Ecological Modelling 337 (2016) 48–62

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

A dynamic environment-sensitive site index model for the prediction of site productivity potential under climate change

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ARTICLE INFO

Article history:
Received 22 December 2015
Received in revised form 29 April 2016
Accepted 6 June 2016
Available online 23 June 2016

Keywords:
Norway spruce
Space-for-time substitution
Nonlinear state space approach
Longitudinal data structure
Prediction error minimization method

ABSTRACT

Accurate and reliable predictions of the future development of forest site productivity are crucial for the effective management of forest stands. Static models which simply extrapolate productivity into the future are inappropriate under conditions of environmental change since they lack a close link between fundamental environmental drivers and forest growth processes. Here we present a dynamic environment-sensitive site index model formulated in the framework of a nonlinear state space approach based on longitudinal data from long-term experimental plots. Estimation of the model parameters was carried out using the prediction error minimization method. Our aim was to identify dynamic relationships between site index and environmental variables and to make conditional predictions of the future development of site index under climate change scenarios. Nonlinear, interactive, as well as accumulative effects of environmental factors (climate/weather and nitrogen influx) on the growth response were considered in the model. In the study, we estimated the dynamic environment-sensitive site index model using data from 604 Norway spruce (*Picea abies* [L.] Karst.) long-term experimental plots in southwest Germany with measurement data covering a period of more than 100 years from the end of the 19th century until today. We used the calibrated model to project future site index changes under increasing growing season temperature scenarios. Conventional climate change impact studies usually utilize a gradient approach and apply space-for-time substitution for the parameterization of models that are calibrated using spatial variability in the data. In contrast, the approach presented here utilizes the longitudinal data structure of multiple real growth time series to simultaneously exploit spatial and temporal variation in the data to provide more reliable and robust projections. Limitations of the space-for-time substitution approach in forest growth modelling are discussed.

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1. Introduction

Accurate and reliable predictions of the future development of forest site productivity are crucial for the effective management of forest stands. In the context of the management of forests for wood production *forest site productivity* is defined as a quantitative measure of the potential of a specific forest stand on a specific site type to produce wood (Hägglund, 1981). In forestry the most widespread indicator of forest site productivity is site index (Skovsgaard and Vanclay, 2008). Site index is usually defined as the mean (or dominant) stand height of a specific tree species at a predefined reference age (Assmann, 1970; Hägglund, 1981). Since site index is highly sensitive to site potential but (almost) insensitive to stand density it is the most commonly used measure of forest site productivity.

From a biological point of view forest site productivity describes a highly complex multigenic trait with various interconnected physiological and biogeochemical processes involved, which are further modified by natural and anthropogenic factors. Consequently, beside site index there is a variety of different approaches to define, assess and analyze forest site productivity (Skovsgaard and Vanclay, 2008, 2013).

Under changing environmental conditions process-based models are considered more adequate than purely descriptive empirical models for projecting the development of site productivity into the future (Bontemps and Bouriaud, 2014; Johnsen et al., 2001; Vanclay and Skovsgaard, 1997). In process-based modelling, forest site productivity is formulated as a function of primary site factors like solar radiation, air temperature, tree available soil moisture and nutrients, tropospheric carbon concentration as well as of tree species

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http://dx.doi.org/10.1016/j.ecolmodel.2016.06.005
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and stand type (Landsberg, 1986; Powers, 2001; Singh, 2013; Tesch, 1980). Eco-physiological understanding of cause-effect relationships is the mechanistic foundation for predicting probable future developments under defined scenario assumptions (Landsberg and Gower, 1997; Landsberg and Sands, 2011).

Many studies utilized process-based growth models to predict future forest productivity under climate changes (Coops et al., 2010; Coops and Waring, 2001; Landsberg et al., 2001). However, an obvious weakness of process-based models is that they might involve serious uncertainties due to imperfect input data, model structure, and model parameters (Burkhart and Tomé, 2012; Matala et al., 2003; Valentine and Mäkelä, 2005). Further improvement of forest growth models is currently hampered by a lack of detailed understanding of climate change effects on physiological processes such as photosynthesis and respiration as well as on carbon allocation and biomass production in trees and forest stands.

Hybrid modelling approaches attempt to overcome some of the limitations of process-based growth models like the uncertainty in predicting growth dynamics in the long term through combining the strengths of process-based models with those of statistical models (Mäkelä and Landsberg, 2000; Weiskittel et al., 2011). Recently, hybrid modelling approaches have been increasingly used to investigate forest growth and site productivity under climate changes (Coops et al., 2010; Coops and Waring, 2001; Tickle et al., 2001). However, since hybrid models do not per se provide deeper insight into the underlying relationships between growth and environment they are not the ultimate solution for growth model improvement.

