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Bayesian optimization of a light use efficiency model for the estimation of daily gross primary productivity in a range of Italian forest ecosystems

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ABSTRACT

In this study we applied a modified version of Prelued, a simple semi-empirical light use efficiency (LUE) model, to eight eddy-covariance Italian sites. Since this model has been successfully applied mainly to coniferous forests located at northern latitudes, in our study we aimed to test its generality, by comparing Prelued's outputs in coniferous, broadleaf forests and in a Mediterranean macchia, at different climatic and environmental conditions. The model was calibrated for daily gross primary production (GPP) observed over one year in each flux site and validated for another year. The model uncertainties on both GPP and model parameters were estimated, applying a Bayesian calibration based on a multiple chains Markov Chain Monte Carlo sampling.

The accuracy of the model estimates of daily GPP over the entire period of simulation differed widely depending on the site considered, with generally good model performance when applied to evergreen and broadleaf forests and poor performances in the Mediterranean macchia. The values of the modifiers accounting for the response to climatic variables suggested the soil water content to be non-limiting in temperate mountain evergreen but limiting in Mediterranean forests. Model uncertainties were always smaller than data uncertainties, with variable magnitude depending on the site considered. Both modeled GPP and uncertainties were largely dependent also on uncertainties on the data, which made their calculation a key process in this modelling exercise.

In conclusion, this semi-empirical model appears to be suitable for estimating daily and annual forest GPP in most of the considered sites, with the exception of Mediterranean macchias, and for supporting its application to a large range of ecosystems provided a site-specific calibration. The Bayesian calibration did not confer a clear advantage in terms of model performances in respect to other methods used in previous studies, but allowed us to estimate uncertainties on both parameter values and model estimates, which were useful to analyse more in detail the ecosystem response to environmental drivers of GPP.

1. Introduction

The gross primary production (GPP), being the largest carbon flux between the atmosphere and the biosphere, is among the main outputs of many forest ecosystem models (Foley et al., 1996; Horn and Schulz, 2011; Landsberg and Waring, 1997; Mäkelä et al., 2008). GPP is also being increasingly targeted by remote sensing

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applications as a proxy to assess global carbon fluxes (such as net ecosystem CO_2 exchange, NEE) and plant light-use efficiency at large spatial scales (Still et al., 2004; Xiao et al., 2005). At the same time, the quantification of GPP is a challenge in most ecosystems because of its dependence on a variety of interlinked meteorological, environmental and biological drivers at several time scales.

Many of the models of forest growth and biogeochemical cycles developed in the last 30 years are complex research tools that replicate forest physiological processes. These are typically detailed, multi-variable models that need large datasets of environmental drivers and careful species-specific parameterisation (Landsberg and Waring, 1997). Therefore, a process of simplification started in the 1990s (Landsberg and Waring, 1997; White and Running, 1994) with the aim of developing generalized models that could be of use in applied forest management.

One step in this direction was represented by the creation of hybrid models like FORCYTE-11 (Kimmins, 1986), that combine the predictive power of process-based models with the short-term believability of mensuration-based models (Kimmins et al., 1999; Landsberg, 2003). Unlike full process-based models, hybrid models are based on the principle that only the processes that are expected to change would be included in the modelling effort (Kimmins et al., 2008).

The effort towards simplification is not limited to hybrid models: a widely used group of simple models for the prediction of GPP is based on the concept of light use efficiency (LUE). These models assume that vegetation has a potential LUE, which departs from the actual LUE because the latter is affected by differences in intercepted photosynthetically active radiation (PAR) and environmental constraints (Kumar and Monteith, 1981; Landsberg and Waring, 1997; Monteith and Moss, 1977). Therefore, the optimal LUE is decreased by modifying factors that account for sub-optimal conditions for photosynthesis (Landsberg and Waring, 1997; McMurtrie et al., 1994). LUE models mainly rely on a simplified representation of physiological processes based on empirical parameters and their mathematical structure is often quasi- or totally multiplicative. As a consequence, LUE models typically require limited input data and are computationally efficient. Some examples of these models are 3PG (Landsberg and Waring, 1997), EC–LUE (Yuan et al., 2007), C-Fix (Veroustraete et al., 1994), CFLUX (Turner et al., 2006) and Preleud (Mäkelä et al., 2008).

