2.10.0 (R Development Core Team 2006), unter Verwendung der Bibliothek gamlss, Version 3.0-1 (STASINOPOULOS und RIGBY 2007).

Eine gute Modellanpassung bei der LMS-Quantilsregressionsmethode ist dadurch gekennzeichnet, dass die transformierte Variable *z* einer Standardnormalverteilung folgt. Ein einfaches grafisches Prüfmaß ist dafür ein Normal-Quantil-Plot (QQ-Plot), bei dem die beobachten Quantile der Residuen des Modells über der theoretischen Quantilen bei Normalverteilung aufgetragen werden (Abb. 1). Dabei entsprechen die Quantilresiduen der transformierten Variable *z* (vgl. DUNN und SMYTH 1996).

Als detaillierteres Prüfkriterium für die Modellgüte schlägt VAN BUUREN (2007) Quantil-Quantil-Plots (Wurmplots) vor. Hierbei wird nicht wie bei den Normal-Quantil-Plots für jedes beobachtete Quantilresiduum das empirische Quantil auf der y-Achse aufgetragen, sondern es wird jeweils die Differenz zwischen empirischem und theoretischem Quantil über den theoretischen Quantilen bei Normalverteilung be-

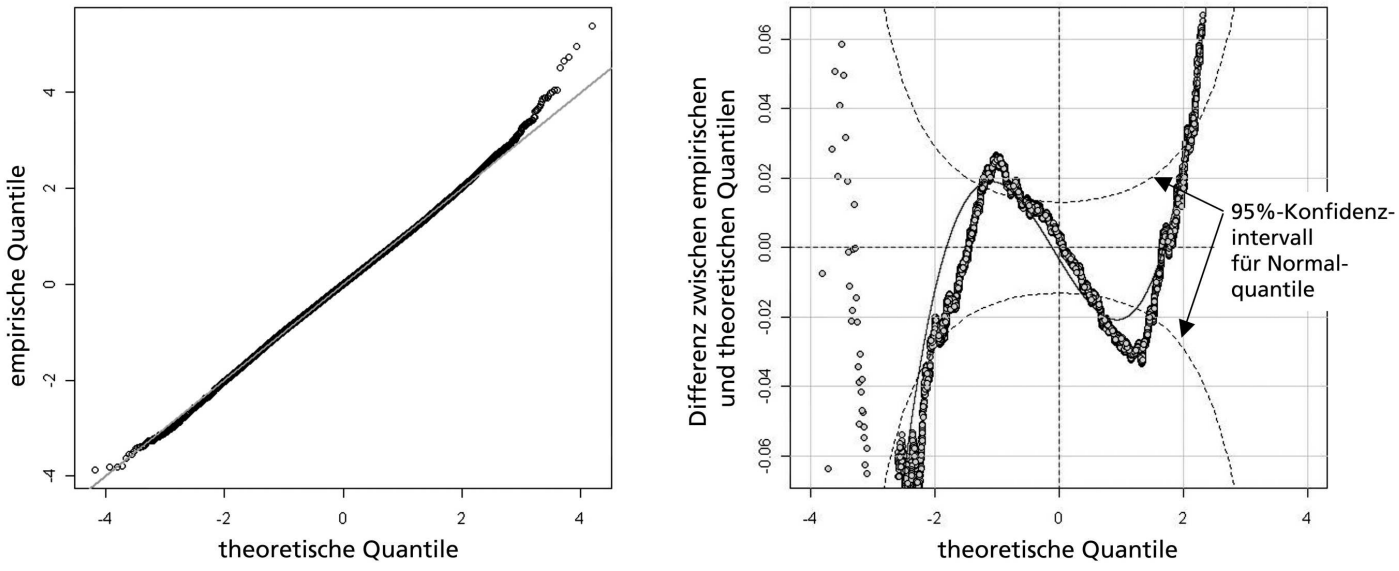


Abbildung 1: *Beispiel eines Normal-Quantil-Plots (links) und des entsprechenden Wurmplots (rechts) für die Quantilresiduen*

Figure 1: *Example of a Normal-quantile plot (left) and corresponding worm plot (right) for quantile residuals*

trachtet (vgl. FENSKE 2008, S. 90 f.). Ein Wurmplot ist somit ein trendbereinigter QQ-Plot, da hier jeweils der senkrechte Abstand der Residuen im Normal-Quantil-Plot zur Winkelhalbierenden abgebildet wird (Abb. 1). Nach VAN BUUREN (2007) sind Wurmplots als Prüfkriterien in GAMLSS-Modellen geeigneter, weil herkömmliche QQ-Plots und statistische Tests auf Normalverteilung zu Fehlinterpretationen führen können (vgl. Abb. 4 in VAN BUUREN 2007). Im Beispiel in Abbildung 1 sind als Abweichungen von der Winkelhalbierenden im QQ-Plot bereits Mängel in der Modellgüte erkennbar. Die Detailanalyse mit Hilfe des Wurmplots offenbart durch den S-förmigen Verlauf der Differenzen, dass in diesem Fall die Enden der angepassten Verteilung zu leicht sind, d. h. die prognostizierten Wahrscheinlichkeiten für das Auftreten extremer Werte werden zu gering geschätzt (VAN BUUREN 2007). Liegen Teile des „Wurms" außerhalb des 95-%-Konfidenzintervalls für Normal-Quantile, so sollte das Modell verbessert werden.

3 Ergebnisse

3.1 Standort-Leistungs-Modell auf Basis des verallgemeinerten additiven Modells

Ziel der Modellierung ist es, die Standortleistungsfähigkeit für jeden beliebigen Forstort und verschiedene Baumarten in Abhängigkeit von Boden- und Klimavariablen aber ohne Kenntnis von Bestandesmerkmalen zu schätzen. Somit wird es möglich, die Standortleistungsfähigkeit unabhängig von der aktuell vorhandenen Baumart in die Zukunft zu projizieren. Die Modellbildung unter Verwendung des Bayesian Information Criterion (BIC) und von Plausibilitätsprüfungen führt für die Baumarten Buche, Eiche, Fichte und Kiefer zu einem einheitlichen Set an Variablen. Das Modell lässt sich wie folgt spezifizieren:

$$hg100_i = \alpha_1 + Nähr_i^T\beta + f_1(Temp_i) + f_2(KWB_i) + f_3(nFK_i) + f_4(Ndep_i) + f_5(RW_i, HW_i) + \varepsilon_i \quad [3]$$

$hg100_i$ – Mittelhöhenbonität im Alter 100 an Stichprobenpunkt i [m]; $Nähr_i^T$ – Indikatorenvektor für klassifizierte Bodennährstoffe; β – zu Nähr gehörender Parametervektor, KWB_i – klimatische Wasserbilanz in der Vegetationszeit (VZ) [mm], $Temp_i$ – Temperatursumme in der VZ [°C], $Ndep_i$ – mittlere Stickstoffdeposition [eq/ha/a]; nFK_i – nutzbare Feldkapazität auf 1,4 m Bodentiefe [mm]; RW_i,HW_i – Gauss-Krüger-Lagekoordinaten; α_1 – Regressionskoeffizient (Interzept); f_1, f_2, f_3, f_4 – eindimensionale glättende Funktionen; f_5 – zweidimensionale glättende Funktion zur Beschreibung des räumlichen Trends

Bei der Baumart Douglasie führen die untereinander korrelierten Prädiktoren bei gleichzeitig deutlich geringerer Datengrundlage dazu, dass sich die Modelleffekte nicht voneinander trennen lassen. Insbesondere der Effekt der klimatischen Wasserbilanz zeigt bei simultaner Schätzung einen unplausiblen Verlauf, wonach zunehmende Trockenheit zu einer gesteigerten Standortleistungsfähigkeit führen würde. Für die Gewährleistung eines biologisch plausiblen Modellverhaltens werden deshalb die Modelleffekte der Variablen Temperatursumme (Temp) und klimatische Wasserbilanz (KWB) mittels einer Vorschätzung bestimmt. Anschließend gehen diese Modelleffekte als Konstanten in ein finales Modell ein, in dem lediglich noch die Effekte der übrigen Prädiktoren geschätzt werden. Darüber hinaus ist die Variable nutzbare Feldkapazität (nFK) im Douglasienmodell nicht signifikant. Für die Douglasie wird somit folgendes Modell definiert:

$$hg_{100_i} = \alpha_1 + Nähr_i^T\beta + \hat{f}_1(Temp_i) + \hat{f}_2(KWB_i) + \hat{f}_4(Ndep_i) + \hat{f}_5(RW_i, HW_i) + \varepsilon_i \quad [3.1]$$

$\hat{f}_1 = \hat{f}_2$ **mittels Vorschätzung bestimmte und konstant gesetzte Effekte;**
übrige Variablen wie für [3] spezifiziert

Die Kenngrößen der Modellgüte in Tabelle 4 weisen mittlere Bestimmtheitsmaße aus, der Standardfehler liegt je nach Baumart meist deutlich unter der Differenz einer Ertragsklasse und ein Bias ist nicht vorhanden.

Tabelle 4: *Kenngrößen der Modellgüte (se – Standardfehler)*

Table 4: *Characteristics of model quality (se – standard error)*

Baumart	R^2	se [m]	Bias [m]
Fichte	0,44	3,1	-7,3e-14
Buche	0,31	3,4	1,6e-14
Kiefer	0,45	2,6	-4,0e-15
Eiche	0,33	3,1	-9,0e-17
Douglasie	0,40	5,0	8,7e-15

Die Modellkoeffizienten, die Kennwerte der glättenden Terme und die grafische Darstellung der nicht-linearen Effekte inklusive der punktweisen Prognoseintervalle (5 % Irrtumswahrscheinlichkeit) der fünf Modelle sind als Anhang zu dieser Publikation auf der Internetseite der NW-FVA abrufbar[1].

Die linearen und nicht-linearen Effekte sind in allen Modellen hochsignifikant. Die Koeffizienten der kategorischen Variablen und linearen Terme sind bezüglich ihrer Wirkungsrichtung aus biologischer Sicht als plausibel zu beurteilen: je besser die Nährstoffversorgung und je höher die nutzbare Feldkapazität ist, desto besser ist die Mittelhöhenbonität.

3.1.1 Anwendungsbereiche des Standort-Leistungs-Modells

Das Standort-Leistungs-Modell schätzt den Erwartungswert der Standortleistungsfähigkeit, definiert als Mittelwert der Höhenbonität, die eine Baumart hypothetisch nach 100 Jahren unter konstanten aktuellen oder zukünftigen Standortsbedingungen erreichen würde. Tatsächlich wird ein Bestand jedoch aufgrund u. a. sich verändernder Klimabedingungen ein variables Höhenwuchspotenzial über das Bestandesleben aufweisen. Ein Anwendungsbereich des Standort-Leistungs-Modells ist somit eine Abschätzung des standortspezifischen Wuchspotenzials verschiedener Baumarten unter Klimawandel, z. B. eine zeitliche Analyse der Veränderung des Standort-Leistungs-Potenzials, eine Gegenüberstellung der projizierten Auswirkungen unterschiedlicher Klimaszenarien oder räumliche Analysen und Vergleiche von z. B. Standortsgruppen.

Zur Analyse der Standortleistungsfähigkeit unter Klimawandel werden Szenariosimulationen eingesetzt. Dabei gilt es, die Unsicherheiten zukünftiger Waldentwicklungen zu quantifizieren und abzuschätzen. Die Wahl des Klimaszenarios hat bei der Projektion der Standortleistungsfähigkeit einen entscheidenden Einfluss. An der NW-FVA werden derzeit die Klimabedingungen für drei 30-jährige Prognoseperioden von 2010 bis 2100, projiziert mit dem regionalen Klimamodell WETTREG (SPEKAT et al. 2006) unter dem Szenario A1B in der trockenen und in der feuchten Variante (IPCC 2007), verwendet. Die Betrachtung zweier Varianten spannt einen Bereich möglicher Klimapfade auf, der einen Teil der zukünftigen Unsicherheit abdeckt.

[1] http://www.nw-fva.de/fileadmin/user_upload/Verwaltung/Publikationen/Zusatz/2012_Albert_Schmidt_Anhang.pdf

Für die konkreten Szenariosimulationen mit dem Standort-Leistungs-Modell verändern sich laut unterstelltem Klimaszenario die Temperatursummen und klimatischen Wasserbilanzen der Standorte, während die übrigen erklärenden Modellvariablen als konstant angenommen werden. Der Boden wird zu Beginn der Vegetationszeit als wassergesättigt angesehen, die nutzbare Feldkapazität steht somit in vollem Umfang zur Verfügung. Die zukünftige Stickstoffdepositionsrate wird ebenfalls nicht dynamisch modelliert, sondern geht in Zukunftszenarien mit dem Wert des Jahres 2004 ein. Dieser Überlegung liegt die Annahme zu Grunde, dass selbst bei abnehmenden Stickstoffeinträgen die Böden mittelfristig als stickstoffgesättigt angesehen werden können. Die Verfügbarkeit der Bodennährstoffe wird sich unter Klimawandel langfristig verändern (vgl. AHRENDS 2010). Im Modell wird diese aber vorerst als konstant angenommen.

Mit Hilfe der klimasensitiven Standort-Leistungs-Modelle kann die aktuelle und zukünftige Leistungsfähigkeit jedes beliebigen Standortes für die fünf Baumarten in Deutschland geschätzt werden (Abb. 2).

Die in Abbildung 2 dargestellten Simulationsergebnisse der Standortleistungsfähigkeit für die Baumart Buche im Zuständigkeitsbereich der NW-FVA verdeutlichen die zeitliche Dynamik, die räumlichen Unterschiede und durch Vergleich der beiden Varianten die klimabedingte Unsicherheit in der Projektion. Im Vergleich der drei Projektionsperioden werden unter dem Szenario A1B in beiden Varianten bis 2040 keine bis leicht positive Veränderungen der Standortleistungsfähigkeit erwartet. In der zweiten Periode sind besonders in der trockenen Variante bereits große Bereiche in der niedersächsischen Tiefebene, in Sachsen-Anhalt und Südhessen erkennbar, für die Verluste bis 7,5 % der Leistungsfähigkeit vermutet werden. Für die Hochlagen der Mittelgebirge werden andererseits Steigerungen des Wuchspotenzials von mehr als 7,5 % in beiden Varianten geschätzt. In der dritten Periode bis 2100 verstärken sich die projizierten Trends weiter. Dabei ist das negative Ausmaß der Veränderung in der trockenen Variante deutlich ausgeprägter als in der feuchten Variante, z. B. werden für die Rhein-Main-Ebene je nach Variante leichte (2,5 bis 7,5 %) bis deutliche (über 7,5 %) Einbrüche der Leistungsfähigkeit projiziert.

Die Häufigkeitsverteilungen der Standortleistungsveränderung für die drei Projektionsperioden in Abbildung 3 quantifizieren die Anteile der Einbußen und Steigerungen für die Baumart Kiefer. Bei der Interpretation der Ergebnisse ist zu beachten, dass es sich um eine inventurpunktbasierte Auswertung handelt und die einzelnen Punkte dabei ganz unterschiedliche Flächenanteile repräsentieren. Die projizierte Entwicklung für die Kiefer folgt dem oben dargestellten Trend für die Buche. Der Anteil von Standorten, die große positive oder negative Veränderungen erfahren, nimmt mit der Zeit zu. Die trockene Variante des A1B-Szenarios führt zu einem größeren Anteil an Standorten mit Leistungseinbrüchen, während die feuchte Variante zu einem erheblichen Prozentsatz Leistungssteigerungen projiziert. Im Vergleich der Varianten kann hier das Maß der Unsicherheit in der Projektion quantifiziert werden: der Anteil von Inventurpunkten auf Standorten mit Leistungseinbußen umspannt einen Bereich von 5 % in der feuchten bis 19 % in der trockenen Szenariovariante für die Projektionsperiode 2071 bis 2100. Der Anteil ohne nennenswerte Veränderung schwankt zwischen 22 und 61 % und Leistungssteigerungen erfahren 20 % der Inventurpunkte in der trockenen und 73 % in der feuchten Variante.

