Universität Potsdam, Geoökologie

Model-based analysis of climate change impacts on the productivity of oak-pine forests in Brandenburg

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Summary

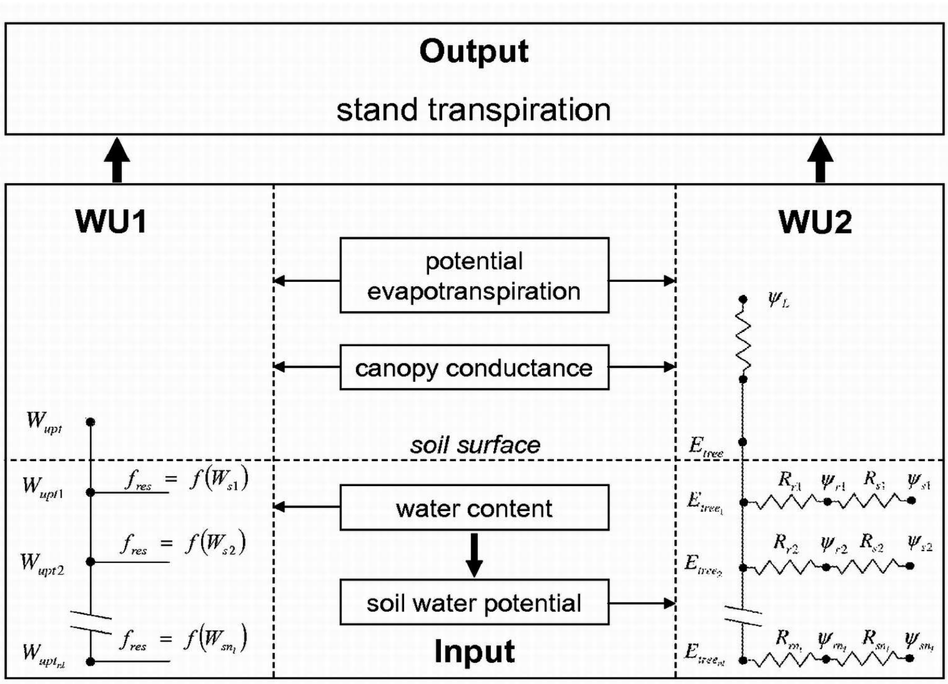
The relationship between climate and forest productivity is an intensively studied subject in forest science. This thesis is embedded within the general framework of future forest growth under climate change and its implications for the ongoing forest conversion of pure pine forests into mixed oak-pine forests. My objective is to investigate future forest productivity at different spatial scales (from a single specific forest stand up to aggregated information for Germany as a whole) with a focus on oak-pine forests in the federal state of Brandenburg. The overarching question is: how are the oak-pine forests affected by climate change described by a variety of climate scenarios? I answer this question by using a model-based analysis of tree growth processes and responses to different climate scenarios with an emphasis on drought events. In addition, a method is developed which considers climate change uncertainty of forest management planning.
As a first 'screening' of climate change impacts on forest productivity, I calculated the change in net primary production (NPP) on the basis of a large set of climate scenarios for different tree species and the total area of Germany. To account for uncertainties associated with climate change projections, it is necessary to use a broad variety of climate change scenarios to derive probabilities of the expected impacts. In process-based models this comes at the cost of large amounts of computing time. These limitations can be circumvented by applying static reduced models (SRM). The term static reduced

model is used to separate it from time-sensitive dynamic models and complex process-based models with a high parameter demand. In my work, the SRMs are developed by regression analyses from a large amount of NPP data generated with a dynamic process-based forest model. I rely on simulated data, since only limited NPP measurement data from forest experimental sites with varying site conditions and forest species are available. Particular, there is a deficit in long-term time series of measurements of carbon fluxes. The SRMs are multiple regression models which were generated with modelled NPP values and independent climate and soil variables.

