Impact of Target Diameter Harvesting on Spatial and Temporal Pattern of Drought Risk in Forest Ecosystems Under Climate Change Conditions

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Abstract: Forests are influenced by many disturbances, especially drought, windthrow, pest attacks, air pollution, and forest management. The climate change results in increasing frequency of weather extremes which will probably cause drought stresses in European forest ecosystems. By integrating several new features within the BROOK90 model, small-scale coupled process-based modeling was carried out for different climate and target diameter harvesting scenarios in the region of Solling, Germany. The results show considerable increment of drought risks towards 2100 compared to "present climate conditions", caused by changes in precipitation and increase of mean air temperature. Beyond this it is shown that for the Solling site the changes of structure and microclimate produced by target diameter harvesting result in a decrease of drought stress and could be implemented to mitigate drought events.

Keywords: Target diameter harvesting, drought stress, climate change, BROOK90, water-balance model.

INTRODUCTION

In the development of forest management strategies the timber production, the maintenance of biological diversity, and soil and water protection are all considered equally important targets [1, 2]. Sustainable forest management (SFM) is the overall objective of the Land Forest Service and private forest holdings today. The key experience has been recognizing the importance of the SFM for the natural self-regulation capacity of the forest ecosystem [3]. According to [4] it is possible to achieve biodiversity, nutrient cycling, and stability gains in an uneven-aged forest stand. Even-aged clear felling and natural regeneration management are commonly applied in practice during the last decades in Germany. Uneven-aged natural regeneration through selective felling is rare, but this method is assumed to yield important ecological benefits [5]. It is ecologically and economically worthwhile to harvest older trees with a greater wood volume [6]. This way the forests could store higher amounts of carbon and develop more quality timber. In selection harvest systems, individual trees or small groups of trees are harvested at periodic intervals. The selection is primarily based on their physical condition or degree of maturity [7]. Also the target diameter harvesting (TDH) regime allows avoiding the whole clearcut areas as a method of final harvesting when individual trees have reached a certain diameter rather than when stands have reached rotation age [8]. So the harvest takes place temporally staged (single-stem), which lets the forest to remain a forest (continuous cover forestry). The choice of this regime however complicates forest operations in the whole and the wood harvest in particular.

Along with human impacts the natural disturbances play an important role in restructuring of plant communities [9]. Wind damage, i.e. windthrow or stem break, is the major natural disturbance that can occur in European forests. The positive feedback of windthrow events on wind forcing in a forest gap was demonstrated by [10]. Another natural disturbance is the drought-induced mortality [11]. The climate projections suggest that the risk of damages for trees will increase as a result of the predicted climatic warming. The regional climate model simulations for the next 100 years project the increase of annual mean temperature (AMT) for Germany within the range between 2°C and 3°C, when using rather mild scenarios SRES B1 and A1B [12]. Heat waves and drought would increase in intensity, frequency and duration [13-15]. Besides the projected higher probabilities of severe storms [16-18], these climatic changes will expose German forest ecosystems to environmental conditions that differ from those experienced in the past [19]. It was pointed out that forest management using adequate decision support systems (DSS) can considerably reduce the risk of damages [20] including drought. The DSS "Forest and Climate Change" which is currently being developed at the Göttingen University is aimed to provide a tool for the quantitative assessment of biotic and abiotic risks of forest ecosystems under the conditions of changing climate [19]. An improved understanding of damages is essential for addressing the environmental and policy implications of climate variability and global change. Therefore, the objective of this study is to assess the spatio-temporal variability of TDH regime on drought risk for two tree species (spruce and beech) typical for Germany under the projected climatic conditions of SRES A1B and B1 in the Solling area.

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MATERIALS AND METHODOLOGY

Investigation Area

The investigation area within the limits of 51.5°N to 52.1°N and 9.3°E to 9.9°E, i.e. about 3600 km^2 encloses the Solling highlands. The Solling is a mountain range in the 'Weserbergland' on the north-western border of the central German uplands, covering the sub-montane and the montane zone up to 550 m a.s.l. It is located between the basins of the river Weser (west) and Leine (east). The hills of the eastern bank are formed mainly of sandstone, which is known locally as 'Buntsandstein' and partly covered with loess. The central part is divided by a rift valley with pure sandy sediments. Its location on the northern fringe of German highlands is very exposed to the long-range transported air pollutants, which reflect in high deposition rates. Therefore, the soils on sandstones and pure sand sediments are generally very acid and nutrient poor dystric cambisols [21], on loess-dominated sites eutric cambisols and haplic luvisols. The Solling itself is an area with a relatively low population density and no major industrial facilities. The woodland history traces back into the 16th century and today the forests cover 42% of the investigation area. It is distributed among 26% deciduous, 11% coniferous, and 5% mixed forests. Following the classification of [22] the Fig. (**1**) shows the spatial distribution of the land-use classes in the Solling based on the CORINE Land Cover 2000 dataset. The area belongs to the suboceanic climate. The so-called "Hochsolling" is an area which belongs to the montane belt with high annual precipitation and cold winters with much snow. The AMT for the period 1950-2000 in the investigation area lies between 6.5°C and 9°C, the mean annual precipitation between 600 mm and about 1000 mm [23].

Model Description

Many physically-based hydrologic models have been developed to simulate the dynamic processes of evapotranspiration and soil water movement (e.g. BROOK90: [24]; CoupModel: [25]). In this paper we use the BROOK90 (Version 4.4e) model - a 1D-Soil-Vegetation-Atmosphere Transfer (SVAT) Model [24, 26] to simulate the water balance of a forest stand. BROOK90 has been developed to be applicable to different and changing land use. It simulates interception by a single layered (horizontally homogeneous) stand, evapotranspiration, soil water, and a streamflow consisting of surface runoff, bypass flow, down slope flow, and base flow. The soil water transport is described by the Darcy-Richard equation. BROOK90 is a detailed, process-oriented model that can be used as a tool to investigate the potential effects of tree species, soil type, and climate scenarios on drought stress. BROOK90 has been used to study the soil water budget of forest stands over a broad set of study sites (e.g. [27-31]).

