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Application of BIOME-BGC to simulate Mediterranean forest processes

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ABSTRACT

The current work investigates on the applicability of a widespread bio-geochemical model (BIOME-BGC) to estimate seasonal photosynthesis and transpiration within water limited Mediterranean forest environments. The use of the model required a preliminary calibration phase, aimed at setting its ecophysiological parameters to properly simulate the behavior of three Mediterranean species (*Quercus ilex* L., *Quercus cerris* L. and *Pinus pinaster* Ait.). For each of these species, the calibration of BIOME-BGC was performed by adjusting the monthly gross primary productivity (GPP) estimates of 10 forest plots to those of a simplified parametric model, C-Fix, which is based on the use of satellite and ancillary data. In particular, BIOME-BGC was run modifying the eco-physiological parameters controlling stomatal conductance, in order to identify the best model configurations to reproduce the spatial, intra- and inter-annual GPP variations simulated by C-Fix. Next, the fraction of leaf nitrogen in Rubisco was adjusted to fit also the magnitudes of the C-Fix GPP estimates. The subsequent testing phase consisted of applying the original and calibrated versions of BIOME-BGC in independent forest sites where the three species considered were dominant and for which field measurements of photosynthesis and transpiration were available. In all cases the use of the calibrated BIOME-BGC versions led to notably improve the GPP and transpiration estimation accuracy of the original model. The results obtained encourage the operational application of BIOME-BGC in Mediterranean forest environments and indicate a possible strategy to integrate its functions with those of C-Fix.

1. Introduction

Forest ecosystems are an environmental and economic resource which is still widely spread. Some authors suggest that their extension is about 40% of the Earth's ice-free land surface and that this is less than the potential extension due to human disturbances (Waring and Running, 1998). Forests are able to provide numerous wood products (e.g. timber, paper products, etc.), prevent soil erosion, contribute to maintain biodiversity and are often used for recreational purposes; additionally they have a great role both in the water and carbon cycles (Waring and Running, 1998). Hence, the estimation of forest ecosystem processes and their variations in time and space is one of the main objectives of applied ecological studies. In general, such estimation is necessary to advance towards sustainable management of forest resources, both on a local and on a regional scale. Specifically, the necessity for monitoring and quantifying the

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amount of carbon accumulated within forests has recently increased also in view of the application of the Kyoto Protocol and related documents (IPPC, 2001).

Numerous studies have been recently conducted and trials have been performed to produce estimates of forest processes on different spatial and temporal scales using various instruments (i.e. eddy-covariance techniques, satellite images, biogeochemical models, etc.). Among the proposed methodologies, those based on the use of remote sensing data and ecosystem simulation models are particularly promising. More specifically, the former have been demonstrated to be efficient in providing direct estimates of vegetation conditions (e.g. LAI, FAPAR, etc.) related to global forest productivity (Waring and Running, 1998; Maselli et al., 2006). Ecosystem simulation models are instead efficient means to combine data from different sources (meteorological and soil measurements, structural and eco-physiological information, etc.) for a more complete characterization of vegetation processes (transpiration, photosynthesis, respirations, allocations, etc.).

The application of both tools, however, encounters specific difficulties in Mediterranean environments, which are characteristic for their climatic and human-induced features. Mediterranean climate is in fact unique for its warm and dry summer season and for its mild and relatively rainy winter. To adapt to such conditions, Mediterranean vegetation has developed specific morphological and physiological features (Odum, 1971). Moreover, Mediterranean environments are characterized by mosaic landscapes generated by a long history of human activities (Van der Leew, 1998). These characteristics cause extreme spatial and temporal heterogeneity of these environments, which makes their study particularly complex (Lacaze et al., 1996; Bolle et al., 2006).