$$\begin{aligned}\log\left(Y_{NPP_{SRM}}\right) &= \alpha + \beta_1 \left(\log X_W\right) + \beta_2 \left(\log X_{CN}\right) \\ &+ \beta_3 \left(\log X_T\right) + \beta_4 \left(\log X_R\right) \\ &+ \beta_5 \left(\log X_D\right) + \beta_6 \left(\log X_D^2\right) \\ &+ \beta_7 \left(\log X_W \log X_{CN}\right) + \varepsilon\end{aligned}$$

$Y_{NPP_{SRM}} \ldots$ annual average net primary production [t C $ha^{-1}year^{-1}$]
$X_W \ldots$ plant available water [mm]
$X_{CN} \ldots$ carbon/nitrogen ratio of the soil
$X_T \ldots$ mean annual temperature [°C]
$X_R \ldots$ mean annual radiation [J cm^{-2}]
$X_D \ldots$ drought index [days], mean annual number of successive days without rain in the growing season
$\alpha \ldots$ intercept of regression
$\beta_i \ldots$ regression coefficients
$\varepsilon \ldots$ residual variance

In this first chapter I used seven climate scenarios generated with STAR 2.0, assuming a 0.5 K stepwise increase of temperature up to 3 K to calculate the NPP under climate scenario conditions. For example, the 2 K climate scenario contains a temperature increase of 2 K in 2060 against the starting point of the scenario in 2007. For each of the seven climate scenarios (0 K, 0.5 K, , 3 K) 50 realizations were available. All in all, the SRMs were then run with seven times 50 climate realizations.
The NPP simulations show two main findings. Temperature increase up to 3 K leads to positive effects on the net primary production of all four selected tree species. However, in water-limited regions this positive net primary production trend is dependent on the length of drought periods which results in a larger uncertainty regarding future forest productivity. One of the regions with the highest uncertainty regarding net primary production development is the federal state of Brandenburg.
To enhance understanding on the model-based analysis of tree growth sensitivity to drought stress and improve its capability, two water uptake approaches in pure pine and mixed oak-pine stands are contrasted. The first water uptake approach consists of an empirical function for root water uptake. The second approach is more process-based and calculates the differences of soil water potential along a soil-plant-atmosphere continuum. I assumed the total root resistance to vary at low, medium and high total root resistance levels. In this second result chapter, I simulate two pure pine stands