Calculation of Drought Stress

In many investigations the relative transpiration index (RTI) was used as an indicator of the critical state of soil water resources availability. RTI describes the ratio of actual transpiration to potential transpiration [29, 32, 33]. The other commonly used indicator is the dynamic relative extractable soil water, REW(t). It could be calculated as the ratio of actual to maximum extractable water according to [34]:

$$REW(t) = \frac{\theta_v(t) - \theta_r}{\theta_{fc} - \theta_r} \tag{1}$$

where θ_v [m^3 m^{-3}] is the actual (correspondingly – daily) volumetric (subscript "v") soil water fraction; θ_{fc} (m^3 m^{-3}) is the maximum soil water content extractable by plants (subscript "fc" means field capacity), and θ_r (m^3 m^{-3}) is the residual soil water content.

For various forest ecosystems types [35] and [36] have identified 40% of REW in the rooting zone as a critical limit, below which transpiration and gross primary production are sharply reduced by drought. The drought stress duration (DSD) is calculated as follows:

$$DSD = \sum_{t=1}^{365} \begin{cases} 1 & if \quad REW < 0.4 \\ 0 & else \end{cases} \tag{2}$$

Climate Scenarios

BROOK90 needs daily inputs of precipitation, maximum and minimum air temperature, solar radiation, water vapour pressure, and wind speed. To describe the dynamic nature and uncertainties of drought stress during the 21st century for each combination of site, soil, and tree species, two different climate scenarios (SRES A1B and B1) were applied. The scenarios calculations for the period of 2001-2100 as well as 20th century scenario C20 for the period of 1960-2000 were done by coupled general circulation model - ocean model, ECHAM5-MPIOM, as defined in German framework program "klimazwei". The modeled data are downscaled using Climate Local Model (CLM) [37] to a spatial resolution of 0.2°×0.2°. The daily mean values of climate variables for A1B, B1 and for C20 with two runs per scenario are obtained from CERA-database [38]. For all variables the time series of run 1 and 2 of A1B and B1 are merged with correspondent runs of C20 so that continuous time series from 1960 to 2100 are built for both runs of A1B and B1. Following notation is assumed in further analysis: A1B_1, A1B_2 and B1_1, B1_2 are correspondingly the merged runs 1 and 2 of C20-A1B and C20-B1. The simple A1B and B1 denote respective merged scenarios averaged over the two runs.

Soil Profiles and Parameters

For the spatially distributed simulation we used the digital soil map of Germany at a scale of 1:1000000 [39] and the digital metadata corresponding to the above-noted soil map. This map is subdivided accordingly to the main land cover types (forest, cropland, and grassland). Only the forest soils were selected and intersected with the geometries of the climate data. The generated database contains 15 different soil types with descriptions of physical and chemical properties for their different horizons. For the simulation of the soil water fluxes, the parameters of the water retention curve and the hydraulic conductivity function were deduced from soil texture with the modified pedotransfer function [40] for each horizon (Table **1**). The Clapp and Hornberger values for porosity are too low for most forest soils. Therefore, we used the correction of [41], which depends on bulk density and organic matter. For soil textural