Building on these premises, the current investigation aimed at evaluating the possibility of routinely modelling major forest processes (i.e. photosynthesis and transpiration) in a typical Mediterranean region (Tuscany, Central Italy). The research was not directed to inter-compare the performances of different models of forest ecosystem processes, which was the subject of previous investigations (e.g. Cramer et al., 1999; Coops et al., 2001). Instead, the focus was on the development of a robust methodology to apply one of the most known of these models, BIOME-Bio Geochemical Cycles (BGC). This model was selected among the possible alternatives due to its specific suitability to provide information on the water, carbon and nitrogen cycles within forest and non-forest ecosystems (Running and Hunt, 1993; White et al., 2000). Additionally, the model is the natural evolution of FOREST-BGC, which was found to be capable of properly simulating transpiration and photosynthetic processes of Mediterranean forest ecosystems (Chiesi et al., 2002, 2005; Anselmi et al., 2004).

BIOME-BGC, however, has found only a few and incomplete applications in Mediterranean areas (Mollicone et al., 2003). Thus, a primary effort was directed to develop a calibration procedure capable of adapting the model to environments different from those for which it was originally created. This procedure relies on the use of monthly GPP estimates derived from an NDVI-based parametric model (C-Fix), which was recently demonstrated to accurately depict productivity features of existing Italian forests (Maselli et al., 2006). The procedure was applied to modify the original BIOME-BGC configurations and simulate the productivity features of three Mediterranean forest species which are typical of Tuscany (Central Italy). Next, the performances of the model were evaluated against existing transpiration and GPP measurements available for the selected three BIOME types.

The current paper first introduces the two models used, C-Fix and BIOME-BGC. This is followed by a description of the study areas and data considered. Next, the data processing and results sections are presented, divided into the following two steps:

1. The first, the calibration phase, is directed to identify optimal BIOME-BGC configurations to characterize the three chosen Mediterranean forest types (*Quercus ilex* L., *Quercus cerris* L. and *Pinus pinaster* Ait.). To this aim, 10 forest plots for each species were selected all over Tuscany and monthly GPP values of 5 years were computed for all of them by using C-Fix. These GPP values were used as reference to calibrate the original BIOME-BGC configurations.
2. The second, the validation phase, consists of applying the original and calibrated versions of BIOME-BGC in three additional forest sites (one for each forest species considered) and evaluating their outputs against independent series of field data (i.e. transpiration and GPP measurements).

The paper concludes with a discussion of the problems encountered and of the future perspectives of the work.

2. Models of forest ecosystem processes

Several models of forest ecosystem processes have been developed and applied to estimate regional and global productivity. They are generally based on various simplifying assumptions and use different formulations and input environmental variables (Cramer et al., 1999). As reported in Matsushita et al. (2004), these models have been categorized into three groups:

- statistical models,
- parametric models and
- process models.

Each group of models has its strengths and limitations. Statistical models are well known for their simplicity but limited generality (Lieth, 1975); parametric models take the advantage of using remote sensing data, but, relying on empirical relationships/constants (e.g. light-use efficiency), lose the link to some critical ecological processes (Potter et al., 1993); process models are based on current knowledge of major ecological/biophysical processes, but suffer from high complexity, difficult calibration, and great computational intensity (Foley, 1994; Liu et al., 1997).

The current approach tends to exploit the advantages of a parametric model (C-Fix) to guide the calibration of a process-based model (BIOME-BGC). The latter is then used to estimate forest photosynthesis and transpiration in a Mediterranean region. The main features of these two models are described in the next sections.

2.1. C-Fix

The C-Fix model, originally presented by Veroustraete et al. (1994), estimates the gross primary production of a forest (GPP) as function of photosynthetically active radiation absorbed by vegetation (APAR) (Veroustraete et al., 2002; Veroustraete et al., 2004). Satellite derived FAPAR estimates must be combined with ground data of incoming solar radiation and air temperature, which are jointly used to simulate first gross photosynthesis and then net carbon accumulation by subtracting autotrophic and heterotrophic respirations. Estimates of GPP can thus be obtained, together with those of net primary production (NPP) and net ecosystem exchange (NEE), which are however less precise due to the more complex estimation of autotrophic and heterotrophic respirations (Veroustraete et al., 2002; Maselli and Chiesi, 2005).