In den beiden ersten Anwendungsbeispielen wurde kein Baumartenwechsel auf den beobachteten Standorten betrachtet. Das heißt für aktuell mit Buche bzw. Kiefer bestockte Standorte wurde in der Projektion jeweils wieder dieselbe Baumart unterstellt. Unter veränderten Klimabedingungen wird es jedoch zu Arealflächenveränderungen der Baumarten kommen. Das folgende Anwendungsbeispiel analysiert, in welchem Umfang potenzielle Buchenstandorte zukünftig als ungeeignet für die Buchenwirtschaft angesehen werden müssen bzw. welche neuen Anbaustandorte diese Baumart hinzugewinnen könnte, wenn die Wuchsleistung als Auswahlkriterium verwendet wird. Ein potenziell für die Buchenwirtschaft geeigneter Standort wird dazu wie folgt definiert: es wird gefordert, dass mindestens die II. Ertragsklasse erreicht wird und zur Verminderung möglicher negativer Trockenheitseffekte darf das Wasserdefizit, berechnet als Summe aus KWB und nFK, am Standort höchstens 270 mm in der Vegetationszeit betragen. Legt man diese Definition zugrunde, so sind 86 % aller BWI-Punkte Deutschlands potenzielle Buchenstandorte (vgl. CZAJKOWSKI et al. 2006). Dieser inventurpunktbezogene Anteil nimmt unter dem Szenario A1B in der trockenen Variante auf 61 % bis 2070 und auf 43 % bis 2100 ab (Abb. 4).

Die als zukünftig ungeeignet eingestuften Standorte befinden sich in den bereits heute trocken-warmen Gebieten wie z. B. Teilen der norddeutschen Tiefebene, dem Rhein-Main-Gebiet, Teilen Frankens und dem Rheintal-Graben. Neue Anbaustandorte könnten für die Buchenwirtschaft aufgrund der projizierten Temperaturerhöhung in den Hochlagen der Mittelgebirge und Alpen erschlossen werden. Allerdings ist zu beachten, dass nicht alle limitierenden Einflussgrößen wie z. B. die Spätfrostgefahr und vernässte Standorte berücksichtigt werden und die Ergebnisse somit lokal überprüft werden müssen.

3.2 Modellierung des Höhenbonitätsquantils

Die Verteilung der Residuen der Standort-Leistungs-Modelle auf Basis des verallgemeinerten additiven Ansatzes (vgl. 3.1) sind symmetrisch und somit dürfen die Schätzungen des Mittelwertes als erwartungstreu angenommen werden. Für die Ableitung von Quantilen ist es aber wichtig, dass auch die bedingte Varianz der Residuen gut durch Verteilungsannahmen approximiert wird. Bei den Residuen des verallgemeinerten additiven Modells treten jedoch Abweichungen von der Normalverteilung auf, z. B. zeigt die bedingte Varianz der Residuen über den Prädiktoren Temp, KWB und Ndep im Douglasienmodell Heteroskedastizität (Goldfeld-Quandt-Test auf Heteroskadastizität mit H_0: $\sigma_1 \neq \sigma_2$: p_{temp} = 6,392e–06; p_{KWB} = 3,054e–06; p_{Ndep} = 1,016e–05). Daher ist eine Quantilsschätzung der Höhenbonität auf Grundlage der oben genannten Standort-Leistungs-Modelle nicht gestattet, sondern die bedingte Varianz muss explizit mit Hilfe von Quantilsregressionsmodellen beschrieben werden (vgl. STASINOPOULOS und RIGBY 2007).

Bei Anbauempfehlungen für eine Baumart stellt sich die Frage, wie groß der Anteil von Beständen sein darf, die auf einer gegebenen Standortseinheit nicht die geforderte Mindestwuchsleistung erreichen. Für die hier folgenden Ausführungen wird definiert, dass eine hinreichend sichere Grundlage für die Baumartenwahl gegeben ist, wenn für mindestens 80 % aller Bestände einer Standortseinheit eine bestimmte Leistungsfähigkeit prognostiziert wird. Somit ist das bedingte 20-%-Quantil der Höhenbonität zu schätzen.

Die Auswahl der verwendeten Prädiktoren aus dem zur Verfügung stehenden Variablenvektor erfolgt, sofern die Effekte signifikant sind und eine Modellverbesserung anhand des Bayesian Information Criterion (BIC) festgestellt wird. Wie auch bei den verallgemeinerten additiven Modellen ist der Effekt der geografischen Lage hochsignifikant und erhöht die Gesamtgüte des Modells. Die Methodik der verwendeten Biblio-

thek gamlss 3.0-1 von STASINOPOULOS und RIGBY (2007) ist jedoch auf eindimensionale glättende Funktionen beschränkt. Zur Beschreibung räumlicher Abhängigkeiten bzw. eines räumlichen Trends werden zweidimensionale glättende Funktionen benötigt, wie sie in der Methodik von WOOD (2006) zur Verfügung stehen. Im Quantilsregressionsmodell gehen daher die Splinebasen der 2-dimensionalen glättenden Funktion aus dem verallgemeinerten additiven Modell zur Schätzung der Mittelhöhenbonität (vgl. Gl. 3) als neue Prädiktoren in Form von linearen Effekten ein.

Für die fünf Baumarten werden folgende Quantilsregressionsmodelle mit jeweils drei Schätzfunktionen für den Erwartungswert μ, die Schiefe λ und den Variationskoeffizienten σ der Höhenbonitätsverteilung parametrisiert:

Buche:

$$\mu_i = \alpha_1 + \text{Nähr}_i^T \beta_1 + f_1(\text{WH}_i) + f_2(\text{Temp}_i) + f_3(\text{Ndep}_i) + \alpha_2 \cdot \text{LP}_{1_i} + \ldots + \alpha_{k+3} \cdot \text{LP}_{k_i} \quad [4.1]$$

$$\log(\sigma_i) = \alpha_1 + \text{Nähr}_i^T \beta_1 + f_1(\text{WH}_i) + f_2(\text{Ndep}_i) \quad [4.2]$$

$$\lambda_i = \alpha_1 + f_1(\text{WH}_i) + \alpha_2 \cdot \text{Ndep}_i \quad [4.3]$$

Eiche:

$$\mu_i = \alpha_1 + \text{Nähr}_i^T \beta_1 + f_1(\text{WH}_i) + f_2(\text{Temp}_i) + f_3(\text{Ndep}_i) + \alpha_2 \cdot \text{LP}_{1_i} + \ldots + \alpha_{k+3} \cdot \text{LP}_{k_i} \quad [5.1]$$

$$\log(\sigma_i) = \alpha_1 + \text{Nähr}_i^T \beta_1 + f_1(\text{WH}_i) + f_2(\text{Ndep}_i) \quad [5.2]$$

$$\lambda_i = \alpha_1 + \text{Nähr}_i^T + \beta_1 \quad [5.3]$$

Fichte:

$$\mu_i = \alpha_1 + \text{Nähr}_i^T \beta_1 + f_1(\text{WH}_i) + f_2(\text{Temp}_i) + f_3(\text{Ndep}_i) + \alpha_2 \cdot \text{LP}_{1_i} + \ldots + \alpha_{k+3} \cdot \text{LP}_{k_i} \quad [6.1]$$

$$\log(\sigma_i) = \alpha_1 + \text{Nähr}_i^T \beta_1 + \alpha_2 \cdot \text{Ndep}_i + \alpha_3 \cdot \text{LP}_{1_i} + \ldots + \alpha_{k+3} \cdot \text{LP}_{k_i} \quad [6.2]$$

$$\lambda_i = \alpha_1 + \text{Nähr}_i^T \beta_1 + \alpha_2 \cdot \text{Temp}_i + f_1(\text{Ndep}_i) \quad [6.3]$$

Kiefer:

$$\mu_i = \alpha_1 + \text{Nähr}_i^T \beta_1 + f_1(\text{WH}_i) + \alpha_2 \cdot \text{Temp}_i + f_2(\text{Ndep}_i) + \alpha_3 \cdot \text{LP}_{1_i} + \ldots + \alpha_{k+3} \cdot \text{LP}_{k_i} \quad [7.1]$$

$$\log(\sigma_i) = \alpha_1 + \text{Nähr}_i^T \beta_1 + \alpha_2 \cdot \text{WH}_i + f_1(\text{Temp}_i) + f_2(\text{Ndep}_i) \quad [7.2]$$

$$\lambda_i = \alpha_1 + \text{Nähr}_i^T \beta_1 + f_1(\text{Ndep}_i) \quad [7.3]$$

Douglasie:

$$\mu_i = \alpha_1 + f_1(\text{WH}_i) + \alpha_2 \cdot \text{Temp}_i + f_2(\text{Ndep}_i) + \alpha_3 \cdot \text{LP}_{1_i} + \ldots + \alpha_{k+3} \cdot \text{LP}_{k_i} \quad [8.1]$$

$$\log(\sigma_i) = \alpha_1 + f_1(\text{Ndep}_i) \quad [8.2]$$

$$\lambda_i = \alpha_1 + f_1(\text{Ndep}_i) \quad [8.3]$$

Nähr – Indikatorvektor für Nährstoffziffer; WH – Wasserhaushalt als Summe der klimatischen Wasserbilanz in der Vegetationszeit (VZ) und nutzbarer Feldkapazität [mm]; Temp – Temperatursumme in VZ [°C]; Ndep – mittlere jährliche Stickstoffdeposition [eq/a·ha]; LP_1 ... LP_k – Splinebasen der 2-dimensionalen glättenden Funktion aus einem Mittelwertregressionsmodell; β_1 – Parametervektor zu Nährstoffziffern; α_1 ... α_k – Regressionskoeffizienten; f_1, f_2, f_3 – 1-dimensionale glättende Splines; k – Basisdimension des zweidimensionalen Splines im Mittelwertregressionsmodell

Die Modellkoeffizienten und Kennwerte der glättenden Terme der fünf LMS-Modelle sowie die bedingten trendbereinigten Quantil-Quantil-Plots (Wurmplots) für die Anpassungsgüte der Modelle sind als Anhang zu dieser Publikation auf der Internetseite der Nordwestdeutschen Forstlichen Versuchsanstalt abrufbar (siehe Fußnote 1).

Die Beurteilung der Modellgüte anhand von Wurmplots wird am Beispiel des Quantilsregressionsmodells der Buche demonstriert (Abb. 5).

Die horizontale Nulllinie der Wurmplots markiert den Verlauf bei Standardnormalverteilung. Abweichungen von der Nulllinie können unterschiedliche Ursachen haben, so deuten die in Abbildung 5 zum Teil auftretenden S-Kurven darauf hin, dass die Randbereiche der Verteilung nicht adäquat beschrieben werden. Bei U-förmigen bzw. invers-U-förmigen Verlauf ist die angepasste Verteilung zu links- bzw. rechtsschief. Insgesamt kann das Quantilsregressionsmodell für die Buche anhand der Wurmplots als geeignet beurteilt werden, da das 95-%-Konfidenzintervall nur selten und dann auch nur geringfügig überschritten wird (vgl. auch VAN BUUREN 2007, Abb. 5 und Abb. 6). Die Modellgüte der anderen Baumarten ist auf Basis der Wurmplot-Analyse ebenfalls als hinreichend zu bezeichnen.

Als problematisch erweist sich die Modellanwendung bei Projektionen im extremen Extrapolationsbereich der Datengrundlage. Besonders im Wertebereich starker Trockenheit wird der wuchsleistungsmindernde Effekt durch den positiven Beitrag einer Temperaturerhöhung überkompensiert und folglich resultieren unplausible Schätzwerte der Standortleistungsfähigkeit. In den unter 3.2.1 vorgestellten Ökogrammen wird diese Modelllimitation durch die zusätzliche Betrachtung des Risikos bei unzureichender Wasserversorgung entschärft.

3.2.1 Aufbau von mehrdimensionalen Ökogrammen

Die Baumartenwahl wird durch ökologische Kriterien und ökonomische Erwartungen beeinflusst. Der ökonomische Erfolg ist dabei u. a. von der Wuchsleistung und potenziellen abiotischen und biotischen Risiken, die zu Produktivitätsverlusten oder Mehraufwändungen führen können, bestimmt. Der ertragskundlicher Beitrag zur Entscheidungsfindung bei der Baumartenwahl unter Klimawandel kann durch das mit dem Standort-Leistungs-Modell geschätzte 20-%-Quantil der Mittelhöhenbonität im Alter 100 als Ausdruck der Wuchsleistung berücksichtigt werden (vgl. Gl. 4.1 bis 8.3). Die Risiken sollen vorerst am Beispiel unzureichender Wasserversorgung Eingang in die Bewertung der Anbauwürdigkeit finden. Die Beurteilung der Anbauwürdigkeit erfolgt somit über die beiden Kriterien Standortleistungsfähigkeit und Wasserdefizit (Abb. 6).

Bei der Klassifikation der Anbauwürdigkeit bestimmt das Kriterium mit der schlechteren Ausprägung die zugewiesene Kategorie. Das Risiko durch Wasserdefizit bezieht sich auf Wachstumsbedingungen, bei denen die Einzelbaumvitalität und die Produktivität der Bestände durch Absterben von Bäumen massiv beeinträchtigt werden könnten. Die Risikoklassen beschreiben somit gutachterlich die Wahrscheinlichkeit und das Ausmaß eines Schadens durch unzureichende Wasserversorgung. Im Anhalt an das Vorgehen von SPELLMANN et al. (2007) werden Wasserdefizitbedingungen in vorläufige auf Expertenwissen basierende baumartspezifische Risikoklassen eingeteilt (Tab. 5). Als Kriterium wird hierzu das pflanzenverfügbare Wasser, definiert als Summe aus nFK und KWB in der Vegetationszeit, herangezogen.

Die fünf definierten Anbauwürdigkeitsklassen werden als lagespezifische, d. h. für einen geografischen Standort gültige, mehr-

Tabelle 5: *Definition des baumartspezifischen Wasserdefizit-Risikos anhand der Summe aus nutzbarer Feldkapazität (nFK) und klimatischer Wasserbilanz (KWB) in der Vegetationszeit (VZ)*

Table 5: *Definition of species-specific risk of water-deficit based on the sum of available soil moisture (nFK) and climatic water balance (KWB) in growing season (VZ)*

	nFK + KWB in VZ [mm]			
Wasserdefizit-Risiko	**Fichte**	**Buche**	**Eiche/Kiefer**	**Douglasie**
hoch	< -350	< -400	< -500	< -550
erhöht	-233 bis -350	-267 bis -400	-333 bis -500	-367 bis -550
mittel	-116 bis -233	-134 bis -267	-166 bis -333	-184 bis -367
gering	0 bis -116	0 bis -134	0 bis -166	0 bis -184
sehr gering	> 0	> 0	> 0	> 0

dimensionale Ökogramme visualisiert. Die beiden Achsen der Ökogramme sind mit den unter Klimawandel dynamischen Variablen Temperatursumme und pflanzenverfügbares Wasser belegt. Die zeitliche Entwicklung der Anbauwürdigkeit unter bestimmten Klimaszenarien kann somit dargestellt werden. Die übrigen im Modell verwendeten, zeitunabhängigen Standortsvariablen beeinflussen das Schätzergebnis mit dem jeweils für den geografischen Standort spezifischen konstanten Effekten. Prinzipiell erhält jeder lagespezifische Forstort mit den ihm eigenen Standortsmerkmalen für jede Baumart ein spezifisches Ökogramm. Der Aufbau des Ökogrammes erfolgt in vier Schritten:

(1) Ermittlung der geografischen Lage des Forstortes (z. B. Abteilung, Unterabteilung o. ä.), für den das Ökogramm gelten soll und Zuordnung der Standortparameter;

(2) Aufspannen eines Temperatursummen- und pflanzenverfügbaren Wasserwertebereiches;

(3) Schätzung des 20-%-Quantils der Mittelhöhenbonität ($hg100_{20\%}$) für den aufgespannten Wertebereich unter Berücksichtigung aller Standortparameter (Gl. 4.1 bis 8.3) und Klassifizierung in die fünf Anbauwürdigkeitsklassen (Abb. 6) sowie

(4) Projektion der Standortsvariablen Temperatursumme und KWB unter unterstellten Klimaszenarien und Visualisierung des resultierenden „Entwicklungspfades" im Ökogramm.