Despite relying on a multiplicative mathematical structure and on several empirical parameters, of which little is known in the literature, Prelued has been successfully applied to several ecosystems, but mainly in evergreen coniferous forest from northern latitudes (Mäkelä et al., 2008; McCallum et al., 2013; Peltoniemi et al., 2012). Most of the LUE-based models work at monthly or annual time scale, and rely on a linear relationship between GPP and absorbed photosynthetically active radiation (APAR) and on a parabolic effect of temperature. Conversely, the Prelued model replicates GPP at a daily time scale, based on a nonlinear relationship between APAR and GPP (Medlyn et al., 2003; Turner et al., 2003), a saturating effect of average daily temperature (which simulates the ecosystem acclimation to temperature, Mäkelä et al. (2004)), and daily meteorological and environmental variables. Such response to these environmental variables improves the fit of the model especially in temperature-controlled ecosystems (McCallum et al., 2013).

One of the critical aspects in the application of Prelued is the estimation of the model parameters and of the uncertainty associated with them. For this purpose we considered the application of the Bayesian model calibration, a method that has become more and more popular in the last few years to obtain insights on both model predictions and uncertainties. The main characteristic of a Bayesian calibration is that it quantifies model inputs and outputs in the form of probability distributions, and applies the rules of probability theory to update the distributions when new data are obtained (Sivia, 1996 Van Oijen et al., 2005). This approach has been widely used in different fields, and recently also to a large number of forest models with different structure and aims (Chevallier et al., 2006; Jansson et al., 2008 Van Oijen et al., 2005 Van Oijen et al., 2011). Even so, the application of the bayesian method to LUE-based models is not as common as its application to process-based models, with a very few studies heading in this direction (Still et al., 2004; Xenakis et al., 2008).

In this study, we applied the Prelued model to eight italian eddy-covariance forest sites, with a Bayesian approach to calibration, and studied in detail the trend in the responses to environmental variables in each site to detect their importance in driving daily GPP. To our knowledge, this model has never been applied before to ecosystems characterized by such a wide range of climatic and environmental conditions. Moreover, since Prelued has never been calibrated following a Bayesian approach, before this study there was no information in the existing literature about uncertainties around the parameter values, nor about uncertainties on the model estimates. The aims of this work were therefore: 1) testing the ability of the Prelued model to simulate GPP at contrasting forest sites characterized by very different climates, elevations and plant functional types, 2) testing if the bayesian approach improves the model performances in respect to other methods, and 3) estimating uncertainties around both parameter values and model estimates of daily GPP..

2. Materials and methods

2.1. Model formulation

The model used in this study was a modified version of Prelued, a LUE-type model of daily photosynthetic production of the canopy, developed by Mäkelä et al. (2008). Daily GPP is calculated as follows:

$$\mathrm{GPP}_j = \beta \mathrm{APAR}_j \Pi_i \mathrm{F}_{ij} \tag{1}$$

where GPP_j is canopy gross primary production (gC m^{-2}) during day j, β is potential daily light use efficiency (gC mol^{-1}), APAR_j is absorbed photosynthetic active radiation (mol m^{-2}) during day j, and $\mathrm{F}_{ij} \in [0,1]$ are modifying factors accounting for suboptimal conditions in day j. The actual LUE of the canopy in day j is the product of β and the current values of the modifiers.

In the original version of the model, four modifiers were considered: a light modifier (FL) was defined so as to yield a rectangular hyperbola when multiplied with the linear response included in the LUE model, a temperature modifier (FS) was defined using the concept of state of acclimation (Mäkelä et al., 2004), a vapour pressure deficit (VPD) modifier (FD) was defined following Landsberg and Waring (1997), and a Soil Water Content (SWC) modifier (FW) was based on the relative extractable water, dependent on wilting point and field capacity.

Since the wilting point is a difficult variable to estimate, FW was reformulated as follows to avoid the need of wilting point as an input variable:

$$\mathrm{FW}_j = \begin{cases} 1 & \mathrm{SWC}_j > \theta_{\mathrm{FC}} \\ \left[1 + \left(\dfrac{\theta_{\mathrm{FC}} - \mathrm{SWC}_j}{\alpha}\right)^{\upsilon}\right]^{-1} & \mathrm{SWC}_j < \theta_{\mathrm{FC}} \end{cases} \tag{2}$$

where SWC_j is volumetric soil water content (SWC) (m^3 m^{-3}), θ_{FC} is SWC at field capacity and α' is the new parameter used instead of α, thus $\alpha' = \alpha\ (\theta_{\mathrm{FC}} - \theta_{\mathrm{WP}})$, where θ_{WP} is SWC at permanent wilting point (Mäkelä et al., 2008).