The estimation of GPP is made through the general equation:

$$GPP = \varepsilon \sum_{i=1}^{N} T_{cor_i} FAPAR_i Rad_i \quad (1)$$

where ε is the radiation use efficiency (set equal to 1.1 gC/MJ APAR, according to Veroustraete et al., 2002), N the number of periods considered, T_{cor} a factor accounting for the dependence of photosynthesis on air temperature T_i, $FAPAR_i$ the fraction of absorbed photosynthetically active radiation, and Rad_i is the solar incident PAR, all referred to period i.

$FAPAR_i$ is estimated as a function of the top of canopy NDVI in the same period ($NDVI_i$) according to the expression proposed by Myneni and Williams (1994):

$$FAPAR_i = a\, NDVI_i + b \quad (2)$$

where the two empirical coefficients a and b are 1.1638 and −0.1426, respectively (Myneni and Williams, 1994).

C-Fix can use inputs averaged over different time periods (most commonly 10-day to monthly). Its applicability to estimate yearly and monthly forest GPP in Italy has been successfully tested by Maselli et al. (2006).

2.2. BIOME-BGC

BIOME-BGC is a bio-geochemical model developed at the University of Montana (Running and Hunt, 1993; White et al., 2000) to estimate the storage and fluxes of carbon, nitrogen and water within terrestrial ecosystems. It requires: daily climate data, information of the general environment (i.e. soil, vegetation and site conditions) and parameters describing the ecophysiological characteristics of vegetation. Differently from its precursor FOREST-BGC (Running and Coughlan, 1988), BIOME-BGC does not require any information on soil carbon or leaf area index (LAI) of the examined stands. The latter model is in fact capable of finding a quasi-climax equilibrium with local eco-climatic conditions through the spin-up phase (White et al., 2000). Consequently, BIOME-BGC outputs are useful to:

- establishing the amount and distribution of C storage by plants;
- predicting the behaviour of different ecosystems in case of changes of CO_2 concentration in the air;
- exploring the controls of water stress and drought on plant carbon balances;
- exploring the inter-annual variability of climate on growing season;
- furnishing important parameters useful to manage the ecosystems and in particular forests.

The version of the model currently used includes complete parameter settings for different groups of biomes (i.e. evergreen neddleleaf, evergreen broadleaf, deciduous broadleaf, shrub, C3 and C4).

3. Study areas

Both calibration and validation phases concerned three Mediterranean forest ecosystems characterized by the presence of Holm oak (*Q. ilex*, evergreen broadleaf), Turkey oak (*Q. cerris*, deciduous broadleaf) and Maritime pine (*P. pinaster*, evergreen needleleaf). Tuscany was selected for the calibration phase due to the availability of several information layers characterizing the whole region. The testing phase was carried out in three forest sites in Central Italy (Castelporziano, San Rossore and Radicondoli; Fig. 1) where the selected species were dominant and field measurements of transpiration and photosynthesis were available.

3.1. Tuscany

Tuscany is the widest region in Central Italy and is situated between 9–12° East longitude and 42–44° North latitude. From an environmental point of view, it is peculiar for its extremely heterogeneous morphological and climatic features. The