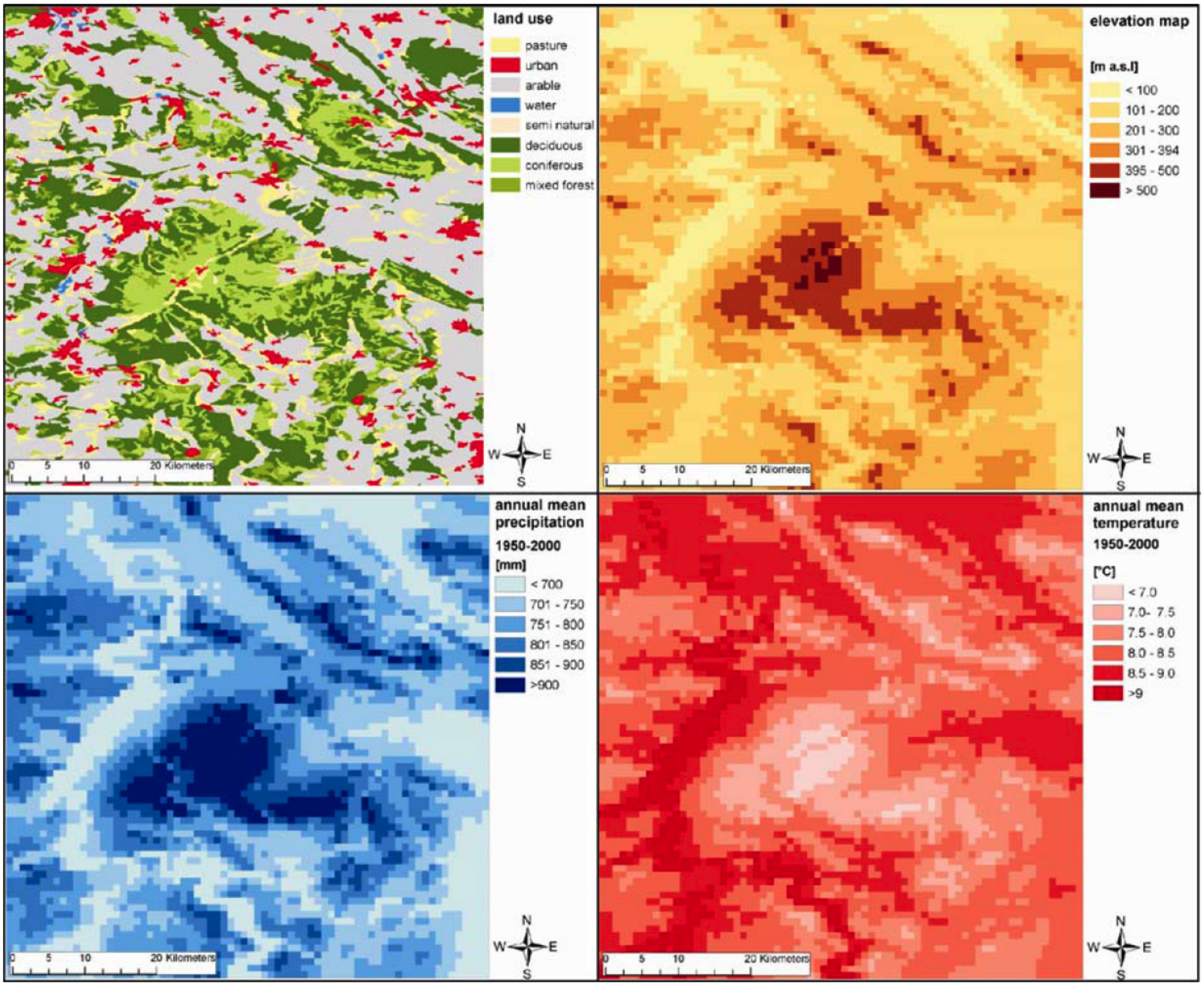

Fig. (1). Map of Solling site showing the different land-use classes (left upper panel), elevation (right upper panel), the annual mean precipitation (left lower panel) and the annual mean temperature (right lower panel). Data sources: [23] and CORINE Land Cover 2000; Umweltbundesamt, DLR-DFD 2004.

classification we used the program Triangle [42]. 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 parameterized the forest floor with the hydraulic parameters for peat [43].

Estimating Root Parameters

In general, the architecture of root systems is mainly influenced by the parent material, the soil type, bulk density, the chemical soil conditions, the depth of ground water, and the species and age of trees. Despite the published results of experimental researches, the rooting depth and root distribution in the soil profile are difficult to estimate and therefore are critical model parameters. For the estimation of the effective rooting depth (ERD) we used the linking rule from [13]. The relative root density was modeled as a function of soil depth using a modification of the second equation from [24]:

$$f = 1 - 0.5^{z/h} \tag{3}$$

where f is the fraction of roots above depth z, and h is the depth at which $f = 0.5$. We recalculated h from the effective rooting depth (ERD) and a constant, calculated from h and ERD given in [24]:

$$h = \frac{ERD}{6.64} \tag{4}$$

Specific Parameters for Tree Species

For most parameters we used the values from standard BROOK90 parameter set for temperate forest [26]. Table **3** provides an additional overview of sensitive factors for the two tree species used in this study. The leaf area index (LAI) of a stand is a key parameter in modeling the canopy characteristics. Defined as the projected leaf area per unit surface area of the ground, it exhibits a strong effect on the water budget of forest ecosystems and therefore is used as an input for process-based hydrology models [24]. It is a

Table 1 Soil Hydraulic Parameters by Texture Class from [40] at Saturation (Subscript s) and at the Upper Limit of Available Water (Subscript fc) Taken from [24]

Texture Class	b	θ_S	Ψ_S	K_s	fi	θ_{fc}	Ψ_F	K_u	θ_r	θ_{ac}
Unit	-	cm³/cm³	kPa	mm Day^{-1}	-	cm³/cm³	kPa	mm Day^{-1}	cm³/cm³	cm³/cm³
clay	11.40	0.482	-1.82	111	0.94	0.425	-7.7	4.3	0.261	0.164
sandy clay	10.40	0.426	-0.60	187	0.93	0.358	-3.7	2.94	0.195	0.162
silty clay	10.40	0.492	-1.71	89	0.93	0.433	-6.5	4.22	0.249	0.183
loam	5.39	0.451	-1.43	600	0.92	0.324	-8.5	6.27	0.118	0.206
clay loam	8.52	0.476	-3.54	212	0.92	0.402	-14.8	7.31	0.226	0.176
silty clay loam	7.75	0.477	-1.43	147	0.92	0.397	-6.0	4.87	0.187	0.209
silt loam	5.30	0.485	-5.55	622	0.92	0.365	-25.0	13.13	0.160	0.205
silt[1]	5.30	0.485	-5.55	622	0.92	0.365	-25.0	13.13	0.160	0.205
sandy clay loam	7.12	0.420	-0.85	544	0.92	0.317	-6.3	4.21	0.141	0.176
sandy loam	4.90	0.435	-0.70	2995	0.92	0.266	-7.9	5.47	0.086	0.180
sand	4.05	0.395	-0.34	15206	0.92	0.188	-7.0	3.96	0.046	0.141
loamy sand	4.38	0.410	-0.17	13507	0.92	0.203	-3.8	3.51	0.049	0.155

[1]Taken from silt loam because there is no silt at [40]. Declaration: b: a pore-size distribution parameter; θ: volumetric water fraction; θ_r: residual soil water content; θ_{ac}: available water fraction; ψ: the matrix potential; K: hydraulic conductivity; fi: Clapp-Hornberger inflection point.

variable depending on stand structure, tree species and age. Our modeling approach is based on the equation described by [44]:

$$LAI = \frac{M_{lit} \cdot (1 + F_{abs}) \cdot SLA}{F_t} \tag{5}$$

where M_{lit} is the annual foliage litterfall (kg m^{-2} a^{-1}), SLA is the one-sided specific leaf area of foliage (m² kg^{-1}) (Table **2**), F_t is the annual foliage turnover rate (kg a^{-1}) and F_{abs} is the fractional mass loss on abscission (F_{abs} = 0.15, [44]). Assuming that there is an exponential relationship between temperature and foliage turnover (F_t = a exp(b·T) [45]), we can rewrite equation 5 as follows:

$$LAI = \frac{M_{lit} \cdot (1 + F_{abs}) \cdot SLA}{a \cdot EXP(b \cdot T)} \tag{6}$$

M_{lit} can be estimated with a modified allometric function for each tree species [45]:

$$M_{lit} = EXP(b_0 + b_1 \cdot \ln(DBH) + b_2 \cdot T) \cdot (n / 10000) \tag{7}$$

where n is the number of trees per hectare, DBH is the diameter at breast height (cm), T is AMT (°C), and b_0 to b_2 are tree specific regression parameters.

