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# Modelling carbon budget of Mediterranean forests using ground and remote sensing measurements

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## Abstract

The current paper illustrates a method to operationally apply the model FOREST-BGC for the estimation of forest carbon fluxes in Mediterranean environments. The work was carried out in a pine forest stand within the coastal area of San Rossore (Central Italy) using both conventionally collected and remotely sensed data. The calibration of the model was performed using estimates of net primary productivity (NPP) derived from the carbon accumulated in the forest stems during the last four decades. Such estimates were obtained by transforming dendrochronological measurements collected in the stand into annual increments of woody biomass and carbon matter. Next, the model performance was validated against values of net ecosystem exchange (NEE) and gross primary productivity (GPP) collected during four years (1999–2002) by an eddy covariance flux tower. A method based on deriving fraction of photosynthetically active radiation (FAPAR) from remotely sensed normalised difference vegetation index (NDVI) data was also calibrated and validated in order to more directly assess forest GPP. The results achieved indicate that the multi-year calibration against past carbon accumulation was essential in properly configuring the model in terms of respiration and allocation functions. Due to the importance of these functions, only the calibrated model was in fact able to correctly simulate the forest carbon fluxes, giving monthly estimates of both NEE and GPP quite close to those measured by the flux tower. These estimates were further improved by the proper integration of remotely sensed GPP evaluation and model carbon partitioning, which could be particularly useful for operational monitoring applications on a regional scale.


*Keywords:* Mediterranean pine forest; FOREST-BGC; Dendrochronology; Eddy-covariance; Remote sensing; Data integration

*Abbreviations:* DBH, diameter at breast height; FAPAR, fraction of absorbed photosynthetically active radiation; FOREST-BGC, forest-biogeochemical cycles; C-FIX, carbon fixation; GPP, gross primary productivity; LAI, leaf area index; MVC, maximum value composite; NDVI, normalised difference vegetation index; NEE, net ecosystem exchange; NOAA, National Oceanic and Atmospheric Administration; AVHRR, advanced very high resolution radiometer; NPP, net primary productivity; SLA, specific leaf area; SPOT, Système Probatoire d'Observation de la Terre; VGT, VEGETATION

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## 1. Introduction

Forest ecosystems are an economic and environmental resource which is widely spread both at local and at global scale. One of the reasons for which, nowadays, they have such a great importance is linked to their essential role within the global carbon cycle (Schimel, 1995). Hence, there is the necessity for understanding their functions and behaviours, especially in relation to different environmental factors and human impacts (Waring and Running, 1998). Dealing with natural and semi-natural forest ecosystems, the uncertainty in determining carbon fluxes is very high since the numerous factors to consider are mostly unknown and the environmental parameters involved are spatially and temporally variable (Griffis et al., 2003).

To face these problems, ecological models have been proposed as essential tools to follow the main ecophysiological processes through terrestrial vegetation, especially dealing with large spatial and temporal scales. They in fact enable the detection and study of the effect of large-scale perturbations (e.g. global climate change and air pollution) on terrestrial environments (Waring and Running, 1998) and the quantification of the main bio-geo-chemical fluxes characterising all land ecosystems. Actually, modern models of ecosystem processes have reached high efficiency and accuracy, but their operational applicability is often limited by the numerous input parameters required, which may be difficult to collect for large vegetated areas. This is especially the case for the parameters describing forest composition and structure, such as tree species, density, age, leaf area index (LAI), etc., which are generally variable in space and/or time and difficult to measure by conventional methods (Lacaze et al., 1996).

In this context, remote sensing techniques have been proposed as a valuable instrument to collect information on terrestrial ecosystems because of their capability to provide synoptic data over wide spatial scales and with high acquisition frequency. These techniques offer the possibility of estimating some basic parameters which are descriptive of vegetation status (such as species, density, volume, etc.) and can, additionally, be used to constrain the functions of bio-geo-chemical models (Franklin et al., 1997). This last possibility is particularly attractive as a tool to circumvent the mentioned lack of spatial information on vegetation parameters useful as model inputs. In this way, the remotely sensed information can be merged with the model functions for a more accurate, spatially distributed simulation of vegetation processes (Waring and Running, 1998; Veroustraete et al., 2002; Running et al., 1989).

On the basis of these considerations, the current work aimed at developing and testing a methodology to apply a well-known model of forest ecosystem processes, FOREST-BGC (Running and Coughlan, 1988), for simulating carbon fluxes in Mediterranean areas. This model has already been applied in different environments all over the world. The performance of the model has been tested using both conventional (McLeod and Running, 1988; Hunt et al., 1991, etc.) and remote sensing inputs (Running et al., 1989; Nemani and Running, 1989; Liu et al., 1997, etc.), always achieving satisfactory results.

The work was carried out in San Rossore, a flat coastal area in Tuscany (Central Italy) mostly covered by Mediterranean pine forests which was a test site of the EU Projects MEDEFLU and CARBOEUROFLUX (http://www.bgc-jena.mpg.de/public/carboeur/projects/cef.html).

The investigation was focused on a stand dominated by *Pinus pinaster* Ait. where flux measurements have been taken by an eddy covariance tower since the end of 1998. The parameters needed to initialise and drive the model were collected from field measurements, the forest management plan of the area and forestry literature. The model was first calibrated against estimates of net primary productivity (NPP) obtained through the elaboration of dendrochronological measurements and forestry data. Next, it was validated against the monthly gross primary productivity (GPP) and net ecosystem exchange (NEE) measurements taken at the flux tower during four years.

Additionally, remotely sensed normalised difference vegetation index (NDVI) data taken by various satellite platforms were used to more directly estimate total forest production. This was obtained through the well-known relationship which links NDVI to the fraction of absorbed photosynthetically active radiation (FAPAR) (Myneni and Williams, 1994). In this way, the hypothesis was tested that the integration of GPP estimates and model functions could render the evaluation of forest carbon budget more direct and efficient.

## 2. The model FOREST-BGC

FOREST-BGC was developed at the University of Montana in order to describe the status of North American homogeneous coniferous forests (Running and Coughlan, 1988; Running and Gower, 1991). The model is able to determine and quantify the most important bio-geo-chemical cycles occurring within numerous forest ecosystems at different temporal scale