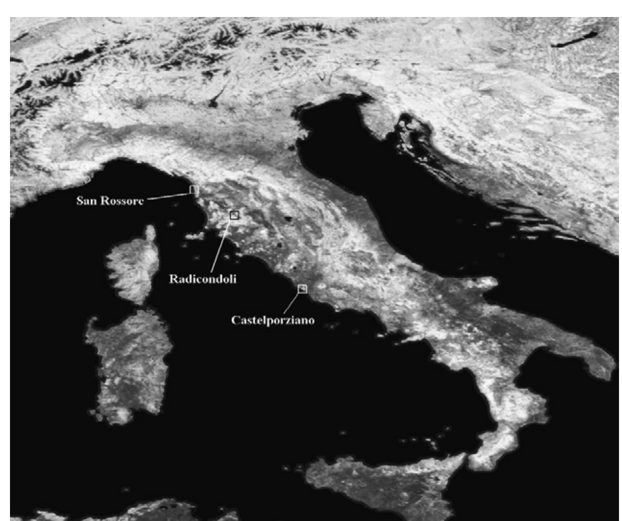

Fig. 1 – NDVI-VGT image of August 2003; the three test sites are indicated.

topography ranges from flat areas near the coast-line and along the principal river valleys, to hilly and mountainous zones towards the Apennines chain. Approximately 2/3 of the region is covered by hilly areas, 1/5 by mountains and only 1/10 by plains and valleys. From a climatic viewpoint, Tuscany is influenced by its complex orographic structure and by the direction of the prevalent airflows (from West/North-West). As a result, the climate ranges from typically Mediterranean to temperate warm or cool according to the altitudinal and latitudinal gradients and the distance from the sea (Rapetti and Vittorini, 1995).

The land use is predominantly agricultural where the land is flat and mixed agricultural and forestry in the hilly and mountainous areas. The main forest types are dominated by various oak types (*Q. ilex*, *Q. pubescens* Willd., *Q. cerris*), some Mediterranean pines (*Pinus pinea* L., *P. pinaster*), chestnut (*Castanea sativa* Mill.), beech (*Fagus sylvatica* L.), white fir (*Abies alba* Mill.) and other minor coniferous and deciduous species (*Pinus nigra* Arnold, *Ostrya carpinifolia* Scop., *Robinia pseudoacacia* L., *Pseudotsuga menziesii* Franco and *Cupressus sempervirens* L.).

3.2. *Castelporziano*

The Presidential Estate of Castelporziano is located at about 20 km from Rome (41.71°N, 13.63°E; Fig. 1) and covers an area of 6100 ha. This area is fairly flat, ranging from sea level to 85 m a.s.l. The climate is of Lower Mesomediterranean Thermotype, Upper Arid/Lower Subhumid Ombrotype (Blasi, 1994).

The wood of Castelporziano (about 100 ha) is a rare example of Holm-oak forest belonging to the *Viburno-Quercetum ilicis* (Br.-Bl. 1936) Rivas-Martinez (1975) association. This association is the warmest and most thermophilous type of such woods in Italy, and grows in a coastal environment on consolidated dunes and on sea-facing slopes (Pignatti, 1998).

3.3. *San Rossore*

This test site is included within the Natural Park of San Rossore (43.23°N, 11.07°E, Fig. 1). This is a protected flat area with sandy soils partly affected by salinity (DREAM, 2003). The climate is Mediterranean sub-humid (Rapetti and Vittorini, 1995) with average yearly temperature of 14.8 °C and rainfall of about 900 mm. The area adjacent to the sea is dominated by the presence of a Mediterranean pine forest (both *P. pinaster* and *P. pinea*).

The test was focused on a homogeneous Maritime pine (*P. pinaster*) stand within which canopy flux measurements are being collected by an eddy covariance tower since the end of 1998. The stand is located about 700 m East from the seashore. The average stand height is 18 m, the average diameter at breast height (DBH) of *P. pinaster* trees is 29 cm and the stand density is 565 ha^{-1} (84% *P. pinaster*, 12% *P. pinea* and 4% *Q. ilex*).

3.4. *Radicondoli*

The Radicondoli study area is situated in the centre of Tuscany (43.23°N, 11.07°E, Fig. 1). The terrain is mainly hilly, with elevation ranging from 300 to 900 m. The climate is Mediterranean sub-humid (Rapetti and Vittorini, 1995), with mean annual rainfall around 800 mm, temperature around 15 °C, mild winters and long dry summers.