3.2.2 Beispiele

Die für die Baumarten Buche, Eiche, Fichte, Kiefer und Douglasie und das Gebiet der Bundesrepublik Deutschland parametrisierten Quantilsregressionsmodelle ermöglichen die Schätzung der mehrdimensionalen Ökogramme für jeden beliebigen Forstort mit seinen spezifischen Standortsmerkmalen. Der ertragskundliche Beitrag bei der Baumartenwahl soll anhand von Ökogrammen für drei Beispielstandorte erläutert werden. Neben der zeitlichen Veränderung der Standortsbedingungen durch den projizierten Klimawandel werden auch räumliche Unterschiede mit Hilfe eines Niederschlagsgradienten entlang der drei Forstorte im norddeutschen Tiefland dargestellt (Abb. 7).

Die Einstufung der Bodennährstoffe ist für die drei ausgewählten Forstorte FO1, FO2 und FO3 gleich. Unterschiede gibt es hinsichtlich der mittleren Temperatur in der Vegetationszeit und des Wasserdefizits (KWB+nFK), die von West nach Ost zunehmen (vgl. Abb. 7).

Der schleswig-holsteinische Forstort FO1 ist mit einer klimatischen Wasserbilanz von -263 mm in der Vegetationszeit derjenige mit dem geringsten Wasserdefizit (Abb. 7). Das gegenwärtig sehr geringe Wasserdefizit (nFK + KWB = -48 mm) lässt folglich neben den beiden Laubbaumarten Buche und Eiche die ertragreiche Fichte als potenziell geeignet erscheinen. Die mehrdimensionalen Ökogramme in Abbildung 8 beschreiben die prognostizierten Ertragsentwicklungen und das Risiko aufgrund des Wasserdefizits für diese drei Baumarten unter dem Klimaszenario A1B in der trockenen und in der feuchten Variante für die drei Zukunftsperioden 2011 bis 2040, 2041 bis 2070 und 2071 bis 2100. Die Projektion der Standortleistungsfähigkeit für die Baumart Buche zeigt unter dem zu Grunde gelegten Klimaszenario A1B eine Verbesserung von der II.5 zur II. Ertragsklasse ab der Periode 2011 bis 2040. Das Wasserdefizit-Risiko verbleibt in der feuchten Szenariovariante auch zukünftig in der Klasse „gering", während es in der trockenen Variante ab 2041 auf „mittel" steigt. Die Standortleistungsfähigkeit für die Baumart Eiche verändert sich nur geringfügig und es wird nur für die trockenen Variante in der letzten Periode ein Veränderung des Wasserdefizit-Risikos von „gering" auf „mittel" projiziert. Die Anbauempfehlung für die Fichte wird dominiert durch das steigende Wasserdefizit-Risiko von aktuell „gering" in die Klasse „mittel", für die trockene Variante ab 2071 sogar „erhöht". Für diesen Forstort empfiehlt sich aus ertragskundlicher Sicht unter Berücksichtigung des Wasserdefizit-Risikos ein Eichenanbau, auch die Buche ist trotz des langfristig mittleren Wasserdefizit-Risikos eine Anbaualternative. Von der Fichte als Hauptbaumart ist hier langfristig eher abzuraten, je nach Risikopräferenz ist sie als Mischbaumart aufgrund ihrer Wuchsleistung attraktiv.

Der niedersächsische Forstort FO2 weist gegenüber FO1 ein höheres Wasserdefizit in der Vegetationszeit auf (–99 mm), so dass die Baumart Fichte bereits mittelfristig als Hauptbaumart hier nicht mehr in Betracht kommt, da ab 2041 nur für die feuchte Variante die mittlere Risikoklasse und ansonsten ein „erhöhtes Wasserdefizit" projiziert wird (Abb. 9). Die Anbauwürdigkeit der Baumart Buche ist aufgrund der sich unter Klimawandel an diesem Standort leicht auf die II. Ertragsklasse steigernden Wuchsleistung und des sich verschärfenden Wasserdefizits in die mittlere Risikoklasse als „mittel" einzuschätzen. Das Wasserdefizit-Risiko für Eiche und Kiefer wird auch zukünftig als gering bis mittel projiziert. Die Baumarten Eiche und Kiefer sind auch bezüglich ihrer relativen Bonität auf diesem Standort für einen Anbau zu empfehlen, während ein Buchenanbau im Reinbestand langfristig als risikoreich erscheint.

Aufgrund des noch ausgeprägteren Wasserdefizites (-110 mm) gegenüber dem niedersächsischen Forstort FO2 und der bereits aktuell schwachen Leistungsfähigkeit schneidet die Baumart Buche in der Bewertung der Anbauwürdigkeit für den brandenburgischen Forstort FO3 noch schlechter ab (Abb. 10). Auch für die Baumarten Eiche und Kiefer wird ab 2041 ein mittleres Wasserdefizit-Risiko projiziert. An diesem Forstort empfiehlt sich die Buche allenfalls als Mischbaumart, Eiche und Kiefer sind trotz steigendem Wasserdefizits aus ertragskundlicher Sicht anbauwürdig.

4 Diskussion

Gesamtkonzept zur Entwicklung von waldbaulichen Anpassungsstrategien

Die umfassende Beschreibung des gesamten Leistungsspektrums einer Standortseinheit mit Hilfe der klimasensitiven Standort-Leistungs-Modelle zur Schätzung des Erwartungswertes und Quantilen der Mittelhöhenbonität bildet den waldwachstumskundlichen Schwerpunkt in der Klimafolgenforschung der Nordwestdeutschen Forstlichen Versuchsanstalt. Die bisherigen Simulationsergebnisse weisen darauf hin, dass sich in den nächsten Jahrzehnten die Leistungsfähigkeit der Standorte durch einen weiteren Temperaturanstieg und der damit einhergehenden Verlängerung der Vegetationszeit sowie durch weiter abnehmende Sommerniederschläge graduell verändern wird. Je nach geografischer Lage können dies negative aber auch, insbesondere in den Hochlagen der Mittelgebirge, positive Effekte für das Wuchspotenzial sein. Dramatischere Auswirkungen auf den Gesundheitszustand der Wälder und die Ertragslage der Forstwirtschaft werden durch sich unter Klimawandel verstärkende und neu hinzukommende abiotische und biotische Risiken erwartet.

Zahlreiche biometrische Risikomodelle werden daher an der Nordwestdeutschen Forstlichen Versuchsanstalt entwickelt, um die Eintrittswahrscheinlichkeit und das Schadensausmaß einzelner Risikofaktoren abschätzen zu können. Die Modellpalette umfasst bisher ein Sturmschadensmodell (Schmidt et al. 2010), zwei Ansätze zur Risikobeurteilung durch Borkenkäfer (Habermann et al. 2010, Overbeck und Schmidt 2011) und ein Modell zur Schätzung der Maikäferengerlingsdichte (Schmidt 2011). Weitere Risikomodelle zu Trockenstress, Waldbrandgefahr und Kieferngroßschädlingen sind in der Entwicklung.

Die Standort-Leistungs- und die Risikomodelle sind Bestandteile des Gesamtkonzeptes der Nordwestdeutschen Forstlichen Versuchsanstalt zur Entwicklung waldbaulicher Anpassungsstrategien für veränderte Klimaverhältnisse (vgl. Spellmann et al. 2011). Das erste Ziel hierbei ist es, die Entwicklung der aktuellen Bestockung zu projizieren, um Anpassungsmaßnahmen zur Stabilisierung der vorhandenen Wälder im mittelfristigen Zeitraum vornehmen zu können. Neben Vulnerabilitätsstudien zur Senkung und Verteilung von Risiken werden hier die Standort-Leistungs-Modelle auf Basis der verallgemeinerten additiven Modelle eingesetzt, um beispielsweise Verjüngungs-, Pflege- und Nutzungskonzepte auf ihre Eignung zu prüfen, Holzaufkommensprognosen zu rechnen und die Möglichkeiten der Kohlenstoffsequestrierung im Bestand einzuschätzen. Das zweite Ziel ist die Bereitstellung von Instrumenten zur Entscheidungsunterstützung für einen standortsgemäßen, und das heißt auch klimaangepassten, Waldumbau. Hierfür ist die Beurteilung der Anbauwürdigkeit von Baumarten unter Klimawandel aus ertragskundlicher Sicht entscheidend, was mit Hilfe der Standort-Leistungs-Modelle auf Quantilsregressionsbasis und den darauf aufbauenden mehrdimensionalen Ökogrammen geschieht.

Die große Unsicherheit der Klimaprojektionen, allein schon durch die Wahl des Szenarios, beeinflusst die Simulationsergebnisse stark. Besonders gravierend wirkt sich diese Unsicherheit bei Entscheidungen zur Baumartenwahl aufgrund der langfristigen Bindung aus. Die mehrdimensionalen Ökogramme greifen diese Problematik auf, indem z. B. durch die Projektion mehrerer Szenariovarianten ein Korridor möglicher Entwicklungen aufgespannt wird. Dies verdeutlicht die Unsicherheit und ermöglicht der Waldbauplanung Anpassungsmaßnahmen im Sinne einer „best case“ und einer „worst case“ Analyse zu ergreifen. Aufgrund dieser Unsicherheit bezüglich zukünftiger Standortsverhältnisse folgert von Lüpke (2009), dass für die Baumartenwahl insbesondere das Resilienzpotenzial der Wälder gestärkt werden muss. Eine Vermeidung des Anbaus von Baumarten an den Grenzen ihrer fundamentalen Nischen, eine geeignete kleinflächige, altersgestufte Baumartenmischung und die Senkung der Produktionszeit können laut von Lüpke zukünftigen Risiken entgegenwirken. Auch die Empfehlungen von Spellmann et al. (2007) zum Fichtenanbau und von Sutmöller et al. (2008) zum Umgang mit Buchenwäldern unter Klimawandel setzen auf risikobewussten Waldbau. Bolte et al. (2011) verdichten die Anpassungsmaßnahmen zu drei Strategien, nämlich aktive Unterstützung z. B. durch Waldumbau, passive Begleitung z. B. durch Duldung von Sukzession und aktive Erhaltung z. B. durch angepasste Pflege- und Nutzungskonzepte.

Modelllimitationen und zukünftige Arbeitsschritte

Die beiden Modellansätze zur Beschreibung des Standort-Leistungs-Bezuges ermöglichen waldwachstumskundlich fundierte Aussagen über die Entwicklung der mittleren Standortleistungsfähigkeit und zu Quantilen der Höhenbonitätsverteilung im Bereich des Parametrisierungsdatensatzes. Weil für die Modellerstellung Beobachtungen aus ganz Deutschland verwendet wurden, befinden sich die zukünftigen klimatischen Verhältnisse im Zuständigkeitsbereich der NW-FVA meist noch nicht im Extrapolationsbereich, so dass Projektionen dort problemlos möglich sind. Dennoch sind das Mittelwert- und das Quantilsregressionsmodell anfällig für unplausible Schätzergebnisse im extremen Extrapolationsbereich. Besonders der Effekt bei sich vergrößerndem Wasserdefizit erscheint nicht hinreichend mit Daten belegt, was die extrem weiten Konfidenzintervalle in dem Bereich andeuten (vgl. Grafiken im Anhang zu dieser Publikation auf der Internetseite der NW-FVA, siehe Fußnote 1).

Im Rahmen einer Weiterentwicklung der Standort-Leistungs-Modelle wird von folgenden Änderungen eine Modellverbesserung erhofft:

1. Erweiterung des Parametrisierungsdatensatzes insbesondere um bereits heute trockene Standorte.
2. Verwendung der Messdaten des Deutschen Wetterdienstes (DWD) für die Temperatursumme und die klimatische Wasserbilanz anstelle der mit WETTREG für die Klimanormalperiode 1961 bis 1990 projizierten Klimadaten. Für die hier dargestellten Untersuchungen waren die DWD-Messdaten noch nicht verfügbar.
3. Flexible Bilanzierung der DWD-Messdaten bezogen auf das Bestandesleben anstelle des fixen Bilanzierungszeitraumes der Klimanormalperiode. Eine derartige flexible Bilanzierung war bei der bisherigen Modellbildung auf Grund der erforderlichen Periodenlänge von 30 Jahren für Klimaprojektionen, wie eben die herangezogene Klimanormalperiode von 1961 bis 1990, nicht möglich.
4. Die Wald-BÜK als Grundlage zur Bestimmung der Bodenparameter eines Standortes ist zwar die einzige flächendeckend für Deutschland vorliegende Quelle, in ihrer räumlichen Auflösung ist sie jedoch für Modellierungszwecke zu ungenau. Zukünftig wäre eine Herleitung der nFK auf der Grundlage statistischer Regionalisierungsmodelle wünschenswert (Overbeck et al. 2011).
5. Neben der wuchsleistungssteigernden Wirkung der Stickstoffdeposition erscheint die Aufnahme der wachstumsmindernden Schwefeldeposition als erklärende Variable sinnvoll (Builtjes et al. 2011, Savva und Berninger 2010, Nellemann und Thomsen 2000).

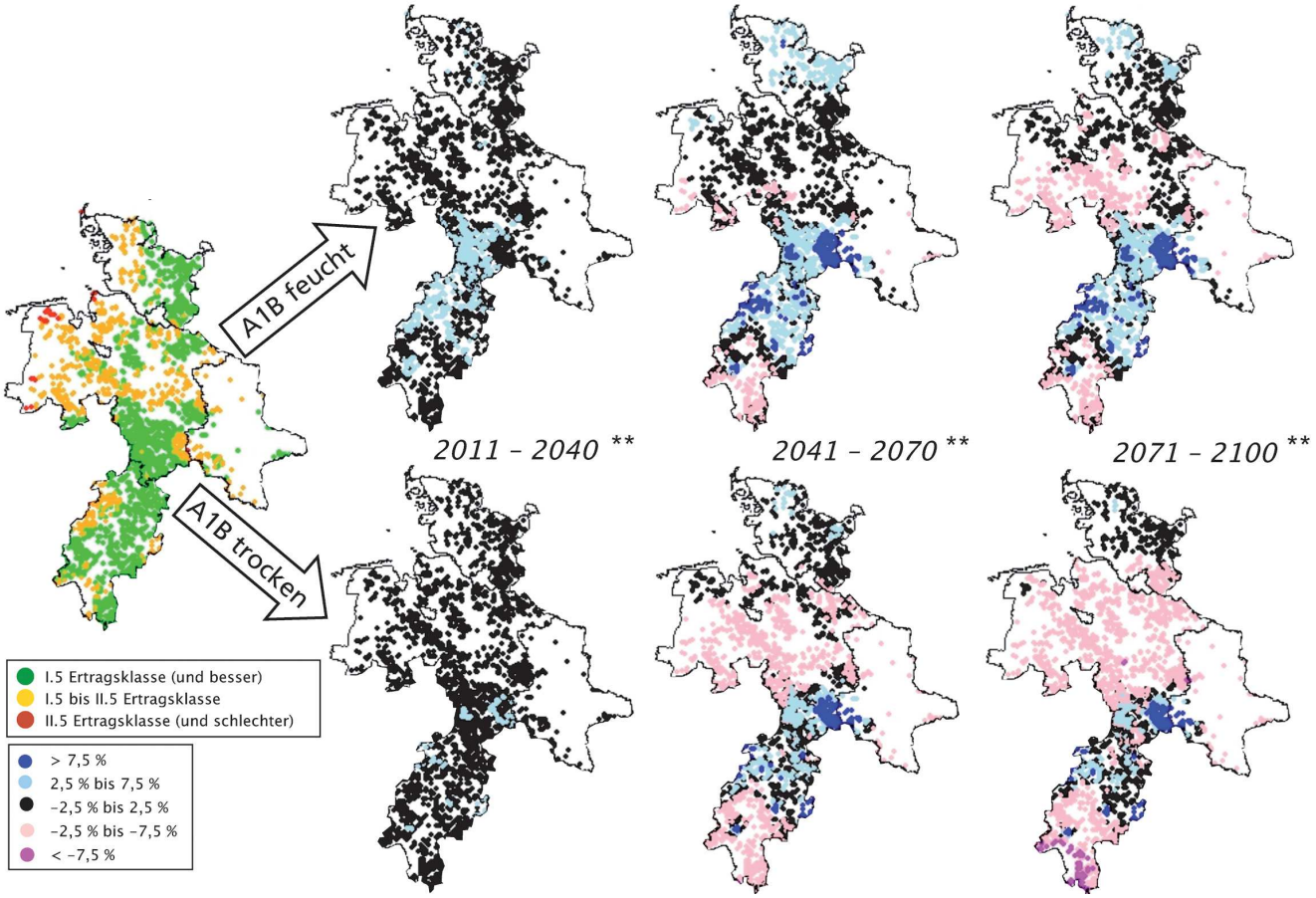


Abbildung 2: *Projektion der Standort-Leistungsfähigkeit für die Baumart Buche unter dem mit WETTREG gerechneten Klimaszenario A1B in der feuchten (oben) und trockene (unten) Variante für drei Perioden (* basierend auf der A1B-trockenen Variante für die Periode 1981 bis 2010; ** Veränderung gegenüber jeweils der feuchten bzw. trockenen Variante der Periode 1981 bis 2010). Simulationsgrundlage sind alle aktuell im Zuständigkeitsbereich der NW-FVA mit Buchen bestockten BWI- und niedersächsischen BI-Punkte.*

