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Of climate and its resulting tree growth: Simulating the productivity of temperate forests

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ABSTRACT

We parametrize the maintenance respiration of a single tree depending on reference climate parameters (light, temperature and precipitation) and the observed stem diameter increase resulting from that climate. The simulated biomass increment results from photosynthesis under the given climate scenario and is then reduced by maintenance and growth respiration. We incorporate this new carbon allocation algorithm into the established individual based gap model FORMIND to reproduce the biomass development of typical central European forest stands.

Yield tables for northern Germany recorded over the last century are used for our parametrizations, along with the climate of the area at the time of recording. The model simulates eight tree species based on data on pine, spruce, beech, oak, ash, poplar, birch and robinia. The model dynamics emerge from tree competition, growth and mortality. These processes are calculated on an annual scale. The climate variables (global radiation, air temperature and precipitation) are entered into the model in daily resolution. This new version of FORMIND version reproduces the forest biomass development represented in the yield tables for northern Germany as well as those for western France. The modeled annual fluxes of gross primary production, woody net primary production and autotrophic respiration correspond with results from eddy flux measurements. Therefore, this version of FORMIND with the new carbon allocation is a suitable tool to investigate the carbon flux, biomass development and potential yield of forests at the individual tree level in the temperate climate zone.

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1. Introduction

Forests provide important ecosystem services, such as sequestering carbon or delivering wood (Bonan, 2008). In Europe (excluding the Russian Federation), 32.2% or 2.1 million km^2 of the total land surface is covered by forest (UNECE and FAO, 2011). European forests sequester up to 6.6 tons of carbon per hectare and year (Valentini et al., 2000). Janssens et al. (2003) estimate the sequestering rate of all European forest at 363 Tg C a^{-1}, which amounts to almost 20% of European carbon emissions of 1995. Around 4% of these forests are undisturbed by human activity, while 29% of the managed forests are monocultures and 51% contain two or three species (UNECE and FAO, 2011).

Apart from the ecological aspects, forests are also important for the economy (forestry, manufacture of wood and paper). The forest sector contributed a value of EUR 119.5 billion to the gross value in the year 2008 (which is 1% of European GDP) and provided jobs for 3.95 million employees in 2010 (UNECE and FAO, 2011). High sequestering rates of carbon and wood production are dependent on different abiotic factors. For example, a moderate increase in temperature can have a positive effect on forest productivity in temperate forests (Solberg et al., 2009). In the case of the extreme European summer of 2003, on the other hand Ciais et al. (2005) estimated a decrease in gross primary production (GPP) of 30% which resulted in an anomalous net source of carbon dioxide. Consequently, changes in temperature could turn forests into carbon sinks or carbon sources.

As we cannot perform long-term experiments on the effects of a changing climate on forest, one option is to rely on integrated models of ecosystem function to explore the potential effects of change on the development of the ecosystem (e.g. Prentice et al., 1993; Bugmann, 1996; Schmid et al., 2006). They simulate ecosystem development as a result of ecophysiological processes described mechanistically, based on a rich literature on the fundamental ecological processes in forests (e.g. Bossel, 1992; Pacala et al., 1996; Haxeltine and Prentice, 1996; Shugart, 1998).

Process-based spatially explicit forest growth models such as FORMIND (Gutiérrez et al., 2009), FORSKA (Prentice et al., 1993),

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FORCLIM (Bugmann, 1996), 4C (Lasch et al., 2005) or iLand (Seidl et al., 2012) simulate individual tree growth dependent on climatic conditions. With these models it is possible to investigate temporal and spatial forest dynamics for several hectares and centuries.

Here we adapted the forest model FORMIND for the first time to the European temperate zone. We also consider the experiences with the related TREEDYN3 model (Bossel, 1996; Sonntag, 1998), which is a single species forest growth model for European species.

The FORMIND model has been applied successfully by e.g. Köhler and Huth (2004) to different forests to understand species-rich forest dynamics in tropical rain forests (with up to 25 plant functional types) and to temperate rain forests in Chile (Rüger et al., 2007; Gutiérrez and Huth, 2012). As the productivity of single trees in FORMIND is based on carbon balance, annual sequestering rates as well as the expected biomass yield in case of harvesting can be simulated.

The new version of FORMIND, which is designed to simulate forests of European species in the temperate zone (FORMIND-fest), includes the following main forest processes: competition, tree growth, recruitment and mortality. As input we use daily time series of incoming light (photo-active photon flux density (PPFD)) above the forest canopy, air temperature, precipitation and potential evapotranspiration (PET). In addition, tree number per hectare, their stem diameter and soil parameters are required.

However, describing and parametrizing different tree species and the effects of climate on their growth processes in a process-based model is a complex task (Fontes et al., 2010). Process-based models have to contend with the following issues (among others): (a) data availability for all needed parameters should be given; (b) a model cannot be completely general in its scope and applicability while at the same time providing locally highly accurate results (Levins, 1966); and (c) the relevant processes to answer the research questions have to be included.