The land cover is characterised by the alternation of agricultural fields, pastures and wood-lands. Two main forest areas are present, which cover about 70% of the land surface. Both areas are dominated by different deciduous species, with the presence of some conifers (mainly pines) artificially introduced to increase land productivity. Among the deciduous species, two Mediterranean oaks, *Q. pubescens* and *Q. cerris*, are by far the most common, but other broadleaved species can also be found such as *Ostrya carpinifolia* Scop., *Acer campestre* L. and *Fraxinus ornus* L. The current test was conducted within a stand dominated by Turkey oak (*Q. cerris*), for which transpiration measurements were available.

4. Study data

4.1. *Digital maps*

A Digital Terrain Model (DTM) of the study region was derived from the Regional Cartographic Service of Tuscany. This DTM has a spatial resolution of 200 m.

The digital forest map produced by Arrigoni et al. (1998) was taken from the same Service. This map describes the distribution of 18 different forest classes at 1:250.000 spatial resolution.

4.2. *Meteorological data*

Daily maximum and minimum temperatures and total precipitation were derived from the regional weather network for the years 1999–2003. In particular, daily maximum and minimum temperatures and daily total precipitation were collected from 94 and 159 stations, respectively.

The same daily meteorological data (maximum and minimum temperatures and precipitation) were obtained for the three test sites considered. Specifically, these data were downloaded from the web for Castelporziano (http://www.fluxnet.ornl.gov/fluxnet/) and derived from the records of two adjacent stations for San Rossore and Radicondoli (Chiesi et al., 2005; Chiesi et al., 2002).

4.3. *Satellite data*

The two Landsat TM/ETM+ scenes currently used were taken in 2000, the first in early spring (March) and the second in summer (July). These scenes were completely cloud free and unaffected by serious atmospheric perturbations all over Tuscany.

NDVI data taken by the Spot-VEGETATION sensor were selected as low spatial resolution satellite imagery. These data were the only which covered the whole study period (1999–2003) and had a radiometric and geometric quality decidedly higher than that of NOAA-AVHRR images (Bolle et al., 2006). The spot images used are freely provided in a pre-processed NDVI format by the Flemish Institute for Technological Research (VITO), Belgium. The pre-processing steps applied comprise the radiometric calibration of the original channels, their geometric registration and an atmospheric correction accounting for molecular and aerosol scattering, water vapour, ozone and other gas absorption (Maisongrande et al., 2004). Next, NDVI images are computed and composited on a 10-day basis (Holben, 1986).

4.4. Reference data: LAI, transpiration and GPP measurements

Reference data were collected by different techniques in three independent forest sites. For all three sites leaf area index (LAI) measurements were taken by means of the LICOR 2000 instrument. In two study sites (Castelporziano and San Rossore) forest GPP data were collected by the eddy-correlation technique. In particular, at Castelporziano monthly GPP data were downloaded from the FLUXNET website (http://www.fluxnet.ornl.gov/fluxnet/) for 1 year (1997), while at San Rossore the same data were available for the years 2000–2002 (Tirone, 2003). In the third study area (Radicondoli), transpiration measurements were collected during the growing season of 1998. Such data were derived from sap flow measurements taken within 20 trees representative of all specific diameter classes of the study stand (Chiesi et al., 2002).

5. Methodology

5.1. Extension of meteorological data

The extrapolation of the daily temperature and rainfall data recorded in the weather stations over the regional surface was carried out by means of the DAYMET procedure (Thornton et al., 1997). DAYMET is a software package that produces surfaces of daily temperature, precipitation, radiation and humidity over large regions, taking into account the effects of complex terrain. Observations can be included from an arbitrarily large number of stations. The relationships of temperature and precipitation to elevation are determined directly from the observations. In addition to the daily observations from a network of stations, DAYMET requires a DTM of the region of interest.