Figure 2: *Projection of site productivity for beech under the climate scenario A1B in the wet (top) and dry (bottom) variante for three periods (* based on the A1B dry variante in the period 1981 to 2010; ** changes based on the wet and dry, respectively, variante in the period 1981 to 2010). Climate parameters are modelled using WETTREG. Projection is made within the area of responsibility of the Northwest German Forest Research Institute for all inventory points of the National Forest Inventory and the Forest Enterprise Inventory of Lower Saxony which are currently stocked with beech.*

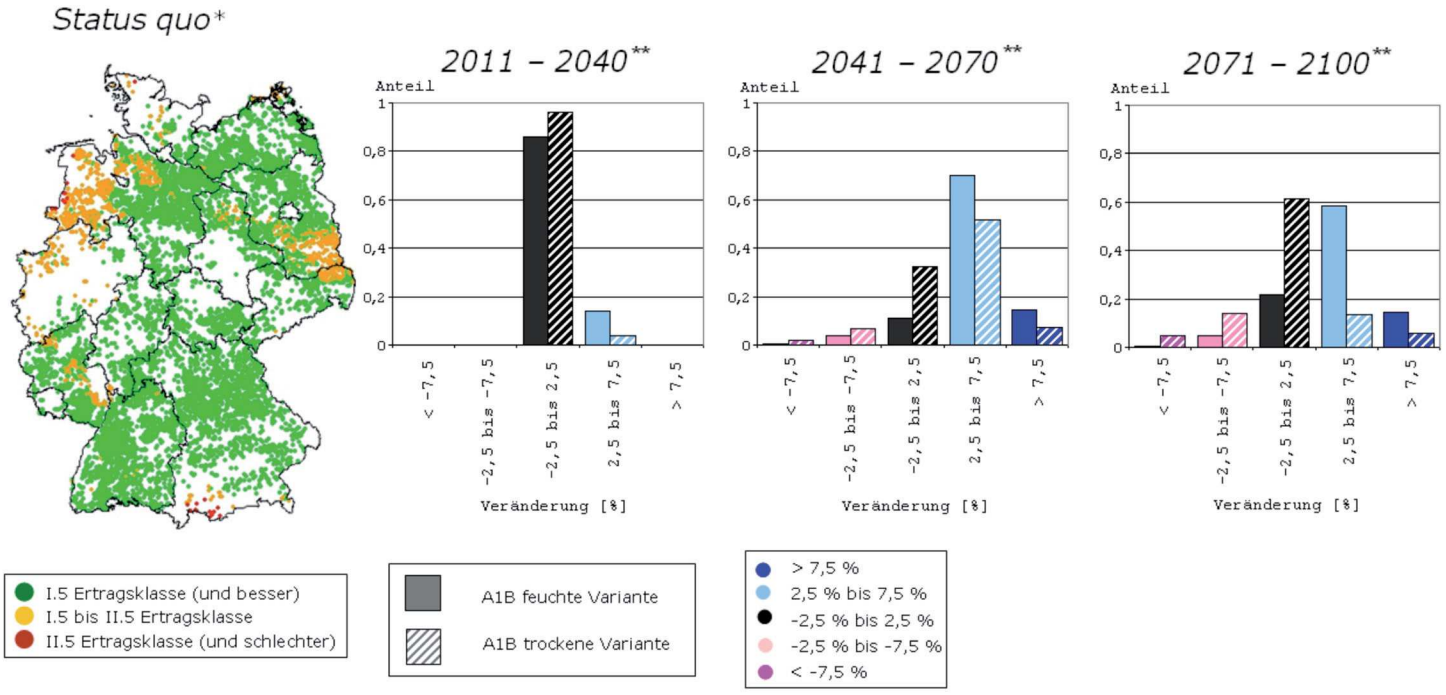


Abbildung 3: *Projektion der Standort-Leistungsfähigkeit für die Baumart Kiefer unter dem mit WETTREG gerechneten Klimaszenario A1B in der feuchten und trockene Variante für drei Perioden (* basierend auf der A1B-trockenen Variante für die Periode 1981 bis 2010; ** Veränderung gegenüber jeweils der feuchten bzw. trockenen Variante der Periode 1981 bis 2010). Simulationsgrundlage sind alle aktuell mit Kiefer bestockten BWI- und niedersächsischen BI-Punkte.*

Figure 3: *Projection of site productivity for pine under the climate scenario A1B in the wet (top) and dry (bottom) variante for three periods (* based on the A1B dry variante in the period 1981 to 2010; ** changes based on the wet and dry, respectively, variante in the period 1981 to 2010). Climate parameters are modelled using WETTREG. Projection is made nationwide for all inventory points of the National Forest Inventory and the Forest Enterprise Inventory of Lower Saxony which are currently stocked with pine.*

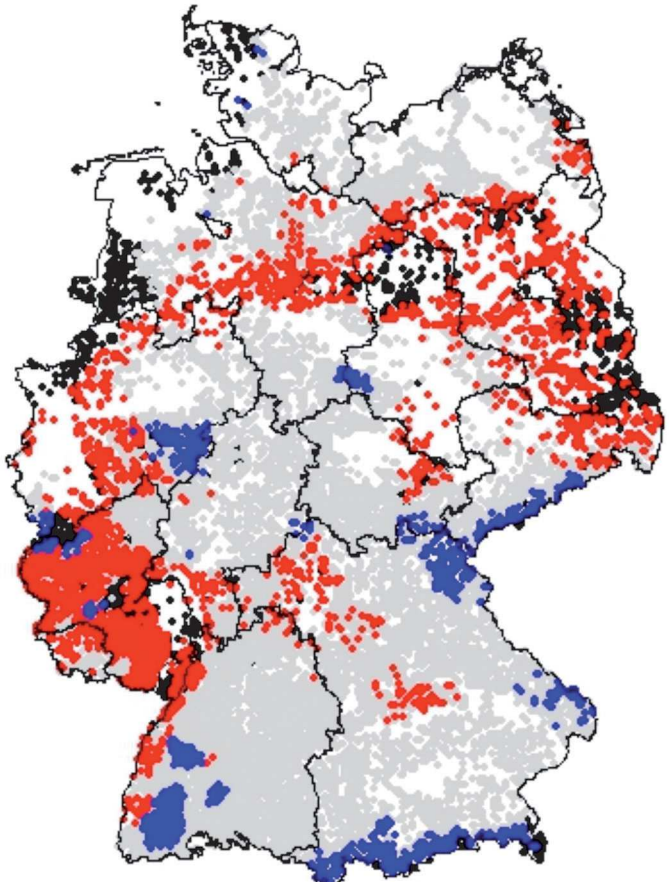


Abbildung 4: *Veränderungen im Buchenanbau vom Status quo zur Periode 2071 bis 2100 unter dem mit WETTREG gerechneten Klimaszenario A1B in der trockenen Variante bezogen auf sämtliche BWI-Punkte in Deutschland, wobei die Wuchsleistung als Auswahlkriterium der Anbaueignung verwendet wird*

Figure 4: *Changes in beech cultivation between status quo and the period 2071 to 2100 projected under climate scenario A1B in the dry variante. Climate parameters are modelled using WETTREG. Projection is made nationwide for all inventory points of the National Forest Inventory*

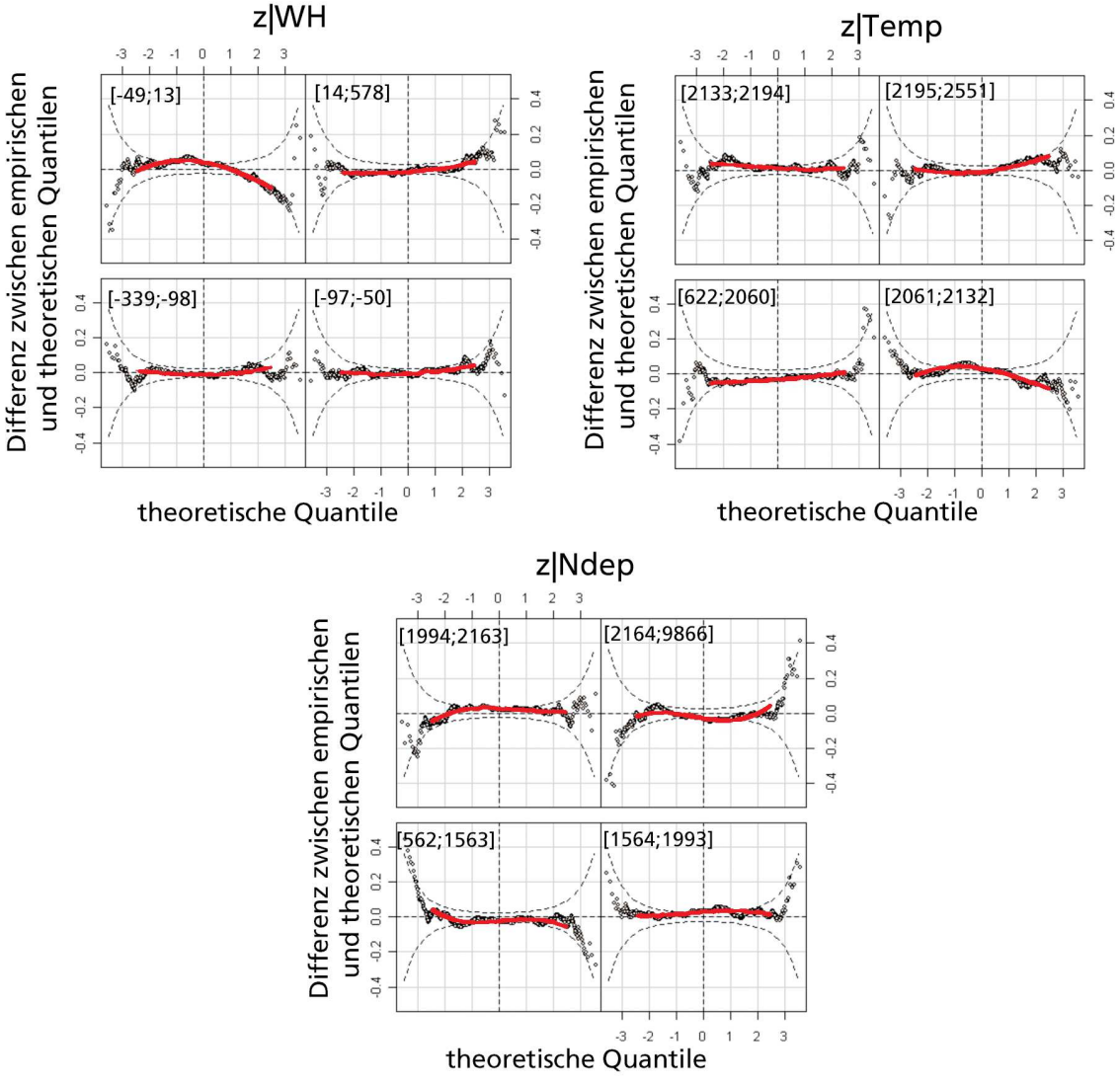


Abbildung 5: *Serien von bedingten Wurmplots der transformierten Response-Variablen z (Quantilresiduen) für die Prädiktoren Wasserhaushalt (WH) in der Vegetationszeit (VZ) (oben links), Temperatursumme (Temp) in der VZ (oben rechts) und Stickstoffdepositionsrate (Ndep) (unten) für das Quantilsregressionsmodell der Baumart Buche. Der Wertebereich der Prädiktoren ist dabei in jeweils vier Klassen gleicher Besetzung aufgeteilt (Klassengrenzen in den Diagrammen angegeben).*

Figure 5: *Series of worm plots of the transformed response variable z (quantile residuals) conditional on the predictor variables water balance (WH) in the growing season (GS) (top left), temperature sum (Temp) in GS (top right) and nitrogen deposition rate (Ndep) (bottom). Worm plots correspond to the quantile regression model of beech. The range of observed values is subdivided into four classes of equal frequency (thresholds are given in the diagrams).*



Abbildung 6: *Definition der Anbauwürdigkeitsklassen (Kategorie) in Abhängigkeit der beiden Kriterien Standortleistungsfähigkeit und Wasserdefizit-Risiko*

Figure 6: Classes of suitability for cultivation (category) depending on the two criteria site-productivity and water-deficit

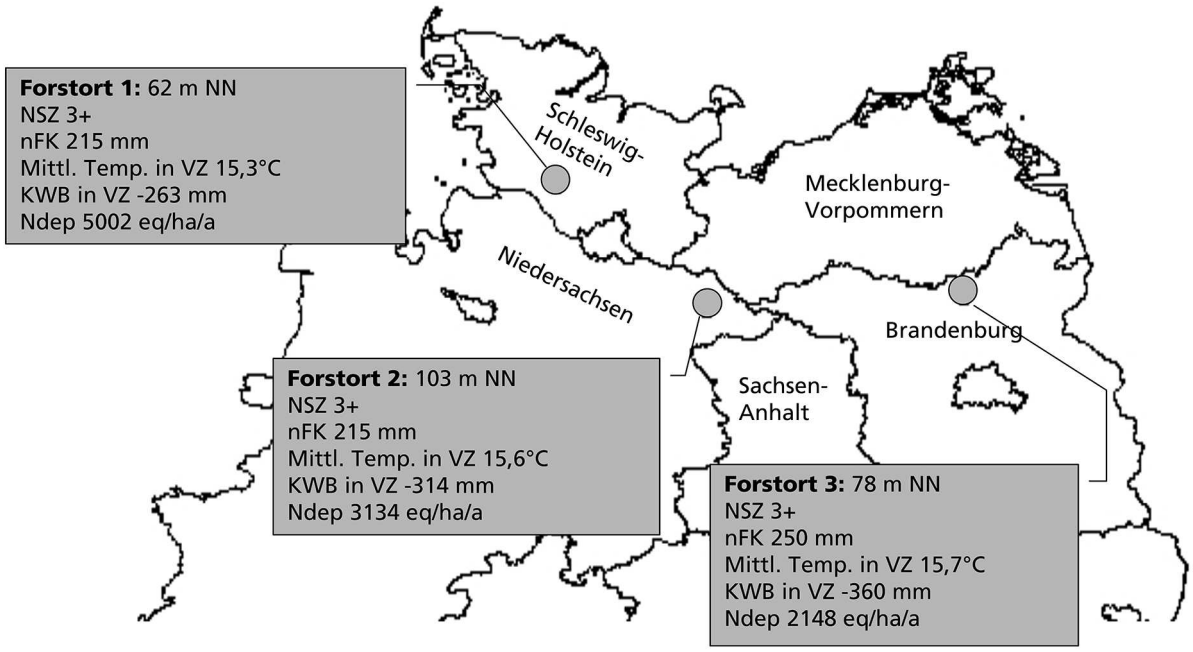


Abbildung 7: *Lage und charakterisierende aktuelle Standortsmerkmale von drei Forstorten in Schleswig-Holstein (FO1), Niedersachsen (FO2) und Brandenburg (FO3), für die Ökogramme erstellt werden.*
NSZ – niedersächsische Nährstoffziffer; nFK – nutzbare Feldkapazität auf 1,4 m Bodentiefe; KWB – klimatische Wasserbilanz; VZ – Vegetationszeit für Buche; Ndep – Stickstoffdepositionsrate im Jahr 2004 (für Projektion fixiert)