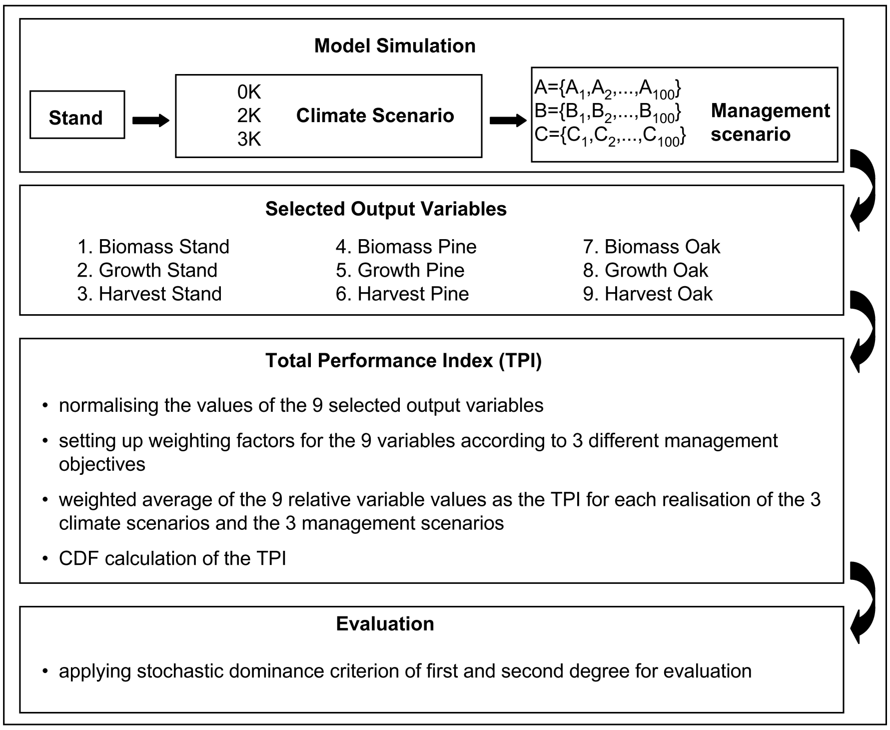


Overview of the two water uptake approaches with the considered model components. With W_{upt} and E_{tree} = sum of water uptake of a tree over n_l number of soil layers, W_s = soil water content, R_r = root resistance, R_s = soil resistance, ψ_L = leaf water potential, ψ_r = root water potential, ψ_s = soil water potential.

and two mixed oak-pine stands. For validation purposes three data sets on different tree-growth-relevant time scales are used: a) transpiration data for a pure pine forest stand at a daily scale, b) soil water potential data for two pure pine stands, and c) long-term tree ring chronologies for all four forest stands. Results show that, except for the mechanistic water uptake approach with high total root resistance, all transpiration outputs exceeded observed values. On the other hand high transpiration led to a better match of observed soil-water content. The strongest correlation between simulated and observed annual tree-ring width occurred with the mechanistic water uptake approach and high total root resistance. The findings highlight the importance of severe drought as a main reason for small diameter increment, best supported by the mechanistic water uptake approach with high root resistance. However, if all aspects of the data sets are considered neither approach can be judged to be superior to the other. I conclude that the uncertainty of future productivity of water-limited forest ecosystems under changing environmental conditions is linked to simulated root water uptake.
Finally my study aimed at examining the impacts of climate change combined with management scenarios on an oak-pine forest to evaluate growth, biomass and the amount of harvested timber. The pine and the oak trees are 104 and 9 years old respectively and represent a typical stand for the ongoing forest transformation process. Three different management scenarios with different thinning intensities and different climate scenarios

are used to simulate the performance of management strategies which explicitly account for the risks associated with achieving three predefined objectives (maximum carbon storage in the forest stand, maximum harvested timber, intermediate with respect to harvest and carbon storage). For the decision process an indicator has been developed which I call the total performance indicator (TPI). The stochastic dominance criterion, which is based on the cumulative distribution function of the TPI, defines the ranking of the management strategies.

I found that in most cases there is no general management strategy which fits best to



Overview of the methodological approach used in the third result chapter of the thesis.

different objectives. However, the cumulative distribution function of the TPI enables an effective comparison of different management strategies under climate change uncertainty. From the physiological forest model perspective, climate warming up to three kelvin leads to mainly positive impacts on tree growth of oak and pine. The analysis of variance in the growth-related model outputs showed an increase of climate uncertainty under increasing climate warming. Interestingly, the increase of climate-induced uncertainty is much higher from two to three kelvin than from zero to two kelvin. This highlights the non-linear behaviour of forest stand production which accompanies temperature increase.

To sum up all the findings of my work, my main conclusions are:

- up to three kelvin, the modelled climate change effects are mainly positive in terms of oak and pine forest stand production and from a modelling perspective there are only minor risks for the ongoing forest conversion,

- this finding is limited, thus current process-based forest growth models do not consider disturbances such as insect calamities or wind damage, which represent one of the major challenges for future modelling research,
- water-limited forest sites, especially those in the north-eastern lowlands with a drier climate, show the largest uncertainty with respect to forest production and sensitivity to drought periods under climate scenario conditions,
- to reduce this uncertainty process-based forest growth models have to incorporate the water uptake process by roots at the process level,
- model-based analysis of future forest growth and management under uncertain climate conditions and varying long-term objectives can be supported by using the total performance indicator and the stochastic dominance criterion.