



# A rapid NPP meta-model for current and future climate and CO<sub>2</sub> scenarios in Europe



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## ABSTRACT

Net primary production (NPP) is the difference in gross photosynthetic assimilation of carbon and carbon loss due to autotrophic respiration, and is an important ecosystem variable that facilitates understanding of climate change impacts on terrestrial ecosystem productivity and ecosystem services. The aim of this study is to rapidly estimate the NPP of European potential natural vegetation for current and future climate and carbon-dioxide scenarios (CO<sub>2</sub>).

A NPP meta-model was developed and evaluated based on the dynamic global vegetation model LPJ-GUESS. LPJ-GUESS was used to simulate NPP under current and future climate change as well as CO<sub>2</sub> scenarios. The NPP dataset produced from these simulations was used to determine the empirical relationships between NPP and driving climate variables (maximum temperature, minimum temperature, summer precipitation, winter precipitation) along with CO<sub>2</sub> concentration. The climate variables' relationships were combined in a synergistic function including CO<sub>2</sub> relationships to estimate NPP. The meta-model was compared with randomly chosen NPP data originated from LPJ-GUESS. Furthermore, the meta-model's performance was evaluated on the European level with LPJ-GUESS simulations.

The meta-model performed reasonably well with regard to estimating total NPP while performances for species-specific NPP were poor. For total NPP, the meta-model generated an agreement of  $R^2 = 0.68$  and RMSE = 0.06 at CO<sub>2</sub> = 350 ppm in comparison to LPJ-GUESS simulations. The consideration of all CO<sub>2</sub> concentration scenarios yielded  $R^2 = 0.62$  and RMSE = 0.08.

A rapid synergistic approach is suggested that enables interactions between climate variables and their intra-annual variability to estimate NPP. This is a useful alternative to traditional empirical models that control NPP with the most limiting climate variable. The meta-model performed reasonably well for estimating total NPP for future climate change and CO<sub>2</sub> scenarios. However, species-specific NPP estimates were unsatisfactory, implying that the synergistic approach cannot account for species specific dynamics. Comparison between the meta-model and LPJ-GUESS at the European scale showed that additional environmental variables (e.g. solar radiation) would be necessary to improve the meta-model.

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## 1. Introduction

Increasing atmospheric carbon-dioxide concentrations (CO<sub>2</sub>) and climate change are altering terrestrial ecosystem processes. This has impacts on services that are provided from ecosystems. It is therefore vital to assess these changes and provide measures of their magnitudes. Vegetation growth integrates various ecosystem processes and plays a key role expressing how productive an ecosystem is in terms of food resources, timber and biofuel production (Li et al., 2011). Net primary production (NPP) is the difference

in gross photosynthetic assimilation of carbon and carbon loss due to autotrophic respiration per area per unit time (Foley, 1994). A positive NPP illustrates an increase of structural biomass in plants (Van Oijen et al., 2010). It is a fundamental property of the biosphere, providing usable energy for all life on Earth (Zaks et al., 2007). NPP is also an important indicator for biodiversity, species composition and ecosystem services. It facilitates understanding of the global carbon cycle by providing information about CO<sub>2</sub> sinks and sources (King et al., 1995; Schuur, 2003).

Understanding the changes in NPP at the global and regional scale usually requires a modeling approach. The MIAMI model (Lieth and Whittaker, 1975) is the original global NPP model, and was formulated on basis of empirical relationship between climate variables and in situ measured NPP values. The MIAMI model

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applies the Minimum Law, which assumes that plant productivity is limited by only a single climate variable (Lieth and Whittaker, 1975). The Minimum Law only considers the climate variable yielding the lowest NPP. However, new techniques and hypotheses about the climatic controls on NPP call for reanalysis of the problem since empirical models based on the Minimum Law hypothesis cannot always provide ecologically explainable estimates of NPP (Zaks et al., 2007).

The Miami model has been widely employed to predict NPP under current climate conditions because it is simple and often applied as a reference approach in empirical model development (Adams et al., 2004; Del Grosso et al., 2008). Extensions of the MIAMI model have been developed to account for CO<sub>2</sub> enrichment and other climate variables (King et al., 1997). Empirical NPP models give crucial measures of terrestrial ecosystem productivity and are major achievements in understanding global patterns of productivity (Zaks et al., 2007). But they should be treated with caution for future climate scenarios since they have been developed under current climate conditions and can lead to unreliable predictions (Adams et al., 2004).

The lack of extensive calibration and validation data limits empirical models to plot-level field measurements, and thus they may not be applicable for large scale studies (Adams et al., 2004; Clark et al., 2001; Schuur, 2003). Field measurements combined with tower-based energy flux estimations provide accurate determination of plant growth of a forest ecosystem over a time period (Fahey and Knapp, 2007). Tower-based measurements offer high temporal resolution estimations of CO<sub>2</sub> uptake or variations in CO<sub>2</sub> concentration flux during the growing season. However, they represent site-specific measurements and are therefore of limited use in the spatial domain.