Figure 7: *Geographic location and current site characteristics of three forest sites (FO1, FO2 and FO3) as examples for multidimensional ecograms. NSZ – soil nutrient class; nFK – available soil moisture for 1.4 m soil depth; KWB – climatic water balance; VZ – growing season for beech; Ndep – nitrogen deposition rate in 2004 (fixed for projection)*

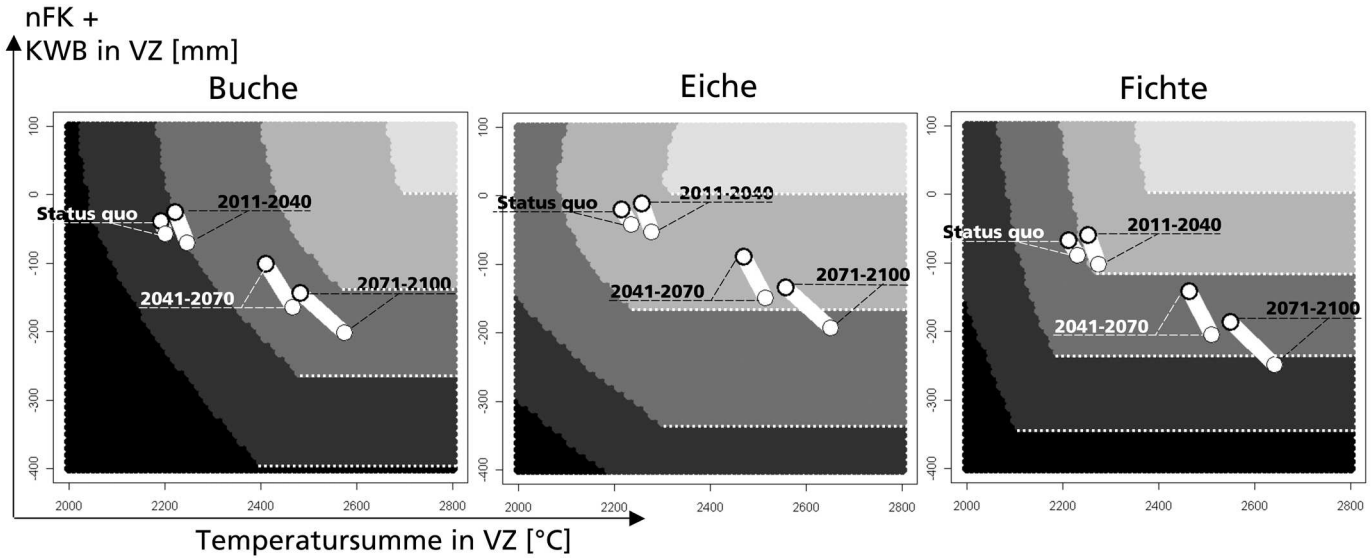


Abbildung 8: *Mehrdimensionale Ökogramme für die Baumarten Buche, Eiche und Fichte für den schleswig-holsteinischen Forstort (FO1). Die weiß gepunktete Linie markiert die Übergänge, wo das Standortleistungskriterium durch das Wasserdefizit-Kriterium als kategorie-bestimmend ersetzt wird.*

Figure 8: *Multidimensional ecograms for beech, oak and spruce at the forest site (FO1) in Schleswig-Holstein. The dotted white lines mark areas, where the water-deficit criterion replaces the site-productivity criterion to determine the suitability for cultivation category.*

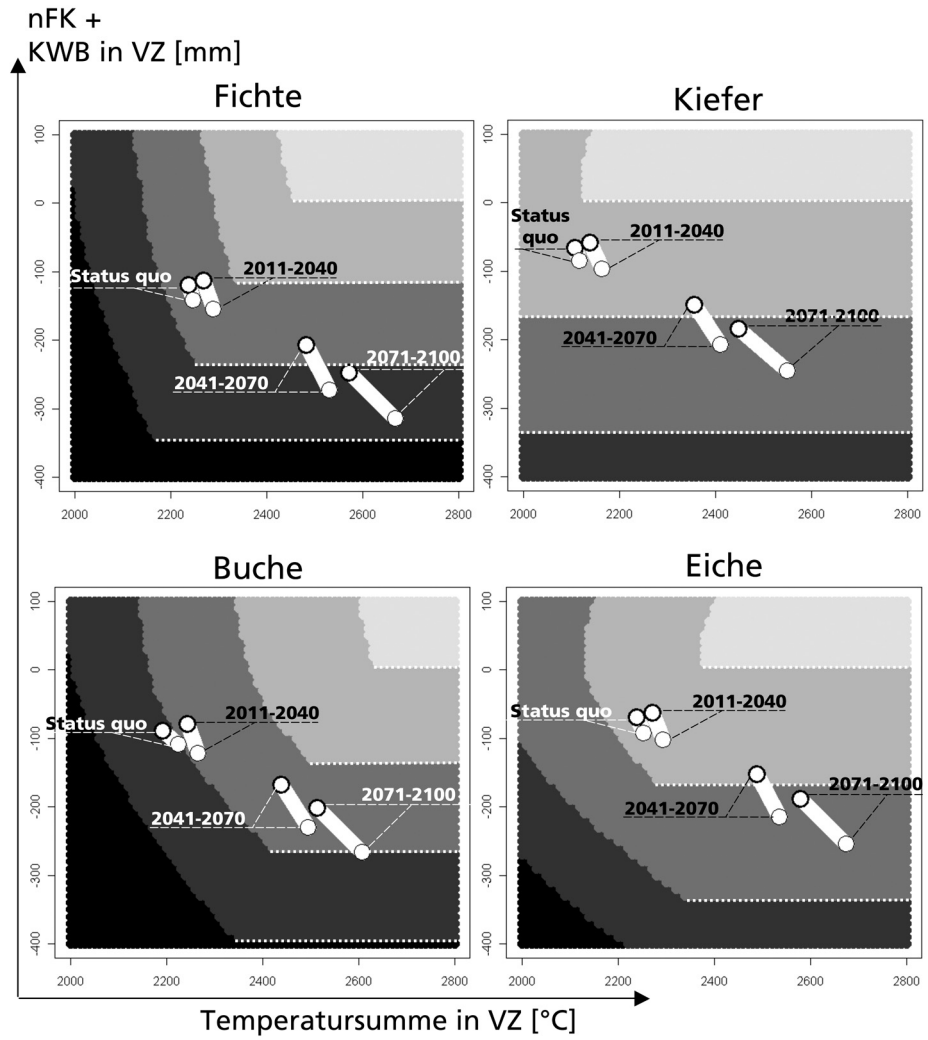


Abbildung 9: *Mehrdimensionale Ökogramme für die Baumarten Fichte, Kiefer, Buche und Eiche für den niedersächsischen Forstort (FO2). Die weiß gepunktete Linie markiert die Übergänge, wo das Standortleistungskriterium durch das Wasserdefizit-Kriterium als kategorie-bestimmend ersetzt wird.*

Figure 9: *Multidimensional ecograms for spruce, pine, beech and oak at the forest site (FO2) in Lower Saxony. The dotted white lines mark areas, where the water-deficit criterion replaces the site-productivity criterion to determine the suitability for cultivation category.*

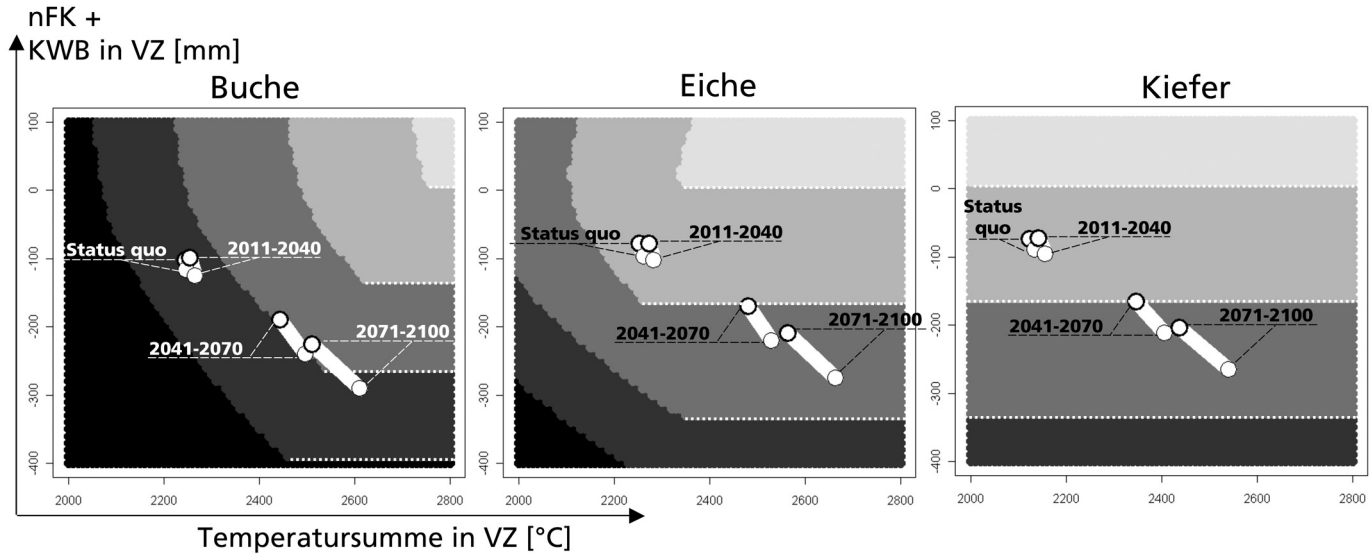
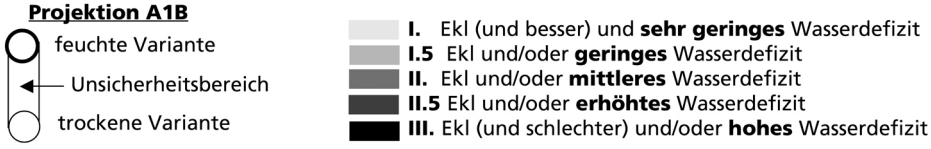


Abbildung 10: *Mehrdimensionale Ökogramme für die Baumarten Buche, Eiche und Kiefer für den brandenburgischen Forstort (FO3). Die weiß gepunktete Linie markiert die Übergänge, wo das Standortleistungskriterium durch das Wasserdefizit-Kriterium als kategorie-bestimmend ersetzt wird.*

Figure 10: *Multidimensional ecograms for beech, oak and pine at the forest site (FO3) in Brandenburg. The dotted white lines mark areas, where the water-deficit criterion replaces the site-productivity criterion to determine the suitability for cultivation category.*

Legende zu den Abbildungen 8, 9 und 10:



6. Viele Untersuchungen quantifizieren den Effekt erhöhter CO_2-Konzentrationen auf das Waldwachstum, allerdings mit zum Teil widersprüchlichen Ergebnissen (z. B. Nowak et al. 2004, Ainsworth und Long 2005, Körner et al. 2005, Körner 2006, Handa et al. 2006). Die Verwendung der CO_2-Konzentration als erklärende Variable in einer niedersächsischen Variante des vorgestellten Standort-Leistungs-Modells resultiert in deutlich höheren Bestimmtheitsmaßen, allerdings führten Prognosen zu unrealistisch hohen Mittelhöhenbonitäten im Extrapolationsbereich (Albert und Schmidt 2010). Eine erneute Integration der CO_2-Konzentration als Modellvariable sollte bei einer Neuparametrisierung jedoch in Betracht gezogen werden.
7. Im Zuge der Neuparametrisierung der Standort-Leistungs-Modelle muss auf Interaktionen zwischen erklärenden Variablen geprüft werden. In einer früheren Modellvariante konnte bereits ein hochsignifikanter Effekt der Interaktion von Bodennährstoffen und Stickstoffdeposition auf die Höhenbonität der Fichte identifiziert werden (Albert und Schmidt 2010).

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Climate-sensitive modelling of site-productivity relationships for Norway spruce (*Picea abies* (L.) Karst.) and common beech (*Fagus sylvatica* L.)

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ABSTRACT

The aim of the presented research project is to fit a site index model capable for predicting changes in site-productivity in a changing climate. A generalized additive model is used to predict site index as a function of soil and climate variables. The climate parameter values are estimated using the regional climate model WETTREG, based on global climate simulations with the global circulation model ECHAM5/MPI-OM for the reference period from 1961 to 1990. The climate values are further regionalized on a 200 m × 200 m grid. The generalized additive model quantifies the partial linear and non-linear effects of the predictor variables on site index. The model is parameterized for Norway spruce (*Picea abies* (L.) Karst.) and common beech (*Fagus sylvatica* L.) in Lower Saxony, Germany. Two case studies investigate the model's ability to generate information in order to support forest management planning decisions under a changing climate. One example analyzes the possible shift in site index of spruce along a precipitation gradient under the International Panel on Climate Change (IPCC) emission scenario A1B in the period from 2041 to 2050. The other case study shows possible future changes in site index of beech along a temperature gradient.

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1. Introduction

Climate change already affects Central Europe, more dramatic implications are expected in the future (IPCC, 2007; EEA, 2008). Generally, the following trends are projected for Central Europe which will have a heavy impact on forest ecosystems: (a) an increase in temperature with warmer summers and considerably warmer winters, inducing extended growing seasons, (b) a shift in precipitation with less rainfall in summer and increased precipitation in winter, (c) more frequent weather extremes such as droughts, torrential rains, gales, and (d) changes in atmosphere chemistry such as increasing CO_2 and NO_x concentrations as well as higher O_3 contamination. Thus, the distinctive features of forest management and wood production need to be reconsidered within the context of changing climatic conditions: (1) the extremely long forestry production period as compared to agricultural production periods evokes immediate need for action, e.g. when considering different species for reafforestation which is often the case after windthrow catastrophes, (2) forests in Central Europe closely depend on naturally provided site conditions as high cost for example, prohibits irrigation to mitigate dry spells or widespread application of fertilizers, (3) forest trees are simultaneously the product and the means of production, thus new and elevated risks threaten the goods and the factories likewise, and (4) many effects and goods provided by forests are unique, e.g. there is no comparable substitute – among many others – for water yield, retentive capacity, erosion protection, soil conservation, and balancing effect on microclimate in urban areas. Hence, it is indispensable to guarantee sustainability of forest management under changing climatic conditions albeit a higher risk and uncertainty. Therefore, adequate adaptation and mitigation measures need to be integrated into strategic forest management planning (cf. Millar et al., 2007).

It is obvious that forest managers need decision support in order to be able to meet the challenges of climate change. The presented results on climate-sensitive modelling of site-productivity relationships are part of the joint research project "Adaptive strategies on sustainable forest management under changing climatic conditions—decision support system forest and climate change" currently conducted by interdisciplinary groups at the Northwest German Forest Research Station, the University of Goettingen and the von-Thuenen Institute. The joint research project analyzes the impact of future climate conditions on forest stands in Germany and aims to provide decision support to forest managers (Jansen et al., 2008).

The aim of the forest growth research project is to fit a site index model capable of predicting changes in site index under non-constant site conditions, i.e. changing climate. A generalized

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additive model is used to predict site index as a function of soil and climate variables. The model is parameterized for Norway spruce (*Picea abies* (L.) Karst.) and common beech (*Fagus sylvatica* L.) in Lower Saxony, Germany.

2. Methods and materials

Generalized additive models are used to describe the site-productivity relationships for beech and spruce. The models are parameterized using yield data from inventory plots of the Lower Saxony Forest Enterprise as well as soil and climate variables from different data sources.

2.1. Data sources

2.1.1. Yield data

A total of 9474 beech plots and 16,552 spruce plots are available. They are distributed across the state-owned forest of Lower Saxony. The sampling design is based on a regular grid (Böckmann et al., 1998). Grid width depends on stand age and forest type, classified as 'broadleaved dominated' and 'conifer dominated'. The inventory plots consist of two concentric circles with a radius of 6 m for tree diameter at breast height (dbh) of up to 30 cm, and a plot radius 13 m for larger dbh. Species and dbh is recorded for all trees. Height measurements are sub-sampled. The beech and spruce plots comprise both pure and mixed stands. Specific yield data characteristics are presented in Table 1.