The extrapolation method is based on the spatial convolution of a truncated Gaussian weighting filter with the set of station locations. The sensitivity to the typical heterogeneous distribution of stations is regulated by an iterative station density estimation algorithm. The extrapolation is made by a locally weighted least-square regression where the independent variable is the difference in elevation associated to a pair of stations and the dependent variable is the difference in the estimated meteorological parameter on the same pair of stations. The regression is calculated over all unique pairs of station used to estimate the meteorological parameter of the point examined.

These relationships vary in space and time, and DAYMET makes a new diagnosis of these relationships for each spatial modelling unit and for each day of observed conditions. Precipitation estimates are performed in two steps: first a binary estimate of precipitation occurrence, and contingent on occurrence, then an estimation of precipitation amount, corrected for elevation effects. Radiation and humidity are estimated using the same relationships as in the MT-CLIM model, following the completion of temperature and precipitation estimates (Running et al., 1987; Kimball et al., 1997; Thornton and Running, 1999; Thornton et al., 2000).

In this work, a cross validation analysis was performed to test the sensitivity of this procedure to variation of parameters and to estimate the errors associated with the final selected parameters. This analysis was performed for a period of 2 years (1996–1997) using a weather station dataset covering homogeneously the Tuscany region. This dataset included 94 stations measuring minimum and maximum temperature and 159 stations for rainfall. The previously described DEM of Tuscany having 200 m spatial resolution was used as the base of the interpolation. For each of the three variables (minimum and maximum temperature, rainfall), the shape parameter of the Gaussian filter (α), the average station number with non-zero weight (N) and the critical value for rainfall occurrence (POPcrit) were independently estimated by an iterative procedure. The error associated to each iteration was expressed as mean absolute error (MAE). Parameters associated to the lower MAE in the period 1996–1997 were the following: $\alpha = 4$, $N = 30$ for maximum temperature; $\alpha = 3.5$, $N = 22$ for minimum temperature; $\alpha = 7$, $N = 17$ and POPcrit = 0.52 for rainfall. The associated errors were 1.74 °C (MAE, daily basis) for maximum temperature, 1.4 °C (MAE, daily basis) for minimum temperature and 14 cm (MAE, annual basis) for rainfall. These calibrated parameters were then used for variables estimation over the whole study period (1999–2003).

5.2. Pre-processing of remotely sensed data

The two Landsat TM scenes of 2000 were georeferenced by a nearest neighbor resampling algorithm trained on 120 ground control points, obtaining a positional accuracy of about 1 pixel. Since these images had to be simply used for photo-interpretation, no algorithm was applied for their atmospheric or topographic correction.

The Spot NDVI data were pre-processed to remove all residual cloud contaminations. The procedure to reduce these defects, fully described in Escadafal et al. (2001), consisted of a preliminary filtering applied to all original 10-day MVCs in order to remove isolated pixels with anomalous NDVI values and replace them with local NDVI averages. Next, a further MVC algorithm was applied on a monthly basis (Holben, 1986) to obtain monthly images for the period 1999–2003.

5.3. Calibration phase

5.3.1. Creation of the reference GPP monthly estimates

The use of GPP estimates produced by C-Fix to calibrate BIOME-BGC relies on the assumption that the former model is capable of faithfully describing the gross productivity behaviour of existing forest ecosystems, at least on a regional scale. This capacity has been demonstrated in several case studies (Veroustraete et al., 2002, 2004) and has been confirmed in Italy by Maselli et al. (2006).

Different forest sites characterized by the presence of Holm oak, Turkey oak and Maritime pine were selected using the previously described forest map and Landsat TM/ETM+ images. In particular, 10 plots were chosen in relatively large areas (at least 2 km × 2 km) where each of the three forest species was dominant according to the Arrigoni's map (Arrigoni et al., 1998). The homogeneity in forest type of each plot was checked by visual examination of the two TM scenes, which confirmed the presence of evergreen/deciduous and broadleaved/coniferous species.