Replacing M_{lit} in (6) with (7) LAI can be calculated as

$$LAI = \frac{e^{(b_0 + b_1 \cdot \ln(DBH) + b_2 \cdot T) \cdot} (n / 10000) \cdot (1 + F_{abs}) \cdot SLA}{a \cdot EXP(b \cdot T)} \tag{8}$$

At a AMT of about 0°C we set the parameter "a" as foliage turnover rate for 0°C ($F_{t,0}$).

$$LAI = \frac{e^{(b_0 + b_1 \cdot \ln(DBH)) \cdot} (n / 10000) \cdot (1 + F_{abs}) \cdot SLA}{F_{t,0}} \tag{9}$$

In regions with an AMT about 0°C (Northern Sweden and Northern Finland) turnover rates from amounts of litter and living needle biomass of Norway spruce and Scots pine show values between 0.1 and 0.15 a^{-1} [46, 47]. Therefore we set this parameter to 0.125 for all coniferous tree species, knowing that this is a critical model parameter. Because the turnover of needles was estimated from litterfall and living biomass we do not take into account the fractional mass loss on abscission for coniferous forests. The parameter for the litterfall model was taken from [48]. For modeling the intra-annual variability of LAI, a growing-season phenological model was introduced to simulate the influence of temperature on the start [49, 50] and the end [51] of the growing season. The result is a model to simulate the temporal and spatial LAI dynamics. The approach allows the robust computation with a low parameter demand.

For the estimation of stem area index (SAI) we used the functions after [52] and [28]:

$$SAI = a \cdot DBH^b \cdot (n / 10000) \cdot c \tag{10}$$

where n is the number of trees per hectare, DBH is the diameter at breast height (cm), a and b are regression parameters (a= 0.0192; b = 2.0947 for beech and a= 0.0553; b = 1.9769 for spruce) and c is the correction coefficient for projected stem area (c = 0.5).

Target Diameter Harvesting Scenarios

To estimate the effects of TDH on drought stress under climate change conditions we run three scenarios for each tree species. As reference unmanaged stands for beech (be1) and spruce (sp1) we use mature stands of the second yield class [53] with a DBH correction according to [54]. In the second variant of beech (be2) all trees are harvested with DBH ≥ 60 cm. In the third variant (be3) the target diameter for harvesting was DBH ≥ 50 cm. The two different utilisation scenarios for spruce are harvesting all trees with DBH ≥ 45 cm (sp2) and DBH ≥ 40 cm (sp3). The diameter distribution and the effects of these harvesting scenarios on

Table 2. Descriptive Statistics of Specific Leaf Area [m^2 kg^{-1}] for Chosen Tree Species

Tree Species	Mean	Median	Min	Max	sd	cv %	n
Norway Spruce	4.43	4.48	3.20	5.65	0.58	13.18	34
European Beech	21.01	21.29	13.9	24.72	2.43	11.57	38

Data sources: [56-66]. Declaration: sd: standard deviation, cv: coefficient of variation.

Table 3. Stand Characteristics and Model Parameters for Different Harvest Intensities of Norway Spruce and European Beech

Parameter	Unit	Norway Spruce			European Beech			Source
Variant		sp1	sp2	sp3	be1	be2	be3	
age	years	90	90	90	120	120	120	[53]
stand density	tree ha^{-1}	371	294	222	202	171	131	[53]
tree height	m	27.5	26.8	26.1	30.3	30.2	29.3	[53]
DBH	cm	38.6	35.8	33.4	44.6	43.9	40	[53]
solid volume	$m^3_{(S)}ha^{-1}$	519	351	228	486	395	243	[53]
max leaf conductance	cm s^{-1}	0.53	0.53	0.53	0.53	0.53	0.53	[24]
max leaf area index	m^2 m^{-2}	6.6	4.6	3.1	7.2	5.1	3.4	eq 9
relative winter LAI	[-]	0.8	0.8	0.8	0.0	0.0	0.0	[28]
SAI	m^2 m^{-2}	1.40	0.96	0.63	0.55	0.45	0.29	eq 10
fine root length	m m^{-2}	3100	3100	3100	3000	3000	3000	[24]
critical leaf water pot.	MPa	-3.5	-3.5	-3.5	-2.6	-2.6	-2.6	[13]
albedo	[-]	0.14	0.14	0.14	0.14	0.14	0.14	[24]
albedo with snow	[-]	0.14	0.14	0.14	0.23	0.23	0.23	[24]

Declaration: SAI: stem area index, DBH: diameter at breast height.

the mean stand characteristics are modeled with the forest simulator BWinPro7 [55]. The resulting stand parameters are summarized in Table **3**.

Preprocessing of GIS Coverage's and Input Datasets

We used the spatial information to produce a "master table" for model runs with the unique attributes of each coverage within the model area. The first step was to construct this table in ArcGis (Version 9.2; ESRI inc., Redlands, CA), which is the unique intersection of the climate, soil and land-use GIS-data layers. In the second step the constructed dataset is used for the initialization of the model runs. The BROOK90 simulations were only run for forest sites. To simulate the mixed stands with equal shares of beech and spruce the simulations were carried out for pure spruce and beech stands separately and the results were averaged with correspondent (in this case - equal) shares [27].

Start and Boundary Conditions

The simulation period started on the 01.01.1960, whereby the evaluations were performed for the following 30-years periods: P0: 1981-2010, P1: 2011-2040, P2: 2041-2070, P3: 2071-2100. Due to the long initialization time from 1960 to the first analysis period the soil profiles were assumed to be saturated at the beginning, with an initial matrix potential of -10 kPa for all locations and horizons. To speed up the calculations, the partial differential equations were solved with a maximum of 20 iterations per day. The minimum allowed iteration time step for BROOK90 is "2" [26]. The maximum change in soil wetness or saturation fraction for any layer in iteration was set to 0.5%. In some very rare cases this parameter was automatically changed when there was a serious water balance problem (> 0.006 mm). For all soils at the lower border of the soil (2 m) free drainage was accepted.

RESULTS AND DISCUSSION

Climate Conditions

To characterize the projected climate conditions in 21st century in Solling area the CLM-data were post-processed according to the recommendations of [67]. The data of A1B_1, A1B_2, B1_1 and B1_2 are aggregated to annual means (sums in case of precipitation). Spatial averaging over the 9 CLM grid points to represent the study area is carried out for all mentioned climate characteristics.