For each plot, site index at age 100 is predicted based on single tree height measurements using a longitudinal height–diameter model by Schmidt (2008) based on the methods of Lappi (1997) and Mehtätalo (2004). It is constructed as a linear mixed model (Pinheiro and Bates, 2004) and estimates population mean curves as a function of age, elevation above sea level, geographic location, quadratic mean diameter (dg) and year of germination. The longitudinal height–diameter model separates the age trend from other site effects to overcome the bias in site index prediction caused by changing site conditions (cf. Spiecker et al., 1996; Kahle et al., 2008a). Site effects are captured by the surrogate predictors of geographic location and elevation above sea level. The change of the age trend over time is covered by the surrogate predictor year of germination. Fig. 1 demonstrates how site index is derived for each plot. Firstly, the model predicts a layer of height–diameter curves by age for the fixed effects assigned to a specific plot. Secondly, on plot and measurement occasion level (nested within plot) the model is calibrated using single tree height measurements by predicting random effects via best linear unbiased predictors (BLUPS). In Fig. 1, the respective global height–diameter curve is selected based on the fixed effects for a 60-year-old stand.

Table 1
Characteristics of spruce and beech plots (SD: standard deviation, dg: quadratic mean diameter, SI_{100}: site index at age 100, nitrogen: mean annual nitrogen deposition during stand life span [1000 eq/(ha a) = 14.01 kg/(h a)], asw: available soil moisture (values correspond to 1 m soil depth), temp: mean temperature in growing season (GS), prec: precipitation sum in GS, $evapo_{pot}$: potential evapotranspiration in GS).

	Spruce		Beech	
	Mean	SD	Mean	SD
Age [year]	70	32	100	44
dg [cm]	33.9	9.9	39.2	16.0
SI_{100} [m]	29.6	2.9	29.2	3.6
Nitrogen [eq/(ha a)]	3379	848	2805	935
asm [mm]	112	51	101	64
temp [°C]	13.5	1.0	14.0	0.7
prec [mm]	367	55	336	36
$evapo_{pot}$ [mm]	441	36	455	29

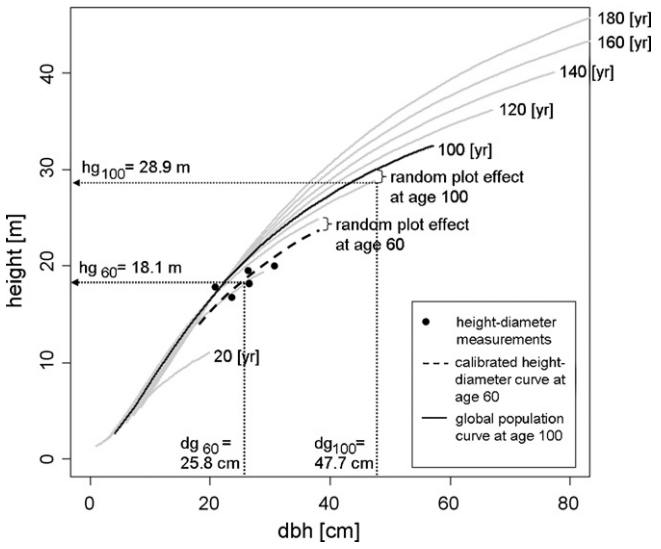


Fig. 1. Site index prediction using the longitudinal height–diameter model (Schmidt, 2008). Shown is a layer of height–diameter curves by age for a certain geographic location, sea level and year of germination.

Taking into account the dg of 25.8 cm which is calculated from plot data, the calibration results in a mean stand height of 18.1 m at measurement age 60. For predicting site index at reference age 100 dg at age 100 is needed. The prediction of a plot dg at age 100 is also done via a linear mixed model according to the method of Mehtätalo (2004). The plot-specific curve at reference age 100 is predicted, based on the expected mean curve and the predicted random plot effects. The predicted dg at age 100 – in our example 47.7 cm – and the random plot effect adjusted global population curve returns a site index of 28.9 m.

Further on, the thus derived site index values for beech and spruce plots are used as response variables in modelling site-productivity relationships with regard to climate sensitivity.

2.1.2. Soil parameters and nitrogen deposition

The soil parameters affecting stand height growth potential are explored during model selection. Soil nutrients, available soil moisture and nitrogen deposition are identified as significant explanatory variables for prediction of site index. Information on soil nutrients is available for each inventory plot from site mapping. Site mapping is a classification method based on physical and chemical soil properties as well as indicator plants (Standortskartierung, 1996). Site survey experts evaluate the information in the field. Site is classified in six discrete classes accordingly. Available soil moisture values are assessed on the grounds of soil texture, humus proportion, bulk density and proportion of skeletal soil for each layer up to 1 m soil depth (Arbeitsgemeinschaft Boden, 1996). Based on approximately 120 representative soil profiles with respective available soil moisture values, a map in the scale 1:50,000 is available for Lower Saxony and thus for all plots investigated in this research (Niedersächsisches Landesamt für Bodenforschung, 2004). Soil nutrient class frequencies are reported in Table 2.

Table 2
Soil nutrient class frequencies of spruce and beech plots (soil nutrient classes are 1 = very poor site to 6 = very rich site).

	Soil nutrient classes					
	1	2	3	4	5	6
Spruce	50	1482	8366	6476	684	25
Beech	20	327	2337	5025	1656	109

The mean annual nitrogen deposition rate during stand lifespan is predicted using a modified version of the MAKEDEP model (Alveteg et al., 1997; Ahrends et al., 2008). The model predicts the annual nitrogen deposition rate based on observed deposition data for Germany during the period from 1995 to 2004 (Gauger et al., 2008) and reconstructed earlier nitrogen deposition values are based on data of the European Monitoring and Evaluation Programme (cf. Ahrends et al., 2008). The nitrogen deposition data has a 1 km × 1 km spatial resolution. This is considered as sufficient to assign plot-specific values. Relevant characteristics on nitrogen deposition are presented in Table 1.

2.1.3. Climate parameters

Climate parameters are computed with the statistical regional climate model WETTREG (Spekat et al., 2006; Umweltbundesamt, 2007). WETTREG calculates various climate parameters for 1977 meteorological stations in Germany and in immediate vicinity for the reference period from 1961 to 1990, based on global climate simulations with the global circulation model ECHAM5/MPI-OM T63L31 (Roeckner et al., 2003, 2004). In order to assign climate parameters to each inventory plot in Lower Saxony, the hydrological model WaSIM-ETH which is driven by meteorological and physical site parameters is applied by downscaling values of all meteorological stations within a 20-km radius with a distance-weighted regression model (Schulla, 1997; Schulla and Jasper, 2007). Thus, regionalized climate parameters are available on a 200 m × 200 m grid.

As trees basically need light, water and nutrients to grow, and the physiological processes are temperature regulated, in our case mean temperature, precipitation sum and potential evapotranspiration each during the growing season (GS) are the climate-sensitive parameters considered having significant predictive ability to model site-productivity relationships. The potential evapotranspiration is estimated using grassland as standard reference according to the method of Penman–Monteith (Monteith, 1965). The beginning of the growing season is species-specifically estimated, based on the statistical model LNVAR by Menzel (1997, p. 52 ff) relating the critical thermal time for shooting to the number of chill days. Either the temperature criterion or the short day criterion, whichever is met first, determines the end of the growing season and is assumed to be species-independent (Wilpert, 1990, p. 106 ff). Mean temperature in GS was derived from daily temperature values which were downscaled as described above. Precipitation sum in GS was derived from daily recorded and downscaled values as well. Relevant characteristics on climate parameters are presented in Table 1.

2.2. Climate scenario

The goal of this research project is to analyze shifts in site index due to changing climatic conditions. Therefore, site-productivity in the reference period from 1961 to 1990 is compared to site index values predicted for the period from 2041 to 2050. In Section 3.2, the site-productivity models are applied under the International Panel on Climate Change (IPCC) emission scenario A1B (IPCC, 2007). Scenario A1B assumes a more integrated world with rapid economic growth, an increasing global population of up to 9 billion in 2050, new and efficient technologies and a balanced emphasis on all energy sources. Under these basic conditions and socio-economic assumptions, the concentration of CO_2 is projected to reach 850 ppm, resulting in a mean increase of the global surface temperature of almost 3 °C in 2100.

All climate variables are projected and regionalized using WETTREG and WaSIM-ETH as described above. WETTREG provides 10 runs with random variation per scenario which are condensed into a dry and a moist variant (cf. Spekat et al., 2006). To show the potential shifts in site index, we applied the pessimistic dry variant of scenario A1B.

Furthermore, soil nutrient conditions are considered as remaining stable for the near future. Soils are assumed to be at field capacity at the beginning of the growing season, thus, available soil moisture is at full disposal during each growing season. Future nitrogen deposition is projected using the modified version of MAKEDEP as described above, with underlying assumptions on emissions according to the Gothenburg protocol (UN/ECE, 2004).

2.3. Modelling approach

The presented site-productivity models for spruce and beech belong to the group of statistical growth and yield models. Based on a wide database of reliable yield measurements, accompanying site information and climate data with high spatial resolution, the statistical approach using a generalized additive model (GAM) seems promising. Although exact growth predictions in complex macroscopic systems such as forests cannot be achieved and many of the details of how the physiological processes are regulated are unknown (Mitscherlich, 1971, 1975; Raven et al., 1999), yet it is possible to reduce the environmental factors to a few selected meaningful state variables. It is the primary objective of model development to identify these meaningful explanatory variables and to quantify the effects on stand productivity (Section 3.1). Afterwards, the predictive abilities of the formulated models will be tested to obtain insight on their strengths and weaknesses (Section 3.2). Finally, model improvement based on the experiences gained might eventually lead to a hybrid model formulation (Section 4).

2.3.1. Applying generalized additive models

We used standard software of the statistic language and environment *R* for parameterization of generalized additive models (Hastie and Tibshirani, 1990; R Development Core Team, 2007). Hereby, the general methodology of Wood (2000, 2004, 2006) is applied which is implemented in the R-library *mgcv*. A particular feature distinguishing the R-library *mgcv* from other methods for adapting generalized additive regression models is the implementation of multi-dimensional penalized regression splines as smooth functions for identifying and describing non-linear multi-dimensional model effects. A special application of this feature used in our approach is the modelling of spatial data trends as a function of northing and easting. To determine the optimal degree of smoothing, extended generalized cross-validation techniques are applied. These result in minimizing a generalized cross-validation score (GCV-score; Wood, 2006).

2.3.2. Model selection

The spruce and beech inventory plots are used as the source of the response variable site index to cover a wide range of different site conditions and geographical locations. Therefore, as a prerequisite, all independent variables have to be available on plot basis as well. Three major criteria determine model selection: (a) biological feasibility of the effects of chosen variables on site index, (b) the models' goodness of fit indicated by the adjusted coefficient of determination, and finally (c) the Bayes information criterion *BIC* (Schwarz, 1978; Burnham and Anderson, 2004) for model comparison. Furthermore, after pre-selecting the predictor variables in order to identify the model best fitting, different models with respect to spline basis dimensions were validated against each other by comparing their BIC values.

Table 3
Formulae of site-productivity models for spruce and beech, adjusted coefficient of determination and standard error (SE).

	R^2_{adj}	SE [m]
Spruce: $SI_i = \alpha_1 + nut_i^T\beta_1 + f_1(prec_i) + \alpha_2^* cep_i + f_2(asm_i) + f_3(temp_i) + f_4(Ndep_i) + f_5(lon_i,\ lat_i) + \varepsilon_i;\quad \varepsilon_i \sim N(0,\ \sigma_\varepsilon^2)$	0.39	2.3
Beech: $SI_i = \alpha_1 + nut_i^T\beta_1 + f_1(wb_i) + f_2(temp_i) + \alpha_2^* cNdep_i + f_5(lon_i,\ lat_i) + \varepsilon_i;\quad \varepsilon_i \sim N(0,\ \sigma_\varepsilon^2)$	0.34	2.9

With:
SI_i = site index (mean stand height at age 100) at inventory point i [m],
nut_i^T = indicator vector for soil nutrient class,
β_1 = parameter vector corresponding to nut,
$prec_i$ = precipitation sum in growing season (GS) [mm],
ep_i = potential evapotranspiration in GS [mm],
cep_i = centered potential evapotranspiration in GS [mm],
asm_i = available soil moisture [mm],
$temp_i$ = mean temperature in GS [°C],
$Ndep_i$ = mean annual nitrogen deposition [eq/(ha a)],
$cNdep_i$ = centered mean annual nitrogen deposition [eq/(ha a)],
lon_i = longitude (location parameter),
lat_i = latitude (location parameter),
wb_i = water balance in GS [mm] (*with* $wb_i = prec_i - ep_i + asm_i$),
ε_i = random error term,
α_1, α_2 = regression coefficients,
$f_1 \ldots f_4$ = one-dimensional penalized regression splines,
f_5 = two-dimensional penalized regression spline describing a spatial trend.

3. Results

3.1. Modelling site index

The formulated site-productivity models for spruce and beech are presented in Table 3.

The six soil nutrient classes are further pooled since there are very few observations in some classes (for spruce, classes 1 and 2 as well as 4, 5 and 6 are pooled; for beech, classes 1 and 2 as well as 5 and 6 are combined; cf. Table 2). The spruce model contains the three hydrological parameters separately: precipitation sum in growing season (GS), potential evapotranspiration in GS and available soil moisture. These variables are combined in the beech model to form the aggregated predictor water balance in GS. This step pays tribute to the fact that the modelled effect of precipitation sum in GS for beech is neither a maximum relationship nor monotonously increasing but rather has, in part, a significantly reductive effect on site index with increasing precipitation sum. This does not seem biologically feasible (cf. Kahn, 1995). Furthermore, both models use mean temperature in GS, mean annual nitrogen deposition over stand lifespan, and geographical location as additional predictors. Geographic location is used to model a spatial trend. This in turn is assumed to be a proxy for all influential factors with a regional autocorrelation not explicitly included in the models (e.g. wind effect) or only described on a rough resolution. Although the effect of the spatial trend on site index is not directly biologically interpretable, its use as a proxy variable is inevitable as the models' performance dramatically improves (without geographic location $R^2 = 0.25$ for spruce and $R^2 = 0.19$ for beech). Moreover, not accounting for the spatial correlation would violate the independence assumption in regression theory.

In order to reduce the high variability of the model intercept, a generally more stable centercept is estimated instead. For this, the values of the variables showing linear effects are centred to their mean transforming the "intercept" into a "centercept" (Koenker, 2005, p. 303).

The estimated coefficients and statistical characteristics of the spruce and beech model (Eqs. (1) and (2) in Table 3) are given in Table 4.

All linear and non-linear effects are highly significant and biologically plausible. Site index is higher if soil nutrient conditions are better. Stand height productivity is reduced with increasing potential evapotranspiration. The fertilizing effect of nitrogen deposition is obvious in the beech model. In order to analyze the non-linear effects, the partial effect of the respective variable on site index is displayed in Figs. 2–6.

Fig. 2 shows the partial effect of mean temperature in GS on site index. Although heavily depending on the site's current temperature, a shift in temperature generally has a stronger effect on site index on spruce than on beech. The different effects of a 1 °C temperature increase on spruce and on beech stands are depicted in the graphics.

Table 4
Estimated coefficients and statistical characteristics of the spruce and beech model (Est = estimated parameter value, SE = standard error, edf = effective degrees of freedom).