The objective of this study is to present a new climate-dependent allocation algorithm for the forest model FORMIND and its parametrization approach. It should be applicable to the temperate climate zone to address questions concerning annual sequestering rates and wood production of forests.

We use yield tables to parametrize eight tree species. These yield tables describe the forest growth for single species and are based on measurements collected between the last two decades of the 19th century and 1968 (Schober, 1971, 1995). Thus the development of the forests described by the yield tables is not influenced by the high nitrogen deposition which occurred in the last third of the 20th century (de Vries et al., 2006, 2009; Kahle, 2008; Thomas et al., 2010; Eastaugh et al., 2011; Sutton et al., 2011). We parametrized eight common tree species occurring in central European forests. In doing so, we extended the respiration approach presented in Dislich et al. (2009) by climate dependency.

First, we checked whether we could reproduce the forest development over time documented in the yield tables of Schober (1995), which are used also in parts of the parametrization. Then we validated our parametrization using other yield tables for western France (ENGREF, 1984), which are based on a different climate and therefore differ in growth compared to the yield tables for north-eastern Germany used by us. Finally, we compare the modeled carbon fluxes with eddy flux measurements of temperate forests presented by Luyssaert et al. (2007).

2. The spatio-temporal model

We developed a new version of the gap model FORMIND: FORMIND for European species in the temperate zone (FORMIND-fest). We incorporated a new algorithm for describing photosynthesis dependence on air temperature and soil water as well as maintenance respiration dependence on air temperature to derive the tree growth. Eight tree types are parametrized to calculate their carbon balance and allometry based on field data on the species *pinus sylvestris*, *picea abies*, *fagus sylvatica*, *quercus robur*, *populus marilandica*, *fraxinus excelsior*, *betula pendula* and *pseudotsuga menziesii*.

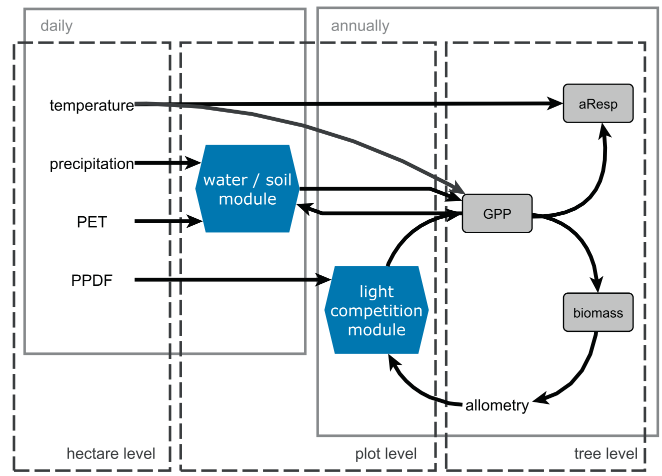

Fig. 1. The concept of carbon balance in FORMIND-fest: all climate input variables are equal for the whole simulated area, in our case, 1 ha. Precipitation and potential evapostranspiration are used to calculate the GPP limitation factors for all trees in that patch, depending on their GPP. The GPP depends also on the air temperature. The available light for a tree is calculated by the light competition module using the photosynthetic photon flux density (PPFD) giving the available light for all trees in the patch. The GPP is split into autotrophic respiration which is influenced by temperature and biomass increment. The biomass determines the allometry which influences light competition within the patch.

2.1. Overview of the forest model FORMIND-fest

The pristine FORMIND model is a process-based, individual-oriented, three dimensional, grid-based forest growth model. So far, FORMIND has been applied to species-rich forests in the tropics (e.g. Köhler, 2000; Köhler and Huth, 2004; Dislich et al., 2009) and Chilean temperate rain forest (e.g. Rüger et al., 2007; Gutiérrez and Huth, 2012). The FORMIND-fest mode builds upon FORMIND while further developing the calculation of gross primary production (GPP) and maintenance respiration (R_m). It is designed to reproduce forest structure and biomass development in central Europe, which emerge from the physiological attributes of each tree type, the competition for light, the amount of water available and air temperature (Fig. 1).

The simulated forest area (1 ha) comprises 25 land patches of 20 m × 20 m in size. These are characterized by vertical light conditions caused by the shade of tree crowns, soil water content, and location within the landscape. Tree positions within a patch are not considered explicitly and therefore light conditions are horizontally homogeneous. However, light conditions differ between the height layers and land patches and depend on the distribution of crowns and the LAI of trees (this is described in detail as the gap model approach in Shugart, 1998 and in Appendix D.1).

In each land patch, we can simulate trees of different age and size. Trees of the same tree type and size, which are located in the same land patch, are considered as one tree cohort. Actual diameter at breast height (dbh), height, crown diameter and stem volume of trees are derived from their biomass based on their allometric relationships (Appendix B). In addition, every tree type has its set of parameters describing its own ecophysiological attributes and mortality (Appendices C–E). Thus each tree cohort is characterized by tree type, stem number and above-ground biomass of a single

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