The spatial variations within the chosen area are very low so that the spatial means are assumed to be representative. To describe the tendencies of climate development the spatial mean values are averaged over the 30-years periods: P0-P3 and relative differences are calculated: $\Delta\varphi i = (\varphi_i - \varphi_0)/\varphi_0 * 100\%$, where φ_i is the 30-years mean value of the spatially averaged climate variable (air temperature or precipitation) for the climatic period i = 1, 2, 3. The analysis of climate scenarios data shows (Fig. **2**) for both scenarios an increase of precipitation to $\Delta P_1 \approx 6\%$ and then a slight monotone decrease towards 2100 to $\Delta P_3 \approx 5\%$. However, air and soil temperatures increase monotonically and rather strongly towards P3 with $\Delta T_3 > 37\%$ in A1B and $\Delta T_3 > 24\%$ in B1 (Fig. **3**).

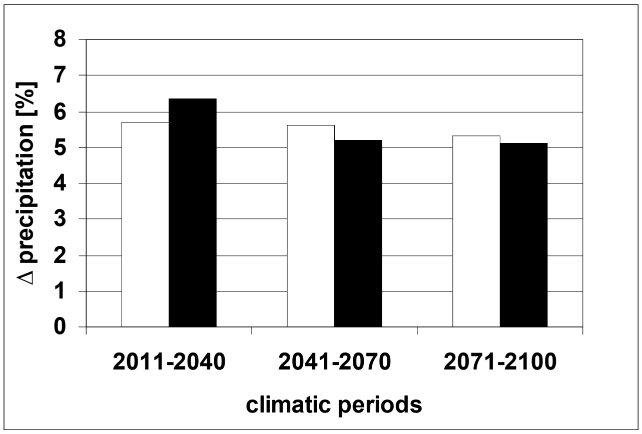

Fig. (2). The changes of annual mean values of precipitation sum averaged over 30-years climatic periods relatively to the reference period (P0= 1981-2011) for two SRES scenarios: □: A1B and ■: B1.

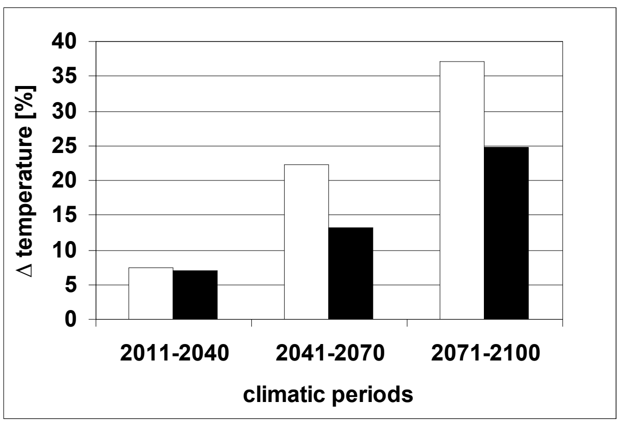

Fig. (3). The changes of annual mean values of temperature averaged over 30-years climatic periods relatively to the reference period (P0= 1981-2011) for two SRES scenarios: □: A1B and ■: B1.

Leaf Area Index

The dynamic and spatial distribution of leaf area is a very sensitive model parameter. This is especially true for the modeling of TDH effects on drought. The dynamic of LAI over a whole rotation period was simulated for each tree species using the growth models from [53]. To compare and evaluate the model we used a set of completely independent literature data. The Fig. (**4**) gives an impression on the quality of estimated LAI. These tests show, that the models satisfactorily estimate the LAI dynamic over a whole rotation period. There is a good level of determination and the agreement between observed and simulated values. However, for beech a systemic underestimation of LAI is observed for some stands. Still it can be concluded that the model yields rather good LAI estimations. Fig. (**5**) shows that the modeled seasonal variations of LAI for beech and spruce under projected future climate conditions for the investigation area correspond to published results [28].

Rooting Depth

Another important difference between spruce and beech forests is the architecture of their root systems. Due to the deeper rooting, the beech is able to utilize water reservoirs in deeper soil horizons. In contrast, the root system of spruce is characterized by a more superficial orientation, especially under sandy and clay soil conditions. In Table **4** the different relative vertical root distribution for different tree species and texture classes used in the model are presented. The *f*-values are rounded to the nearest 0.01.

Model Results and Discussion

For mapping the impact of TDH on spatial and temporal pattern of drought risk the model results were post-processed. The data of A1B_1, A1B_2, B1_1 and B1_2 are aggregated to period means and plotted by the intersection of soil type, forest type, and climate region. The results are the absolute difference of DSD in the reference period (P0) and stands (sp1 and be1) to the absolute value for different harvest diameter regimes (sp2-sp3 / be2-be3) and climate conditions (P1-P3).