At broader spatial scales remote sensing based vegetation indices have been employed to derive NPP and biomass (Ito, 2011). These methods incorporate uncertainties, because they are also location-specific, particularly in the case of purely empirical approaches. Though the integration of vegetation indices into light use efficiency models enhances their capacity to predict NPP and biomass across biomes, local calibration of these models (e.g. assignment of vegetation-specific physiological parameters such as maximum light use efficiency) is still required (Seaquist et al., 2003). The utility of satellite derived NPP estimates include their ability to capture fine-scale detail in actual vegetation distribution, mapping vegetation change in ecosystems, as well as for calibration and validation of mechanistic ecosystem models (Smith et al., 2008; Tang et al., 2010).

Empirical or semi-empirical models have been criticized for the application of pre-processed climatologies as regards their calibration and development. Calculations of mean annual temperature and precipitation over a predefined time period do not capture patterns that are important for driving processes at shorter time scales thereby introducing spatial and temporal uncertainties. Therefore, impacts of ongoing climate change may be averaged out and the actual response of ecosystem production to climate may not be fully represented. Assumptions of an equilibrium ecosystem state are not satisfied under conditions of climate change and thus modeled NPP can be exaggerated (Del Grosso and Parton, 2010; Shoo and Valdez Ramirez, 2010). Finally, empirical NPP models are incapable of elucidating physiological and biochemical processes (e.g. photosynthesis or respiration) since they are formulated implicitly (King et al., 1997).

By contrast, dynamic global vegetation models (DGVMs) are capable of simulating fundamental plant growth processes by applying biophysical laws and biogeochemistry on a diurnal basis (Sitch et al., 2003; Smith et al., 2001). This gives the advantage of being able to run DGVMs with future climate change scenarios in order to predict the NPP of ecosystem resources without

extrapolation. DGVMs have been applied for comparing the response of vegetation growth on CO<sub>2</sub> enhancement experiments locally and predicted globally (Hickler et al., 2008). However, large scale applications of DGVMs are time-consuming and computationally burdensome.

One approach for alleviating the computational burden of complex models is the meta-modeling concept, which aims to emulate the performance of complex models with simplified but efficient techniques (Ratto et al., 2012; Razavi et al., 2012). Meta-modeling is therefore suitable for overcoming time-consuming DGVM simulations. A useful technique is the development of an empirical model derived from results of DGVM simulations under various climate change scenarios. The DGVM simulation results and their driving climate variables are analyzed for empirical relationships in order to describe NPP as a function of the corresponding climatologies. This DGVM-based empirical model, referred to as a *meta-model*, can be applied for climate change scenarios, though it lacks the implementation of physical and biogeochemical processes in favor of computational speed. Such a method can therefore overcome the dependence of empirical NPP modeling applied to actual climate conditions and the limited number of available NPP field measurements, while minimizing extrapolation errors.

The development of a NPP meta-model is necessary since time-consuming simulations undermine the ability of DGVMs to be integrated in rapid and holistic assessment models. The CLIMSAVE (climate change integrated methodology for cross-sectoral adaptation and vulnerability in Europe) project is a unique example of an integrated assessment modeling framework that applies different sectoral models (e.g. urban growth, economic and coastal fluvial flood models) to holistically address impacts of climate change and increasing CO<sub>2</sub> concentrations on the environment (Harrison et al., 2012). Combining a wide range of sectoral models provides not only an assessment of the consequences of climate change on the different sectors but also allows a better understanding of their cross-sectoral feedbacks. On CLIMSAVE's web-based integrated assessment platform (IAP—[www.climsave.eu](http://www.climsave.eu)), the models have to interact rapidly on demand in order to provide reliable information about the risks of climate change to stakeholders and interested European citizens (Harrison et al., 2012). A DGVM-based meta-model is useful because it can be implemented in an IAP (e.g. CLIMSAVE IAP) in order to contribute with valuable cross-sectoral information about plant growth under climate change.

The overall aim of the study is to develop and test a rapid NPP meta-model based on DGVM simulations where the objective is to predict NPP of European potential natural vegetation (PNV) for current and future climate as well as CO<sub>2</sub> scenarios. This study hypothesizes that the meta-model is able to emulate species-specific and total NPP estimates generated by DGVM simulations. Furthermore, it is hypothesized that NPP can be described by a synergistic function of seasonal temperatures, seasonal precipitation and atmospheric CO<sub>2</sub> concentration. NPP can be therefore controlled synergistically by all climate variables instead of the most limiting one.

## 2. Materials and methods

### 2.1. Dynamic global vegetation model

In the current study, European PNV is described by NPP (kg C m<sup>-2</sup> year<sup>-1</sup>), which was simulated with the dynamic global vegetation model LPJ-GUESS (Smith et al., 2001). LPJ-GUESS combines mechanistic representations of plant physiological and biogeochemical processes and is driven by various climate variables, atmospheric CO<sub>2</sub> concentration, and soil characteristics

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