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Productivity of *Fagus sylvatica* under climate change – A Bayesian analysis of risk and uncertainty using the model 3-PG

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A B S T R A C T

To assess the long-term impacts of forest management interventions under climate change, process-based models, which allow to predict transient dynamics under environmental change, are arguably the most suitable tools available. A challenge for using these models for management decisions, however, is their higher parametric uncertainty, which propagates to predictions and thus into the decision-making process. Here, we demonstrate how this problem can be addressed through Bayesian inference. We first conduct a Bayesian calibration to generate an estimate of posterior parametric uncertainty for the process-based forest growth model 3-PG for *Fagus sylvatica*. The calibration uses data from twelve sites in Germany, together with a robust (Student's t) error model. We then propagate the estimated uncertainty together with economic uncertainty to forest productivity and Land Expectation Value (LEV), allowing us to evaluate alternative management regimes under climate change. Our results demonstrate that parametric and economic uncertainty have strong impacts on the variation of predicted forest productivity and profitability. Management regimes with increased thinning intensity were overall most robust to economic, climate change and parametric model uncertainty. We conclude that estimating and propagating economic and model uncertainty is crucial for developing robust adaptive management strategies for forests under climate change.

1. Introduction

European beech (*Fagus sylvatica* L.) is the most abundant broad-leaved tree species in Central Europe (Bohn et al., 2003; Ellenberg, 1996). Due to its high shade tolerance, it would naturally dominate large parts of the region, particularly in Germany (Christensen et al., 2005). In the recent past, markedly during the last 200 years, large areas originally dominated by beech forests were replaced by faster growing conifer species, e.g. Norway Spruce (*Picea abies*) and Scots Pine (*Pinus sylvestris*), with the aim of reestablishing forests on degraded land, increasing forest profitability and supplying wood for the forest industry (Spiecker, 2003). The focus of forest management, however, has shifted during the past decades towards a multipurpose approach. A consequence of this change in values is an increasing interest in recovering the naturalness of European forests. Efforts are thus being made to adopt close-to-nature management systems, increase the complexity of forest stands and promote the natural vegetation (Brunet et al., 2010). The restoration of natural forest composition is also motivated by the objective to recover forest biodiversity and ecosystem functioning in degraded forests ecosystems (Burton and Macdonald, 2011). For example, the forest administration of Baden-Württemberg describes beech-dominated forests as an especially valuable forest type, due to its perceived closeness to nature and connectivity function. Therefore, the long-term goal of the forest administration is to increase the proportion of this type of forests (LFBW, 2014).

One of the most important management recommendations for forest restoration and rehabilitation is restoring the species composition and stand structure of natural forests (Halme et al.,

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2013). At the same time, however, when planning an increase of the share of *Fagus sylvatica*, it is crucial to take into account future climate development (Ravenscroft et al., 2010). Climate change is predicted to affect important forest processes, such as carbon assimilation, water balance, nutrient cycling, species distributions and disturbance regimes (Davis et al., 2017; Laflower et al., 2016; Pan et al., 2011; Seidl et al., 2014; Tarancón et al., 2014). Hence, it is crucial for managers and decision-makers to evaluate the behavior of beech stands under climate change, assess the suitability of forest policies targeted at increasing the share of this species, and avoid risks that might lead to a loss of ecosystem functioning or profitability.

Arguably the most suitable tool to assess the impacts of novel climatic conditions on forest ecosystems are process-based forest models. The advantage of these models over more empirical or statistical models is that they are built on explicit processes and interactions in forest ecosystems that describe not only demography and stand structure, but also carbon, water and nutrient cycles (Busing et al., 2007; Friend et al., 1997; van Oijen et al., 2005). As such, they should be better suited to predict forest responses to environmental changes (e.g. alterations in atmospheric CO_2, precipitation regimes, air temperature, nitrogen deposition, etc.), as well as transient dynamics (Hartig et al., 2012). Because of these advantages, many studies have applied process-based forest models at different spatial and temporal scales for evaluating forest responses to climate change (e.g. Koca et al. 2006; Morin and Thuiller, 2009; Rollinson et al., 2017), risks related to climatic changes (e.g. Allen et al., 2010; Cailleret et al., 2014; Soja et al., 2007) forest productivity (e.g. González-García et al., 2016) or shifts on species distribution (e.g. Morin et al., 2007; Snell et al., 2014).