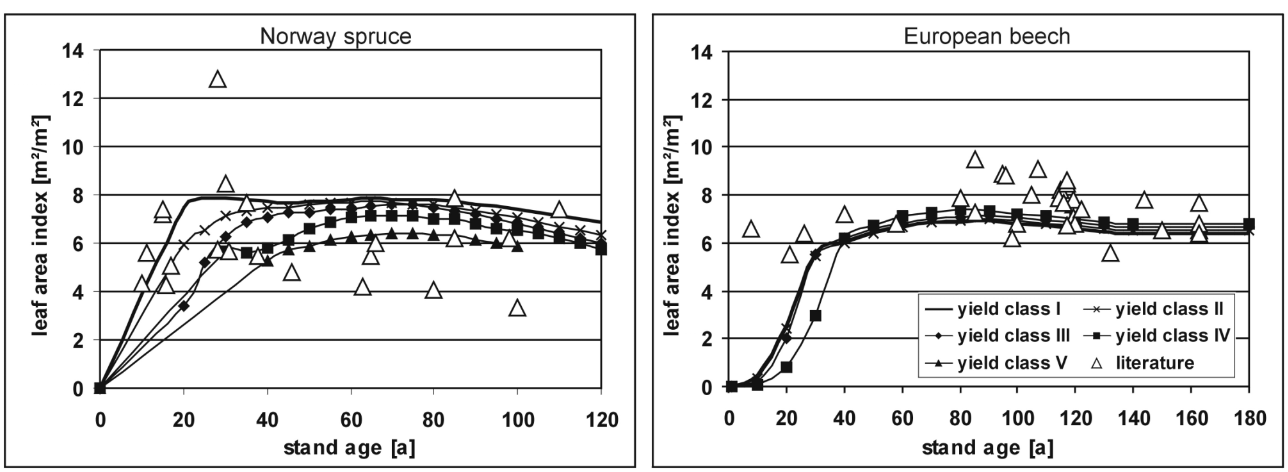

Fig. (4). Simulated long-term dynamic of leaf area index compared with literature data (left site: spruce and right site: beech). Data sources: [28, 56, 68-72].

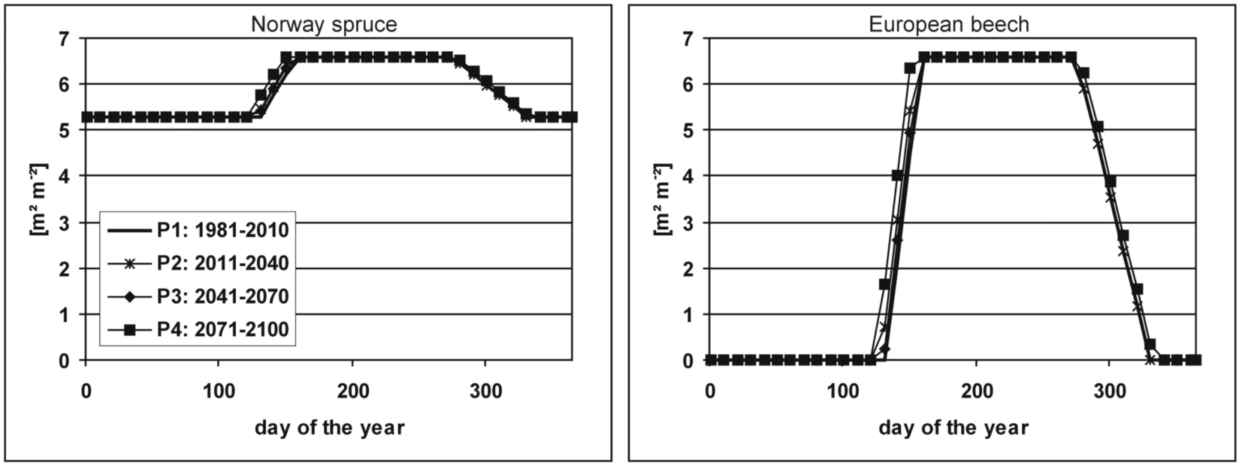

Fig. (5). Simulated seasonal variation of leaf area index for spruce and beech sites under climate change conditions in the investigation area (left site: spruce and right site: beech).

Table 4. Example for the Relative Vertical Root Distribution by Tree Species and Soil Texture Up to the Effective Rooting Depth

Depth	Norway Spruce				European Beech			
cm	Sand	Loam	Silt	Clay	Sand	Loam	Silt	Clay
10	0.35	0.34	0.28	0.42	0.26	0.25	0.21	0.32
20	0.23	0.22	0.20	0.24	0.19	0.19	0.16	0.22
30	0.15	0.15	0.15	0.14	0.14	0.14	0.13	0.15
40	0.10	0.10	0.10	0.08	0.11	0.11	0.10	0.10
50	0.06	0.07	0.08	0.05	0.08	0.08	0.08	0.07
60	0.04	0.04	0.05	0.03	0.06	0.06	0.07	0.05
70	0.03	0.03	0.04	0.02	0.04	0.04	0.05	0.03
80	0.02	0.02	0.03	0.01	0.03	0.03	0.04	0.02
90	0.01	0.01	0.02	0.01	0.02	0.03	0.03	0.01
100	0.01	0.01	0.01	-	0.02	0.02	0.03	0.01
110	-	0.01	0.01	-	0.01	0.01	0.02	0.01
120	-	-	0.01	-	0.01	0.01	0.02	-
130	-	-	0.01	-	0.01	0.01	0.01	-
140	-	-	-	-	-	0.01	0.01	-
150	-	-	-	-	-	-	0.01	-
160	-	-	-	-	-	-	0.01	-
170	-	-	-	-	-	-	0.01	-
180	-	-	-	-	-	-	-	-
190	-	-	-	-	-	-	-	-
200	-	-	-	-	-	-	-	-

A comparison of tree species effects on DSD is given in Fig. (**6**). The plotted values are area weighted average values for spruce and beech in the investigation area.

The Fig. (**6**) clearly demonstrates that under the "present climate conditions" the spruce stands have a higher drought stress duration than the beech stands, due to their higher winter LAI values (Table **3**) and shallower root system [13]. The differences between the tree species are substantially smaller in the subsequent periods. On the one hand this could be an effect of rising temperatures associated with climate change and leading to a longer vegetation period (Fig. **5**). These changes are better pronounced for beech than for spruce because of the higher differences between their winter and summer LAI (see Table **3**). On the other hand

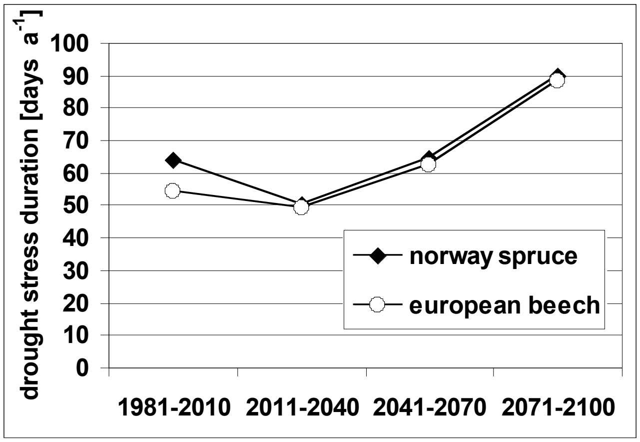

Fig. (6). Scenarios of drought stress duration (days per year) for the different tree species, SRES scenario A1B and forest management variants sp1 and be1.

a further impact results from the increment of precipitation (Fig. **2**), which will not be normal distributed over the year. The climate data for study area shows a clear increase in winter precipitation and a decrease in summer precipitations. By the higher amounts of winter precipitation the soil water storage could be totally refilled. Under these climate conditions and soils with relatively low water storage capacity the restore is nearly independent from the LAI in the winter.