Prediction of site index from environmental factors is the aim of many statistical growth modelling studies (Albert and Schmidt, 2010; Monserud et al., 2008; Nigh et al., 2004; Nothdurft et al., 2012; Sharma et al., 2015; Stage and Salas, 2007; Weiskittel et al., 2011). Studies of this type typically are based on a gradient approach, which is used either independently or in combination with the chronosequence approach (Burton et al., 1991; Joshi et al., 2003). In gradient analysis, spatial environmental gradients are regarded as treatments, equivalent to formal experiments (Manly, 2001). A widespread example is the case where samples taken from different sites along an elevation gradient are considered as different temperature treatments. Chronosequences are a type of space-for-time substitution where the temporal development is inferred from the study of differently aged sample stands (Assmann, 1970; Fleming, 1999; Pickett, 1989).

Crucial basic assumptions underlying the gradient approach are that the environmental gradient is causal and deterministic, e.g. is a ‘true gradient’ (Legendre and Legendre, 2012), and that the environmental conditions and the growth of the trees are in equilibrium at the given sites. These are the underlying assumptions in many inventory-data-based modelling studies where long-term mean baseline climate data at the site are used to infer site index (Albert and Schmidt, 2010; Monserud et al., 2008; Nigh et al., 2004; Nothdurft et al., 2012). A further assumption is that the growth response across the spatial environmental gradient is analogue to the dynamic growth response in time, when site factors at a specific location change due to environmental changes (Albert and Schmidt, 2010; Monserud et al., 2008; Nigh et al., 2004; Nothdurft et al., 2012).

Gradient studies share potential limitations common to other observational studies, as they usually lack randomization and interspersion of treatments (Hurlbert, 1984). If treatments are not mixed in space and time but confounded with some other spatial or temporal environmental gradient, confounding factors that vary along the gradient may themselves affect the response variables of interest (Brown et al., 2011; Manly, 2001). The same is true for design-based sampling schemes like in repeated regional-scale forest inventories, where – without explicit reference to environmental gradients – differences in site conditions between sites build the basis for statistically modelling predictive environment-site index relationships (Albert and Schmidt, 2010; Nothdurft et al., 2012). Spatially spread data of this type can be considered as a cross-sectional look at current climate-productivity-relationships (Monserud et al., 2008; Nigh et al., 2004; Fontes et al., 2003).

Thus, although data from temporary inventories provide spatial variability, they do not represent growth sequences. If the predicted effect of climate change on forest productivity is solely based on the relation between current climate and current productivity levels, then the result is likely to be confounded since other relevant factors might have been omitted. Actually, one has to consider that site indices do not only vary spatially but temporally as well. In this context, Yue et al. (2014) have recently developed a new approach to assess temporal changes in site index over more than a century based on repeatedly measured data from long-term experimental plots. Their results for Norway spruce (*Picea abies* [L.] Karst.) growing in southwestern Germany demonstrated that the trajectory of site index development over time has definitely not been stable but exhibits an increasing trend since the mid-20th century.

For obvious reasons, conventional static models simply extrapolating productivity into the future are inappropriate under conditions of climate change. Such models lack a close link between fundamental environmental drivers and forest growth processes. Therefore, the aim of the present study was (1) to develop a dynamic environment-sensitive site index model in the framework of a state-space approach based on data from repeated measurements of long-term experimental plots and (2) to apply this methodology to the prediction of site index changes of Norway spruce stands in southwest Germany under climate change scenarios. Norway spruce was chosen, as the species is of major economic importance in Europe (Teuffel et al., 2005) and growth data are available from an extensive network of long-term experiments.

2. Material and methods

2.1. Growth data

This study exploited a data base derived from repeated measurements of long-term experimental plots with Norway spruce in Baden-Württemberg (southwest Germany). It is basically the same data base that has been used in the study of Yue et al. (2014). The data have been gathered and compiled and are maintained by the Forest Research Institute (FVA: Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg). All the experiments included in the analysis consisted of even-aged stands. The oldest measurements dated back to the end of the 19th century. However, only a few data from such old experiments were available. In the course of time the number of plots increased consistently reaching a maximum in the 1990s (297 plots). The thinning treatments varied from unthinned, dense stands, across low intensity thinnings from below, and crop-tree thinnings with high intensity, to open grown stands of almost solitary trees. Since dominant trees/future crop trees are remaining, the applied thinning regimes hardly affected dominant height. A more detailed characterisation of the range of treatment types is given by Yue et al. (2014).

In comparison to Yue et al. (2014) the database exploited in this study has been enlarged as new data from most recent measurements of ongoing experiments have been added and additional data available from paper documentation of older experiments are successively being integrated into the FVA's digital database (Lenk et al., 2014). Thus, the number of experimental plots covered by the database has increased to 603 and the number of different experimental locations to 248. A map with the locations of the experiments from which measurement data were available for

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