	Est.	SE	edf
Spruce model (Eq. (1))			
Parametric coefficients:			
Intercept	28.258	0.070 ***	
nut.class 3	1.215	0.075 ***	
nut.class 4	2.033	0.077 ***	
cep	−0.025	0.002 ***	
Approximate significance of smooth terms:			
f_1 (prec)			2.961***
f_2 (asm)			2.902**
f_3 (temp)			3.982***
f_4 (Ndep)			3.944***
f_5 (lon,lat)			28.846***
Beech model (Eq. (2))			
Parametric coefficients:			
Intercept	27.080	0.164 ***	
nut.class 3	1.223	0.175 ***	
nut.class 4	2.423	0.171 ***	
nut.class 5	2.925	0.182 ***	
cNdep	0.002	0.000 ***	
Approximate significance of smooth terms:			
f_1 (wb)			1.894***
f_2 (temp)			4.268***
f_5 (lon,lat)			37.947***

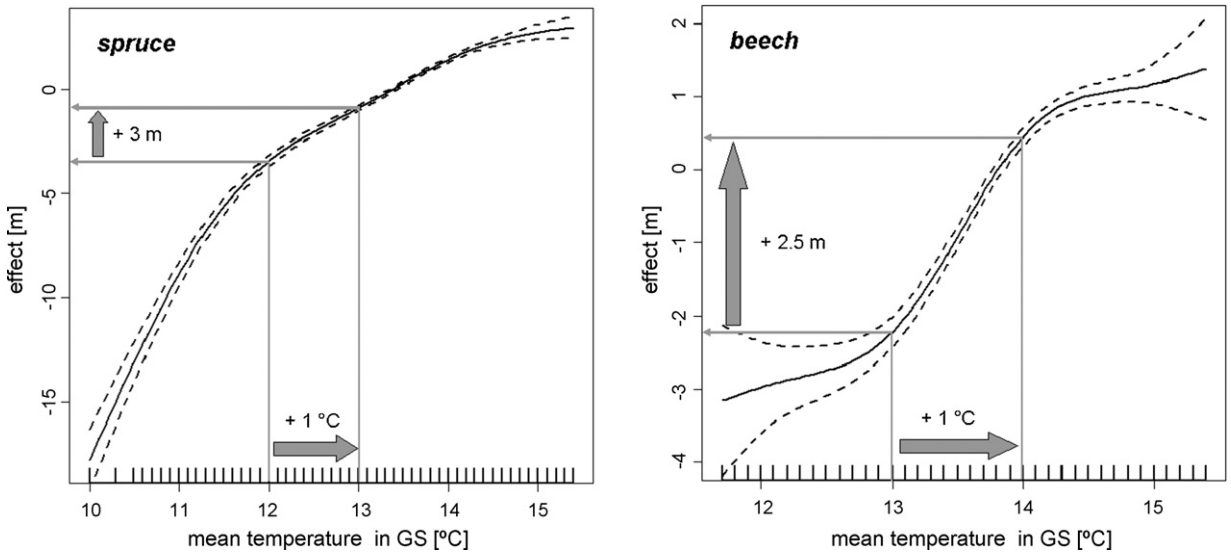


Fig. 2. Partial effects of mean temperature in growing season (GS) on site index for spruce (left) and beech (right). Dashed lines indicate 95% pointwise prognosis intervals. The covariate is displayed as a rug plot. The effect of a 1 °C increase is displayed with all other factors held constant.

A much smaller sensitivity on changing plant-available water conditions in comparison to shifts in temperature is indicated by the partial non-linear effects of the two hydrological variables precipitation sum in GS and available soil moisture in the spruce model (Fig. 3) as well as water balance in GS in the beech model (Fig. 4).

The impact of changes in mean annual nitrogen deposition on site index of spruce stands is strongest in the value range up to approximately 3000 eq/(ha a) (Fig. 5). The effect then rapidly levels off and shows an increasing impact again where the 95% prognosis interval already indicates large uncertainty.

Fig. 6 illustrates the partial effect of the geographic location on site index. This static effect has several accounts that are not further identifiable. Nonetheless, the generally positive effect on site index with increasing distance to the sea, for example, might be attributable to a reduction in mean wind force.

3.2. Applications of site-productivity models under climate change

As the site-productivity models are constructed to analyze shifts in site index under changing climate, a first test of model behaviour is conducted, applying the conditions of scenario A1B in the dry variant in the period from 2041 to 2050 to sites along a precipitation and a temperature gradient. Two examples demonstrate that even the site-productivity models at this stage of development generate useful information for forest management.

3.2.1. Precipitation gradient

From the forest growth perspective, the projected reduction of precipitation during the growing season will cause severe drought stress on many forest sites in Central Europe, inducing decreasing increment or even dieback. A shift in site index along a precipitation gradient illustrates the long-term consequences of changes in the water regime on forest productivity. Fig. 7 displays four regions in north-eastern Lower Saxony with a decreasing precipitation trend during the growing season.

The spatial gradient of decreasing precipitation holds true for the reference period from 1961 to 1990 as well as for the future period from 2041 to 2050 (the correlation coefficient between precipitation sum in GS and distance to coast is −0.89 in the reference period and −0.96 in the period from 2041 to 2050). In the

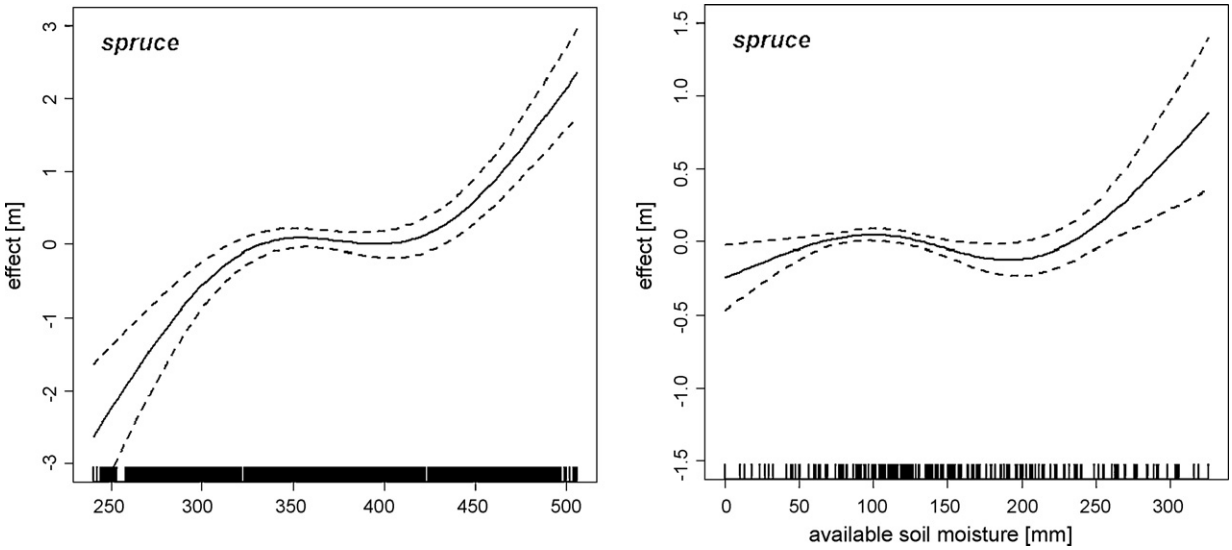


Fig. 3. Partial effects of precipitation sum in growing season (GS) (left) and available soil moisture (right) on site index for spruce. Dashed lines indicate 95% pointwise prognosis intervals. The covariate is displayed as a rug plot.

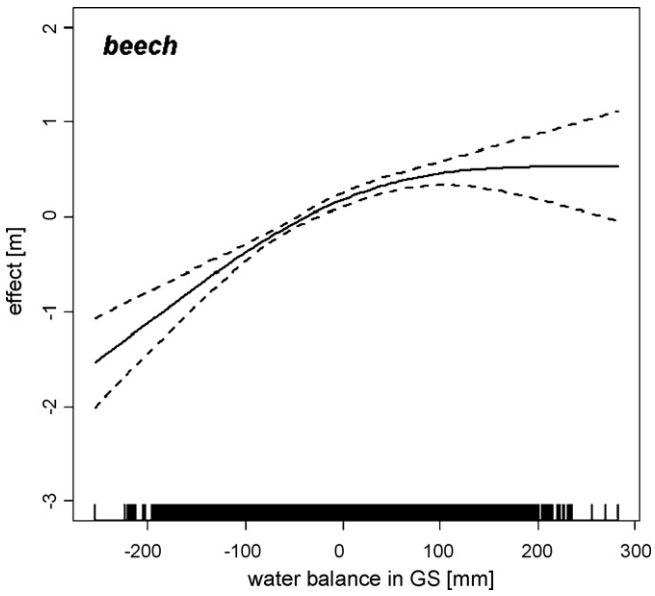


Fig. 4. Partial effect of water balance in growing season (GS) on site index for beech. Dashed lines indicate 95% pointwise prognosis intervals. The covariate is displayed as a rug plot.

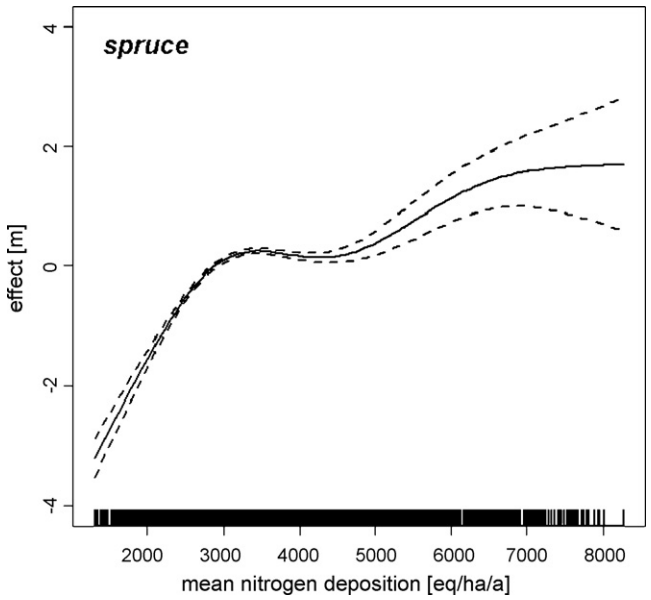


Fig. 5. Partial effect of mean nitrogen deposition on site index for spruce. Dashed lines indicate 95% pointwise prognosis intervals. The covariate is displayed as a rug plot.

four regions a temporal gradient with decreasing precipitation is also observed (−9.2% in region 1, −11.3% in region 2, −12.9% in region 3, and −13.0% in region 4). The predicted temporal and spatial changes in mean site index of the four regions are highly significant.

As other variables such as mean temperature in growing season or mean annual nitrogen deposition do not show such a clear spatial trend, the increasing negative impact on site index along the spatial gradient can be attributed for the most part to decreasing precipitation. The predicted temporal change in site index within a region is caused by projected changing values in all climate variables. Along with the reduction in precipitation, an increase in mean temperature in growing season is projected for the period from 2041 to 2050. Thus, the potential evapotranspiration will be higher in the future. The mean annual nitrogen deposition will also be lower. Overall, a decline in site index is predicted for each region in the future. At average, the positive effect of increasing temperatures cannot compensate the negative impact of changes in precipitation, potential evapotranspiration and nitrogen deposition on site index.

When interpreting these results, it is important to consider that predictions are burdened with uncertainty resulting from the climate scenarios as well as site-productivity model prediction error. Although these results are to be regarded as preliminary, a meaningful application of the formulated site-productivity models for forest planning purposes is obvious. Under the assumption of scenario A1B in the dry variant, the model predicts lower productivity in spruce stands in north-eastern Lower Saxony. Whether this loss is acceptable, or silvicultural means can counteract and compensate, or forest conversion with different species is needed, needs to be decided by forest managers. In any case, decision support in terms of information about future stand productivity can be provided.

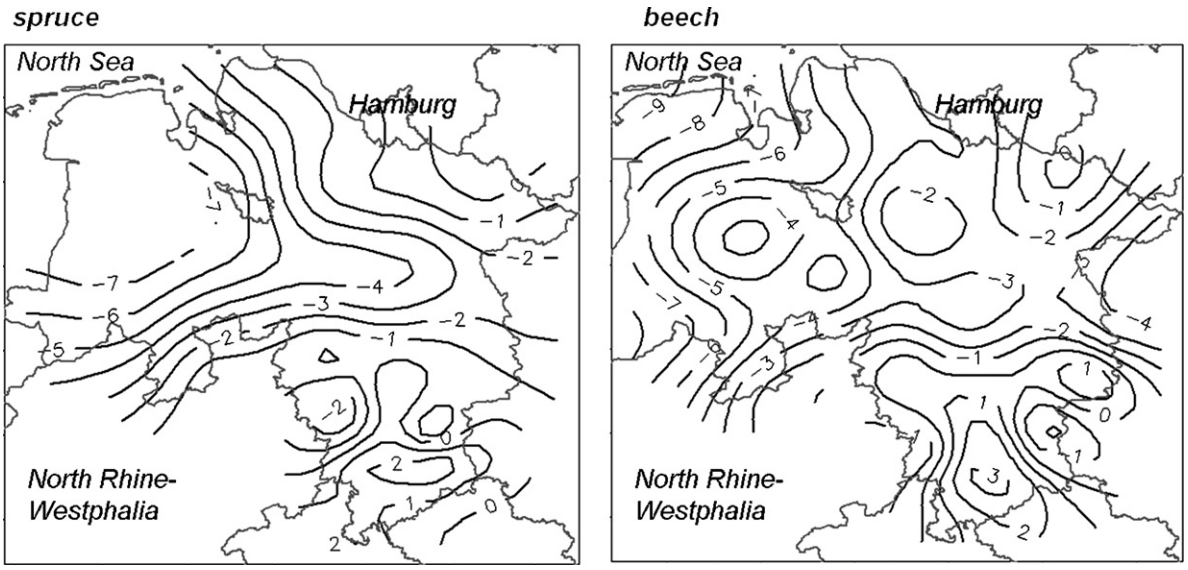


Fig. 6. Partial effect of geographic location on site index for spruce (left) and beech (right). The values along the isoline indicate the impact on site index in meters.

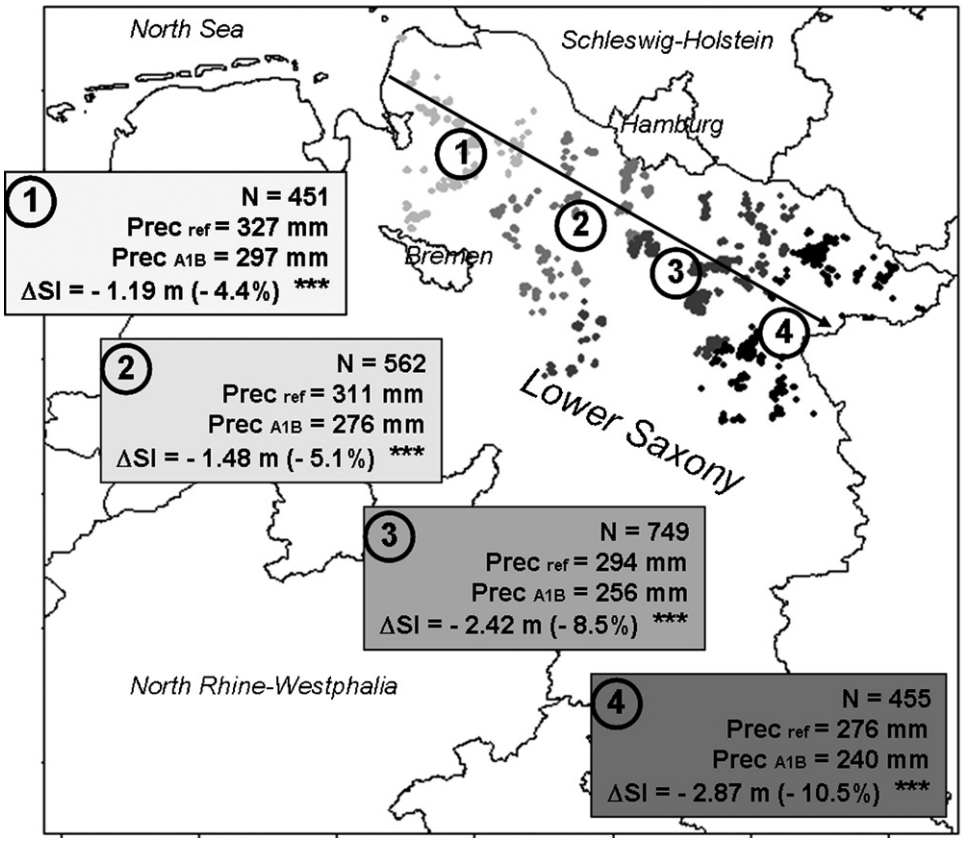


Fig. 7. Precipitation gradient along four regions in Lower Saxony, Germany (N = number of spruce plots; $Prec_{ref}$ = mean precipitation sum in growing season in respective region for the reference period 1961–1990; $Prec_{A1B}$ = precipitation sum in growing season in respective region for the period 2041–2050 under scenario A1B—dry variant; ΔSI = change in mean site index of spruce plots in respective region).