At this point it must be mentioned that the available soil water content of the forest soils derived from the digital soil map of Germany in the Solling region [39] could raise a problem for the assessment of absolute drought stress. Comparing these values with other investigations in the same area [73] the field capacity of the soils is underestimated. Most probably the solifluction layer of loess material with the loamy texture and relatively high clay- and relatively low stone content is underrepresented in the current scale of the used soil map. Therefore the absolute drought stress duration

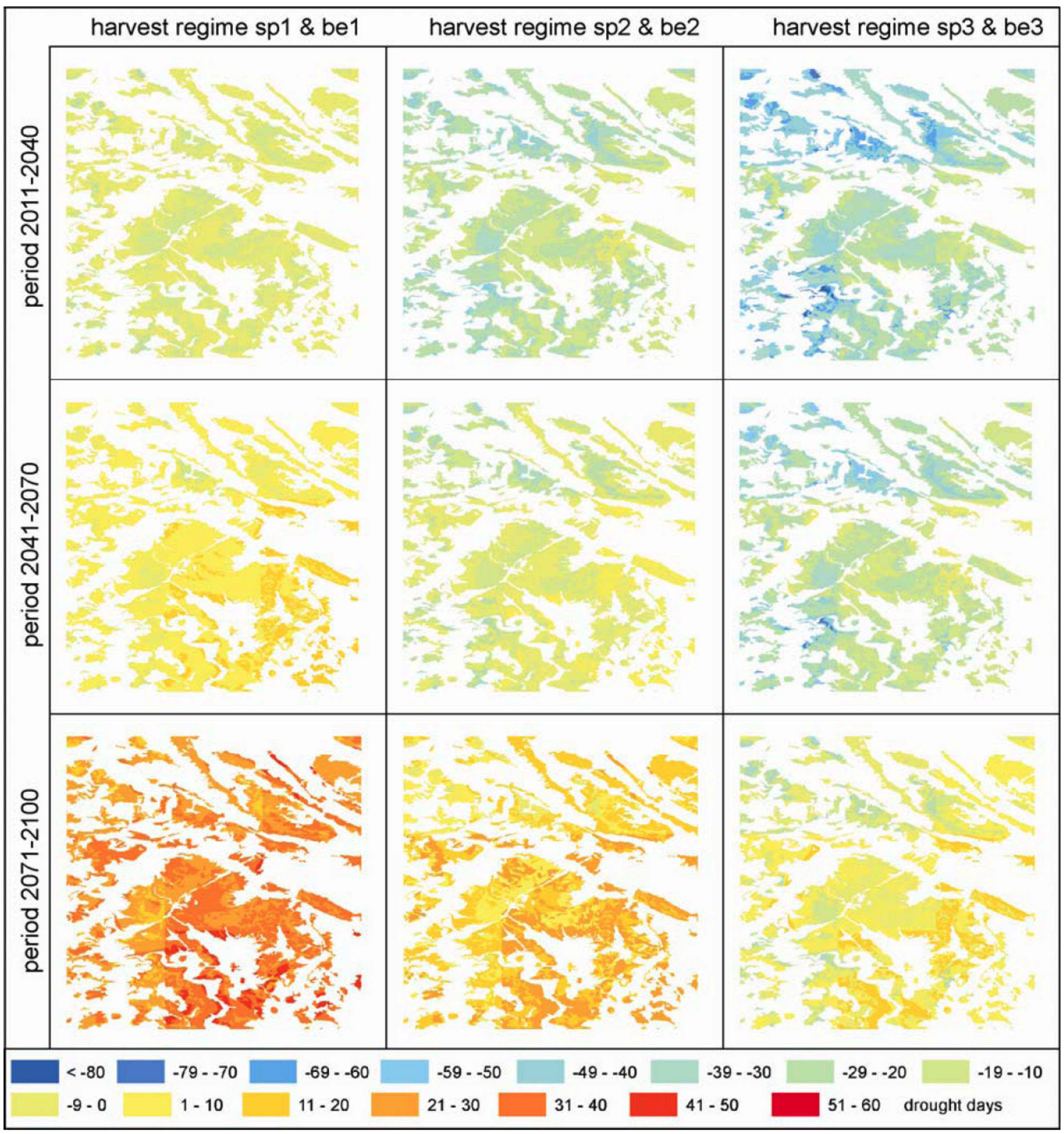

Fig. (7). Scenarios of spatial and temporal drought stress variation in forest ecosystems for different target diameter harvesting regimes under A1B climate change conditions, presented as mean yearly differences of drought duration for a given period.

