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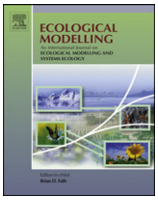

Enhancing gap model accuracy by modeling dynamic height growth and dynamic maximum tree height

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ABSTRACT

Gap models are flexible tools for the simulation of forest dynamics under different climatic conditions. An important area, however, has not yet received the attention it deserves: the formulation of height growth and maximum tree height. In most gap models, every tree approaches a fixed maximum height regardless of site conditions, and tree height as such is approximated via stem diameter. To address these issues, we converted maximum height from a parameter to a variable that depends on site-specific climatic conditions. We also established tree height as a separate state variable besides diameter, to allow for competition effects to influence the ratio between height and diameter growth. The new model formulations were tested against data from the Swiss National Forest Inventory (NFI) and from a forest growth and yield research plot. Lastly the new model version was applied to study productivity changes due to climate change along an environmental gradient.

The new model formulations increased the accuracy of simulations of stand characteristics without negatively influencing the general applicability of the model. The height/diameter relationship of a Douglas-fir stand in Switzerland simulated with the new model version resembled measurements closely, and biomass simulated along an environmental gradient agreed better with measurements (NFI) when using the new model version. Simulations with site-specific maximum height showed that the maximum heights of the dominant species on the gradient did not differ significantly from NFI data, whereas static maximum heights did.

The application of the old and new model versions to simulate productivity under climatic change along the same environmental gradient showed that the conversion of a static parameter such as maximum height to a site-specific variable is not only a desirable, but a crucial feature to incorporate, since climate-induced changes in productivity are simulated to be more pronounced with the new model formulation. We conclude that dynamic height growth and site-specific maximum tree height can significantly improve simulation results of forest succession models, especially with regard to forest management under climate change.

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1. Introduction

With rapidly changing environmental conditions and the associated loss in the applicability of traditional yield tables and growth models (Pretzsch, 1992) the interest of forest scientists and stakeholders in more reliable methods to estimate the future growth of forest is rising. Gap models have proven to be flexible tools with regard to estimating the impact of climatic change on natural forest dynamics (e.g. Didion et al., 2011; Huo et al., 2010), yet few have both the capacity to simulate forest management and the necessary accuracy in simulating forest stand structure to serve as decision support tools.

Key aspects of locally accurate forest models are the simulation of height and diameter growth, as they result from allocation priorities under varying environmental conditions (Waring and Schlesinger, 1985). The allocation of total growth into diameter vs. height growth and the absolute height that is achievable under given conditions have not received much attention to date in forest gap models (for an exception, see Lindner et al., 1997). Assmann (1970) emphasized that height rather than diameter growth should be used as an indicator of growth patterns, as it is less influenced by management. Many individual-tree growth models simulate height and diameter increment separately (Vospernik et al., 2010), yet most gap models treat height as a derived variable that depends solely on the current diameter of a tree (e.g. Kellomäki et al., 2008;

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Kienast, 1987; Pacala et al., 1996; Pastor and Post, 1985), where all growing trees approach an asymptotic value of maximum height, regardless of site conditions. Such models are unable to account for thinning effects that may occur after thinnings of a specified intensity and are marked by an increase in diameter increment, yet not in height growth (e.g. Crecente-Campo et al., 2009; Pothier and Margolis, 1991). They cannot mimic the growth behavior of shaded trees in the understory either, which may invest dramatically varying amounts of resources in height vs. diameter growth with changing light conditions (e.g. Holbrook and Putz, 1989; Naidu et al., 1998).

There are several other factors that make a more reliable simulation of height and diameter growth an important feature: for instance, tree height to diameter (h/d) ratio influences vulnerability to wind and snow breakage (Kimmins, 2003), it may allow to infer the fraction of belowground biomass (Delagrange et al., 2004), and it is also important in terms of the fate of a tree in the stand, since in reality small initial differences in height tend to increase with age and allow for little change in rank in subsequent years (Ammer et al., 2008).

Besides a static h/d relationship, it is a strong simplification to assume that the maximum height that is being approached by the growth function is a site-independent constant (Albert and Schmidt, 2010). Foresters have long known that the “site” as a composite of climate, soil, topography, hydrology and other factors determines tree growth (Kimmins, 2003). In forest growth models, this is routinely taken into account, e.g. by choosing different potential height growth curves depending on site conditions (e.g. Pretzsch, 2001). It is therefore important to find a way to relate maximum potential tree height to site characteristics in gap models as well. An accurate estimation of maximum height influences not only stand structure and stand growth dynamics, but also derived properties such as productivity and carbon storage. Simulating these features accurately is particularly important in times of environmental change, as there is evidence that site index (e.g. Albert and Schmidt, 2010; Boisvenue and Running, 2006; Bravo-Oviedo et al., 2010) and maximum stand height (e.g. Bontemps et al., 2009; Kahle et al., 2008) is changing.

