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Modelling carbon and water cycles in a beech forest Part I: Model description and uncertainty analysis on modelled NEE

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Abstract

A forest ecosystem model (CASTANEA) is developed with the aim to bridge the gap between soil–vegetation–atmosphere (SVAT) and growth models. A physiologically multi-layer process-based model is built, completed with a carbon allocation model and coupled with a soil model. CASTANEA describes canopy photosynthesis and transpiration, maintenance and growth respiration, seasonal development, partitioning of assimilates to leaves, stems, branches, coarse and fine roots, evapotranspiration, soil heterotrophic respiration, water and carbon balances of the soil. Net primary productivity (NPP) is calculated as the difference between gross photosynthesis and plant respiration. The net ecosystem exchange (NEE) between soil-plant system and atmosphere is calculated as the difference between gross photosynthesis and total respiration (soil + plants). The meteorological driving variables are global radiation, rainfall, wind speed, air humidity and temperature (either half-hourly or daily values). A complete description of the model parameterization is given for an eddy flux station in a beech stand (Hesse, France). A parametric sensitivity analysis is carried out to get a classification of the model parameters according to their effect on the NEE. To determine the key input parameters, a +10% or −10% bias is applied on each of the 150 parameters in order to estimate the effect on simulated NEE. Finally 17 parameters, linked to photosynthesis, vegetative respiration and soil water balance, appear to have a significant effect (more than 2.5%) on the NEE. An uncertainty analysis is then presented to evaluate the error on the annual and daily NEE outputs caused by uncertainties in these input parameters. Uncertainties on these parameters are estimated using data collected in situ. These uncertainties are used to create a set of 17,000 simulations, where the values of the 17 key parameters are randomly selected using gaussian random distributions. A mean uncertainty of 30% on the annual NEE is obtained. This uncertainty on the simulated daily NEE does not totally explain the discrepancies with the daily NEE measured by the eddy covariance technique (EC). Errors on daily measurements by EC technique and uncertainty on the modelling of several processes may partly explain the discrepancy between simulations and measurements.

Keywords: Model; Carbon; Water; Growth; Eddy fluxes; NEE; NPP; Soil; Beech forest; Uncertainty analysis; Sensitivity analysis

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1. Introduction

Long-term accurate estimates of (i) *carbon and water fluxes* between forest ecosystems and the atmosphere and (ii) *carbon storage* in trees and soil, are crucial to assess the role of forested areas in the global carbon cycle and in the continental water balance.

During the last century, several types of forest models have been developed with different objectives. Among the oldest, the empirical "*forestry*" models (Schober, 1975; Dhôte, 1990, 1991), with a time step of one year or more, predict stem growth without considering seasonal and inter-annual climatic changes. These models use empirical rules based on large data sets from field plots. They are able to reproduce tree growth over a century, according to forest management, age of stocking assuming no change in climate trend. However, climate change probably explains the increasing trend in radial growth (Becker et al., 1994) and in tree height (Dhôte and Hervé, 2000).

During the last two decades, several biophysical carbon/water fluxes models have been developed, considering the canopy as a single layer (i.e. "big-leaf"), a multi-layer or a three dimensional volume (Wang and Jarvis, 1990; Aber and Federer, 1992; Amthor, 1994; Baldocchi and Harley, 1995; De Pury and Farquhar, 1997). They assess mass and energy exchange between the canopy and the atmosphere by coupling the fluxes of carbon dioxide and water vapour. The leaf physiologically based photosynthesis model by Farquhar et al. (1980), linked with a stomatal conductance model (Jarvis, 1976; Ball et al., 1987; Collatz et al., 1991) provides a theoretical framework for spatially integrating fluxes from leaf to canopy level. These process-based models integrate accurately the canopy functioning over time from seconds to days (Caldwell et al., 1986; Baldocchi, 1992; Leuning et al., 1995; Williams et al., 1996; Wang and Leuning, 1998). They are not designed, however, to predict the seasonal and inter-annual variations of tree growth and stand biomass increment. *Forest growth* models, based on ecological and biogeochemical principles, focus on how carbon and water fluxes vary from daily to annual and decadal time scales. They are able to predict changes in plant carbon pools (i.e. organs) by understanding there respective size and turnover time (Mohren, 1987; McMurtrie et al., 1990). Some of these models consider litter and soil mineralization processes with the aim to predict soil organic matter dynamics (Running and Coughlan, 1988; Korol et al., 1991; Running and Hunt, 1993; Hoffmann, 1995; Bossel, 1996). However, they tend to ignore the effects of microclimate spatial variability within the plant canopy and, as they generally use a daily time step, they need empirical (i.e. not physiologically based) leaf and canopy photosynthesis sub-models. As hydrologic processes control drought effect on photosynthesis (Schulze, 1986) soil carbon and nitrogen dynamics (Parton et al., 1987), some of these models also couple the carbon budget with a model simulating the water cycle. The rainfall reaching the ground is shared out into soil evaporation, transpiration, interception, infiltration or runoff. According to the application domain, the hydrology models are more or less sophisticated. For example, the evapotranspiration can be calculated as function of a potential evaporation (Kim et al., 1996) or estimated following Monteith (1965) or Shuttleworth and Wallace (1985). The soil can be divided into numerous layers (Braud et al., 1995) or parameterized into one or several buckets (Eagleson, 1978). Nevertheless, detailed SVAT models are difficult to use for the investigation of the spatial and temporal variability of land surface fluxes. The large number of parameters they involve requires detailed field studies and experimentation to derive parameter estimates (Boulet et al., 2000). Simple water balance models using simple soil and stand parameters and basic climatic data are often sufficient to predict temporal variation in soil water content (Granier et al., 1999).

In this paper we focus on the complete description of a model simulating carbon, water and energy fluxes and we precisely describe the parameterization in the case of a beech forest stand (Hesse Euroflux site, France). A precise description of the CASTANEA structure and parameterization is given to account for the complexity and the large number of variables and parameters of this physiologically multi-layer process-based model. An effort concerning the parameterization has been done to have confidence in the model validation at eddy flux stations. Given the large number of input parameters, a sensitivity study, to determine the key parameters and their effect on the simulated output variables (uncertainty analysis), is presented. The uncertainty on the daily and annual simulated net ecosystem exchange (NEE) is then estimated using Monte-Carlo simulations.