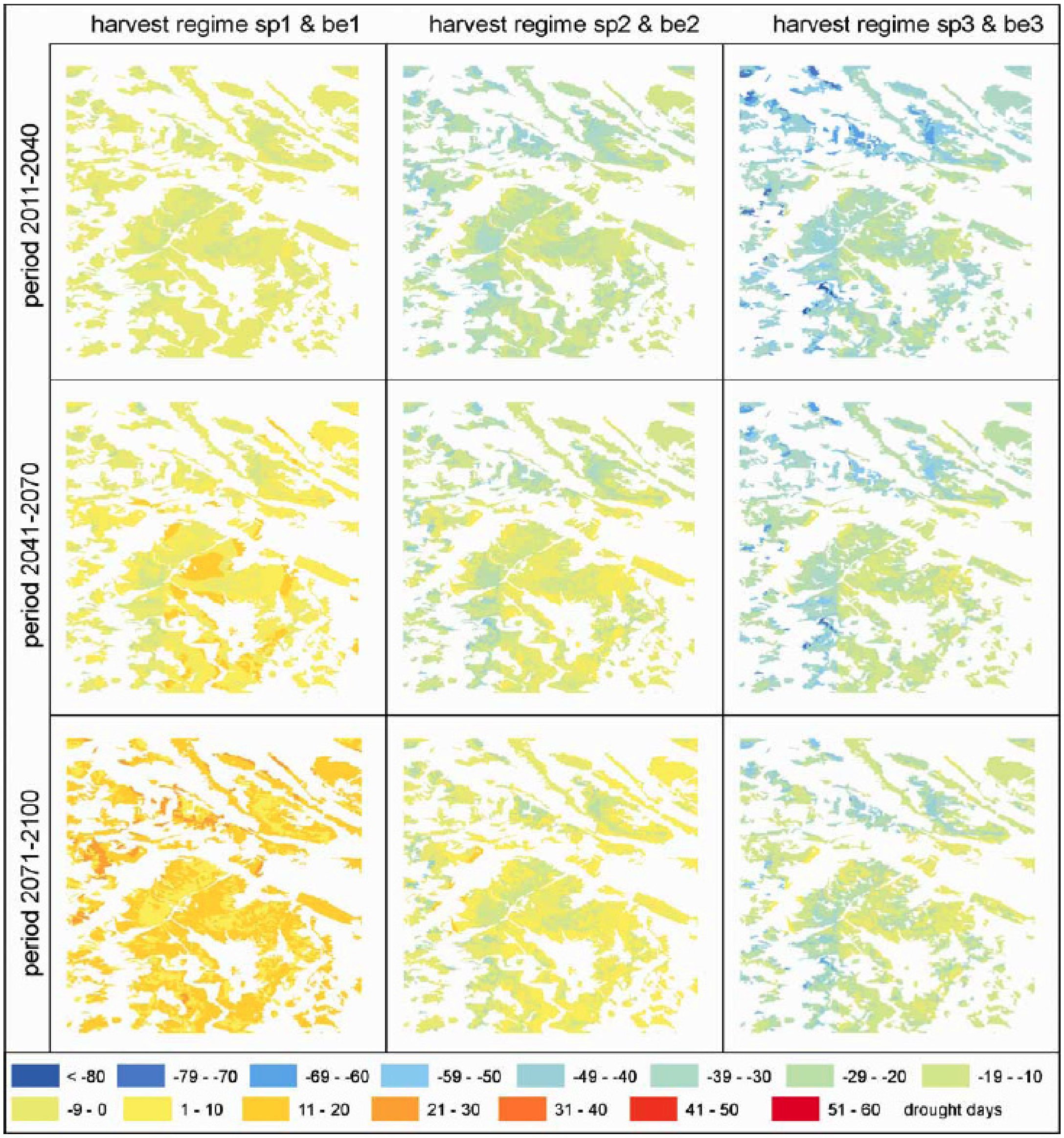

Fig. (8). Scenarios of spatial and temporal drought stress variation in forest ecosystems for different target diameter harvesting regimes under B1 climate change conditions, presented as mean yearly differences of drought duration for a given period.

seems to be slightly overestimated for this region. For example in 2003 [35] found water stress durations of 28 to 172 days in various forest ecosystems in Europe. However for a further discussion of temporal and spatial trends the dataset is sufficient.

When estimating the trends of DSD in 21st century (Figs. **7**, **8**) comparing to present conditions, i.e. comparing the projected drought for periods 1, 2, 3 to the reference P0, it is obvious that the values generally decrease from P0 to P1 and sometimes even to P2 and then increase towards 2100. The decrease in drought risk in the first period could be explained by the increase of precipitation (Fig. **2**). For this period the additional water flux from precipitation is higher than the increase of evaporation due to the increase of air temperature (Fig. **3**). The changes at the end of the century are considerably higher than "present conditions". The changes are generally stronger under A1B (Fig. **7**) than under B1 conditions (Fig. **8**).

The contribution of structure changes caused by TDH to drought risks is generally higher for spruce than for beech. However, in each particular case the value and sign of these contributions are of more complicated character depending on combination of scenarios, tree species, and soil types. The spatial pattern of drought calculated considering variants sp/be2-3 is similar to the pattern of "standard" simulation itself but shows lower values for all species and soils. A more intensive TDH strongly reduces the drought stress intensity in all periods. As expected the effect of intensive harvesting regime is very high on spruce sites with the lowest extractable soil water capacity (< 100 mm) on sandy soils with high stone content.

The impact of TDH also shows that the main uncertainty of our approach is linked to the estimation of LAI, as the latter is highly dependent on tree species and stand structure. The results show that LAI is one of the crucial parameters determining model response of evapotranspiration, runoff and accordingly duration of drought stress [24]. We lack data covering the whole variety of combinations of tree species and competition situations. Thus, any general rule on LAI estimating, like we have used for this approach and the following modeling, may provide some average LAI value, but not all specific situations for different TDH regimes.

An additional uncertainty results from the impact of ground vegetation, which is not included in the simulations. Especially in forest with opened up canopy the proportion of understorey is high and consequently the evapotranspiration rate is enhanced [74, 75].

Another crucial parameter is the estimation of the effective rooting depth and the relationship between plant water status and the depletion depth of the plant rooting system. During extreme drought events plants seem to be able to adapt the depletion depth temporarily below the ERD [76], but this cannot be included in our approach. Much more work on ERD and distribution is clearly needed [24].

CONCLUSIONS

The results of present study show: (1): considerable increment of drought risks towards 2100 compared to "present climate conditions", caused by changes in intraannual precipitation distribution and increase of mean air temperature, (2): the decrease in drought risks in the first period could be explained by the increase of precipitation and the only slight increase of temperature in this period, (3): the changes are generally stronger under A1B than B1 conditions and (4): for Solling sites the changes of structure and microclimate caused by different TDH scenarios, provide a decrease of drought stress. The magnitude of this decrease could almost compensate the increase of drought risks induced by climate warming.

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