The goal of this paper is hence to (i) show how the traditional growth equation used in gap models can be altered to account for a changing ratio in diameter to height growth, (ii) propose a way to convert a usually static growth-constraining parameter such as maximum tree height to a dynamically calculated variable, and (iii) explore if these model changes improved the overall results and also determine how sensitive simulations under climate change are with regard to these changes. Our model development focuses on ForClim, which showed promise of becoming a decision support tool based on the implementation of a versatile management submodel (Rasche et al., 2011). We validate the new model version against long-term growth-and-yield plot and National Forest Inventory (NFI) data.

2. Methods

2.1. Model description

ForClim is a gap model that was developed with the premise to use as few parameters as possible and operate with the least amount of ecological assumptions (Fig. 1). It simulates forest dynamics on independent small patches of land and is currently parameterized for 31 species in Europe. Tree development is primarily determined by light availability and climatic parameters; besides these, only nitrogen availability, soil water holding capacity and slope/aspect are used to characterize site properties. The submodels WEATHER and WATER provide values for soil moisture, minimum winter temperature and growing season temperature, based on the long-term weather data and soil water holding capacity of the site. Values are drawn from a probability distribution around the climate parameters – derived from the standard deviation calculated from the time series – separately for each of the patches.

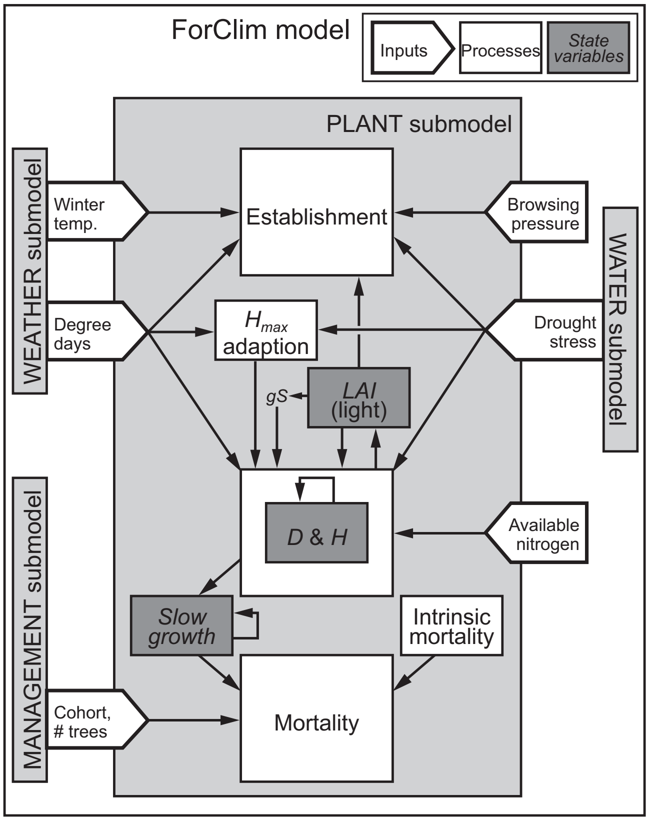

Fig. 1. Structure of the ForClim model with submodels PLANT, WEATHER, WATER and MANAGEMENT.

The submodel PLANT simulates establishment, growth and mortality of single tree cohorts. *Growth* is modeled based on the carbon budget approach by Moore (1989), in which an optimal growth rate is calculated and then decreased according to environmental factors, which also determine tree *establishment* rates. These factors include light and nitrogen availability, growing season temperature, soil moisture and crown length. Tree *mortality* consists of an age-related and a stress-induced component. For silvicultural treatments, an extensive MANAGEMENT submodel can be activated, which presently comprises the methods thinning, clear cutting, strip felling, target cutting, group selection (“Swiss femel”), shelterwood felling, continuous cover forestry (“plentering”) and planting. A more detailed description of the original model can be found in Bugmann (1996). Changes to the original model are described in Bugmann and Solomon (2000), Risch et al. (2005), Didion et al. (2009) and Rasche et al. (2011, ForClim v2.9.8).

Mathematical symbols in ForClim follow the notation suggested by Swartzman and Kaluzny (1987), with the first letter denoting the type of the symbol: u for input/output variables, k for model parameters and g for auxiliary variables; state variables do not possess a prefix. Below, this notation is used throughout to avoid confusion, even in equations from other sources.

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