For forest management, one of the most important outputs of these models is productivity in biomass and wood volume. Productivity is not only decisive for the commercial value of the forest (Liang et al., 2016), but typically also correlates with other important ecosystem services (Bonan, 2008; de Groot et al., 2002; Tilman et al., 2012). Forest managers can use productivity estimates to plan and evaluate different management options and adjust management plans accordingly (Temperli et al., 2013). To predict productivity under environmental changes, process-based models are of particular interest, because they allow deriving key variables, such as stem volume, stem biomass and carbon sequestration. Although stand-level forest growth models are typically simpler than fully-fledged physiological gap models, they still commonly use numerous parameters that determine the behavior of a range of interacting processes in the model. Not all of these parameters are well-known, and it can be expected that parameters may also vary regionally with provenances and growing conditions (Moran et al., 2016). The resulting parametric uncertainty should be propagated to the models' predictions, meaning that a sensible economic analysis will have to consider that a range of possible model outcomes exists, and each of those could lead to very different management implications. For developing robust management plans, it is therefore crucial to quantify and account for this parametric model uncertainty (Reyer et al., 2016).

One of the best-developed frameworks for estimating and propagating parametric model uncertainty is Bayesian inference. In a nutshell, Bayesian inference is a statistical method that allows expressing, estimating and propagating uncertainty, represented by probability distributions, for each variable of interest in a model, including parameters and model predictions (Hartig et al., 2012; Lichstein et al., 2010). As such, it provides a natural way to compute parametric model uncertainty and subsequently forward it into economic models of forest profitability, e.g. net present value (NPV) or land expectation value (LEV) (Cyert and DeGroot, 1987; Dorazio and Johnson, 2003). As an additional advantage, the Bayesian framework also seamlessly allows including uncertainty in input and drivers of the model. This means that climate change uncertainty, one of the main issues faced by forest managers, can be integrated with parametric model uncertainty in the planning process (Hallegatte et al., 2012; Pasalodos-Tato et al., 2013). Applying this framework in combination with risk analysis enables the selection of robust forest management alternatives, which perform well regardless of future climate paths (Hadka et al., 2015).

Currently, one of the most broadly applied physiology-oriented process-based model is 3-PG (Three Physiological Principles Predicting Growth), developed initially by Landsberg and Waring (1997). 3-PG predicts stand productivity based on photosynthetically active radiation (PAR) and canopy quantum efficiency. The canopy quantum efficiency is constrained by environmental factors, such as temperature, water availability, vapor pressure deficit, stand age and fertility (Almeida et al., 2004b; Landsberg et al., 2001a). The Net Primary Productivity (NPP) is obtained as a constant rate of the Gross Primary Productivity (GPP), and the carbon is allocated to different tree components, according to specific ratios (Amichev et al., 2011). Promoted by its easy accessibility, flexibility and the limited number of parameters, 3-PG has been applied to assess forest productivity of a variety of species and sites (e.g. Fontes et al., 2006; Landsberg et al., 2003; Minunno et al., 2010; Nightingale et al., 2008). Moreover, the model has been successfully calibrated for temperate forest species applying a Bayesian approach (e.g. Minunno et al., 2010; Xenakis et al., 2008).

Considering the importance of developing robust management scenarios for beech forests, the main goals of this study are: (1) To calibrate 3-PG for beech stands in Germany and evaluate the fit of the model and accuracy of the model's predictions; (2) evaluate the impacts of uncertainty on forest productivity and profitability under climate change and (3) to identify robust management regimes towards climate, economic and parametric model uncertainty.

The calibration was performed with a data set composed of intensively monitored permanent inventory plots. The data provided various standard inventory variables, including stand density, stand diameter at breast height (DBH), stand height, standing volume; and site parameters, including climate and soil characteristics. We applied allometric equations for deriving foliage, root and stem biomass of each plot. For the calibration, we used Bayesian inference, to estimate parameters uncertainty from direct information (prior) and indirect information (model outputs). We then forwarded the parametric uncertainty to posterior model predictions (e.g. for stand biomass and volume). We used the results to evaluate the impacts of parametric model uncertainty on the profitability of beech stands under climate change, in terms of Land Expectation Value (LEV), Value-at-Risk (VaR) and Conditional Value-at-Risk (CVaR) of alternative management regimes.

2. Material and methods

2.1. The 3-PG model

The 3-PG model is based on two main sets of calculations: (1) defining the biomass increment and (2) allocating the growth to different tree compartments, determining the growth pattern of the stand (Landsberg et al., 2001b). These calculations are performed in five submodels (Forrester and Tang, 2016): (1) a carbohydrate assimilation submodel, computing the gross primary productivity (GPP) based on the photosynthetically active radiation (PAR) intercepted by the forest stand and the canopy quantum efficiency. The canopy quantum efficiency is constrained by