3.2.2. Temperature gradient

As long as the water regime is not limiting forest growth, a climate change-induced increase in mean temperature in the growing season will have a positive effect on stand productivity, as is the case in mountainous regions. An example from the Harz Mountains demonstrates the predicted effect of rising temperatures on stand productivity in beech forests (Fig. 8).

Naturally, mean temperature in growing season is highly correlated with altitude ($r_{temp,alt} = -0.87$ for the reference period and $r_{temp,alt} = -0.86$ for 2041–2050). Again, there is also a temporal gradient in temperature (in the four altitude classes 1–4, the relative temporal change in mean temperature during the growing season is +9.9%, +11.0%, +11.5%, and +11.9%). Along the temperature gradient, the site-productivity model for beech predicts altitudinal and temporal trends in site index. These trends are highly significant.

At altitudes below 300 m, a future decrease in site index is predicted, whereas the higher the reaches, the more the site index will improve under scenario A1B—dry variant. Along the temperature gradient, basically a clearly decreasing precipitation is projected under the climate change scenario. Nitrogen deposition is projected to be slightly lower in the period from 2041 to 2050 than in the reference period. Thus, the positive future trend in site index with regard to altitude can be attributed to projected temperature increases. This heightens productivity more than the negative impact of precipitation reduction, higher evapotranspiration and declining nitrogen deposition. Beech stands in mountainous regions seem to benefit from projected climate changes. If more evidence strengthens these results, it will have a significant impact on forest planning from the forest growth perspective, e.g. higher yields at current beech sites above 300 m altitude or intensifying beech plantings at higher altitudes.

4. Discussion

It is difficult to quantify precisely how the overall effects of climate change will influence forest management. Besides prediction errors in growth and yield models as well as uncertainties of the climate scenarios, there might be more serious implications on forests through extreme climatic events than long-term shifts in productivity, e.g. drought induced dieback, windthrow, pest and disease outbreaks, etc. However, the climate-sensitive site-productivity models are a first step to provide forest management with relevant information on how to take adaptation steps or apply mitigation measures against changing climatic conditions. Still, the presented modelling approach covers a complex field: the dependent variable site index itself is estimated, using the longitudinal height–diameter model (Schmidt, 2008), some of the independent variables are not measured but predicted as well, the data sources are of different reliability, and finally the application of the site-productivity models under climate change relies on projected values with underlying scenario assumptions. Thus, model predictions contain a lot of uncertainty. This needs to be accounted for and communicated clearly to the model user.

4.1. Remarks on the statistical approach and the models' performance

Although many researchers see process-based models as best suited to predict the effects of climate change on forest growth (e.g. Landsberg, 2003; van Oijen et al., 2008a), Pretzsch (1996) argues in favour of statistical quasi-causal approaches (cf. Kahn, 1995) to provide forest management information as the only reasonable alternative to traditional yield tables in the near future. We formulate statistical models suitable for explicitly predicting site index under non-constant environmental conditions, i.e. climate

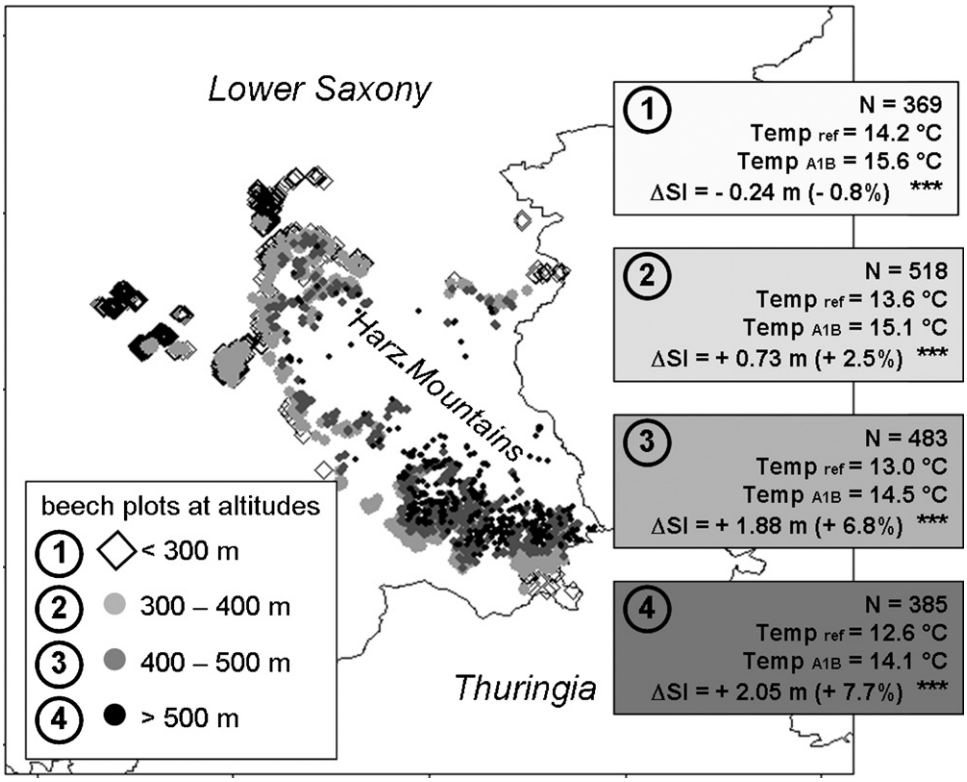


Fig. 8. Temperature gradient along four altitude classes in the Harz Mountains, Lower Saxony, Germany (N = number of beech plots; $Temp_{ref}$ = averaged mean temperature in growing season for the reference period 1961–1990; $Temp_{A1B}$ = averaged mean temperature in growing season for the period 2041–2050 under scenario A1B—dry variant; ΔSI = change in mean site index of beech plots in respective altitude class).

change. The primary objective of statistical growth and yield models is to provide forest managers with relevant information for forest planning purposes (Gadow, 1996). From this point of view, these models serve prediction purposes rather than strive to understand the ecophysiological functionality of forests as process-based models do (cf. Bunnel, 1989; Mohren and Burkhart, 1994). Postulating good fit, the statistical models' advantages are the high accuracy within the range of parameterization data as well as the ability to quantify prediction precision (Vanclay, 1994). Especially the benefit to allow for the calculation of confidence intervals helps to account for uncertainty of predictions. For responsible forest management decisions, this is indispensable.

One major advantage of the parameterization data used in this research is the high quality and high resolution of the climate variables making the statistical approach promising. It is possible to link yield data on plot level directly to the corresponding climate-sensitive predictors. Kahn's (1995) quasi-causal site-productivity models, for example, rely on more inaccurate climate data since these sophisticated regionalization techniques were not available at that time. Concerning parameterization data, it is also advantageous that the dependent variable site index is estimated using the longitudinal height–diameter model. It separates the age trend from other site effects in order to overcome the bias inherent to most traditional site index systems, which correlate height growth potential solely with stand age and thus assume constant site conditions over time. Therefore, these height–age site index systems do not adequately describe the height growth potential as the estimated site index shows an age trend in most European forests (Spiecker et al., 1996). This trend is caused by a shift of site fertility due to, among others, nitrogen deposition (Kahle et al., 2008a). However, one restriction applies to our models: we assume that the mean climate values of the reference period from 1961 to 1990 that were used for parameterization are close to the values of antecedent periods, as some of the yield data comes from forest stands grown before 1961. This assumption seems justifiable looking at how the radiative forcing has developed over time although temporal fluctuations of climatic conditions occur (IPCC, 2007).

The quality of predictions from statistical models relies heavily on parameterization data (Mendoza and Vanclay, 2008). It is therefore indispensable to define the range of conditions over which reliable projections can be expected (Vanclay, 2003). Some theoretical considerations about the presented site-productivity models and climate change illustrate the predictive abilities. All climate scenarios project increasing temperatures for Central Europe. As the non-linear effect of temperature levels off at higher values in the spruce and beech models, extrapolating beyond the observed upper temperature limit today will result in conservative partial effects on site index with increasing uncertainty (cf. Fig. 2). The asymptotic form of the non-linear partial effect of temperature is in agreement with Loehle's (2000) SORTIE forest simulation model which incorporates an asymptotic rather than a parabolic temperature-growth response function. Precipitation in growing season is expected to decrease in the future. While in the beech model, the partial effect of water balance at the lower limit is slowly declining, the partial effect of precipitation sum in the spruce model might lead to considerable underestimation of site index due to the steep decline at the lower extrapolation range (cf. Figs. 3 and 4). The nitrogen deposition rate is projected to decrease slowly. Thus, extrapolation does not seem to affect large forest areas in the near future (see Table 1 for standard deviation of nitrogen deposition). The predictions of the site-productivity model along the precipitation and temperature gradients, as shown above, did also not reveal any severe problems in the extrapolation range. Especially, projected temperature and precipitation sum during growing season for the spruce plots of the precipitation gradient result in partial effects beyond the limits of the parameterization data (cf. Fig. 7). Altogether, the changes in

site index predicted along the two gradients are consistent with simulation results of the modified patch model PICUS v1.2 (Lexer et al., 2002). For Austrian forests, the patch model predicts increasing competitiveness of broadleaved species at higher elevations. This corresponds with our results of accelerated site indices predicted for beech along the temperature gradient (cf. Fig. 6). Furthermore, Lexer et al. (2002) report that spruce at low-elevation sites would suffer from a changing climate and eventually drop out as a crop tree. This is reflected in our findings as well, namely dramatically reduced site indices along the precipitation gradient (cf. Fig. 5).

The independent variables integrated in our models describe main effects, i.e. without interaction terms. This is in accordance with results obtained when past growth trends were analyzed applying four process-based models (van Oijen et al., 2008b). Also, the selected variables temperature, evapotranspiration and precipitation are assumed as increasingly important driving forces on forest growth in the future. However, nitrogen is seen as the most important influence on site-productivity improvement in the past. Mellert et al. (2008) report that precipitation as a proxy for plant water availability primarily accounts for short-term fluctuations of tree growth. Our models, however, comprise all hydrological variables affecting plant water availability, i.e. precipitation, evapotranspiration, and available soil moisture. They thus might better cover long-term effects as well. However, the impact of changes in the hydrological variables on site index in both spruce and beech models are much lower than the impact of changing temperature (cf. Figs. 2–4). Fries et al. (1998) and Monserud et al. (2006) confirm the findings that temperature variables are the strongest predictors of site index.

As regards the variable available soil moisture, further model improvement is necessary. The partial effect shown in Fig. 3 displays a weak impact on site index and furthermore the decline, although marginal, between available soil moisture values from approximately 120 to 200 mm is not feasible. We attribute this to the relatively imprecise data source since the values are obtained from a map with a scale of 1:50,000 in lack of any better data. Ongoing research will provide a pedotransfer function to assign more precise values to yield plots.

In sum, the parameterized site-productivity models already reach satisfactory accuracy and predictions in the extrapolation range seem feasible. However, some findings recommend the inclusion of nitrogen deposition and soil nutrient interaction in the models (e.g. Egli et al., 1998; Körner, 2006) and the accounting for a potential fertilizing effect of elevated atmospheric CO_2 concentration (e.g. Valentine, 1997; Kahle et al., 2008b).

4.2. Adding nitrogen deposition and soil nutrient interaction to the models

For calcareous and acid soils, Egli et al. (1998) report significantly different radial growth rates of beech seedlings under increased nitrogen deposition whereas for spruce no soil nutrient and nitrogen deposition interaction effect on growth could be detected.

Thus, we also include a soil nutrient class and nitrogen deposition interaction term in our site-productivity models. In the spruce model, the interaction term is highly significant, the impact on site index increases with decreasing soil nutrient availability. This decreasing impact is in accordance with the findings of Egli et al. (1998). However, the coefficient of determination indicates no considerable model improvement when taking into account the interaction term. In the beech model, the interaction term is not significant. Therefore, we followed Vanclay's (1994) advice to create a model as parsimonious and as simple as possible and refrained from adding the interaction term in both the spruce and beech model.

4.3. Incorporating CO_2 into the site-productivity model

Many experiments quantify the impact of elevated CO_2 concentration on forest growth, unfortunately with no universally valid findings (e.g. Nowak et al., 2004; Ainsworth and Long, 2005; Körner et al., 2005; Körner, 2006; Handa et al., 2006). Nevertheless, some experiments indicate enhanced tree growth on soils with good nutrient supply under elevated CO_2, while no or very little effect is seen on sites where soil nutrients limit plant growth (e.g. Kirschbaum et al., 1998; Oren et al., 2001; Körner, 2006). Furthermore, the positive impact on growth seems to affect only young trees (Egli et al., 1998; Asshoff et al., 2006). Considering enhanced juvenile growth, site index will increase under elevated CO_2 in some cases. The possibly beneficial impact of elevated CO_2 on tree growth under drought conditions is another important finding (Hättenschwiler et al., 1997; Ellsworth, 1999; Körner, 2006).

Valentine (1997) presents a metabolic height growth model which explicitly accounts for CO_2 fertilization on site index. Consequently, we fitted alternative site-productivity models. These incorporate CO_2 concentration as a predictor. The variable mean atmospheric CO_2 concentration during stand lifespan [ppmv] has a highly significant linear effect on site index for both species. The interaction terms with soil nutrient classes are also highly significant in both models.

The unrealistically high site index values when making predictions under elevated CO_2 concentrations of scenario A1B for the period from 2041 to 2050 are a major drawback. In our case, it is not permitted to extrapolate the linear effect of CO_2 on site index. Therefore, the alternative site-productivity models are rejected in favour of the formulations given in Table 3, although the adjusted R^2-values indicate a noticeable better fit for spruce (0.43 instead of 0.39) and beech (0.36 instead of 0.34).

On these grounds, the parameter CO_2 concentration serves as a good example and advocate for a hybrid modelling approach. Hybrid approaches ideally comprise the best properties of the other two model approaches. Shortcomings of statistical models are lack of flexibility and generality. Process-based models are often not designed to fulfil the information needs of forest managers (Kimmins, 1993). The rationale behind hybrid models is to overcome these deficiencies by providing relevant management information based on generally applicable relationships. Given more universally valid findings on the impact of elevated CO_2 it seems plausible to integrate it as a predictor on an expert knowledge basis, thus overcoming the problems in the extrapolation range.

5. Conclusions

A rapid anthropogenic climate change already affects forest ecosystems. The negative impact on forest health and vitality will escalate in the future. Consequently, adaptation and mitigation measures need to be taken. Adaptation of forests and forestry is still possible with contributions from forest science, forest management and forest policies.

While forest management has always faced uncertainties, it still aimed at maintaining past patterns of sustainable forest use. As recently proposed by experts, a paradigm change towards a proactive forest management accounting for new severe factors of uncertainty and risk seems necessary (Carle et al., 2008). Monitoring and assessing the impact of climate change on forests is essential in order to be able to take effective adaptation measures. Potential shifts of stand productivity under different

climate scenarios can be analyzed using the presented site-productivity models. For example, adapting rotation length, target diameter or even a change in species can be considered from a forest growth perspective.

The advantage of the presented site-productivity models is that partial effects of single predictors on site index are quantified and estimated confidence intervals help accounting for prediction uncertainty. The preliminary results demonstrate that site-productivity models can generate useful information to support forest management decisions. The analysis of the two case studies, though afflicted with uncertainty, indicates a decline in productivity of spruce stands with decreasing precipitation in the growing season in north-eastern Lower Saxony and enhancing productivity of beech stands in mountainous regions due to the positive impact of rising temperatures.

The current models can be improved by enlarging the parameterization data to all of Germany. Thus, more extreme site conditions will be covered. Not only sites that already nowadays have very low precipitation or high temperatures in the growing season will expand the dataset but also certain combinations of site conditions not found in Lower Saxony, e.g. the warm and wet sites of the Black Forest in south-western Germany.

The application of climate-sensitive site-productivity models indicates a potential shift in site index due to changing environmental conditions. Other stress factors such as wind, drought and pest might influence forest ecosystems more heavily. Refraining from catastrophic events, the potential climate induced changes in forest ecosystems regarding productivity, species composition, species competitiveness, etc. will be gradual. Forest management still has the opportunity to integrate adaptation and mitigation strategies into strategic planning.

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