Daily meteorological data were extracted from the maps produced by DAYMET over 5 pixel × 5 pixel (1 km × 1 km) windows placed in correspondence to the selected 30 forest plots. For the same points, daily solar radiation estimates were produced by applying MT-CLIM (Running et al., 1987). Similarly, monthly NDVI data were extracted from the VGT pixels (1 km × 1 km) corresponding to the 30 forest plots.

Using these meteorological and NDVI data, C-Fix was applied to estimate GPP for all 30 forest plots on a monthly basis during the entire study periods (1999–2003). Thus, 600 GPP estimates (10 plots × 5 years × 12 months) were obtained for each forest type, covering most relevant spatial and temporal (intra and inter-year) variability over the study region. These 600 estimates were usable as a reference data set for the calibration of BIOME-BGC.

5.3.2. *Parameter setting of BIOME-BGC*

The calibration of BIOME-BGC was carried out by adjusting its monthly GPP outputs to reproduce the relevant C-Fix estimates for each species considered. BIOME-BGC was therefore applied to simulate the GPP behaviour of all study plots by using the available environmental and meteorological data. Among the BIOME-BGC initialization parameters, only those related to geographical position and terrain morphology were modified for each plot, while those descriptive of soil features were kept all equal to medium conditions due to the lack of relevant information for the entire regional area. All BIOME-BGC simulations were performed running the model in a "spin-up and go" mode, i.e. preliminarily finding an internal equilibrium of the model state variables (White et al., 2000). Concerning the eco-physiological parameter settings, the first trials were performed using the default biome type parameterization (i.e. *ebf*, evergreen broadleaf forest, for Holm oak; *enf*, evergreen needleleaf forest, for Maritime pine; *dbf*, deciduous broadleaf forest, for Turkey oak). These default parameters are shown in Table 1. The only deciduous species considered, Turkey oak, had a parameterization slightly different from the others, due to the choice of not using BIOME-BGC model phenology. In this case, the onset and end of the growing season were imposed to each plot considering the relevant mean daily air temperature values filtered by a moving average of order 31 (i.e. on a monthly basis). The growing season was defined as the period with filtered mean temperature higher than 10 °C.

Since both spatial and temporal GPP variations and total GPP values had to be adjusted for each species, the model calibration was performed in two steps. First, starting from the default parameter settings, different model runs were carried out modifying the maximum stomatal conductance and associated cuticolar conductance. These conductances are in fact the main parameters which regulate the resistance of forest species to summer drought, which is a typical Mediterranean feature. The 600 simulated monthly GPP values of each species were regressed against the reference data obtained by C-Fix in order to find correlation maxima which could be indicative of the optimal reproduction of spatial and temporal GPP variations.

The same operation was repeated after limiting the sensitivity of the model response to water stress, which could serve to more faithfully reproduce the behaviour of Mediterranean ecosystems. This was obtained by modifying the parameters related to vapour pressure deficit (VPD) and leaf water potential (LWP), which regulate stomata closure. These parameters were proportionally reduced within acceptable ranges (0.5–1.0 of the original values), still with the aim of identifying absolute correlation maxima.

The optimal configuration found in terms of stomatal and cuticolar conductances for each of the three species was used as a basis for driving further model simulations aimed at making the two data series (from C-Fix and BIOME-BGC) similar also in terms of average GPP values. This was obtained by modifying the fraction of leaf nitrogen content in Rubisco, which expresses the photosynthetic efficiency of the species, in order to minimize the root mean quadratic differences (root mean square error, RMSE) between the two GPP data sets.

5.4. *Validation phase*

The validation phase consisted of applying both the original and calibrated BIOME-BGC configurations to the three ecosystems for which field measurements were available. In these cases the standard daily meteorological data derived from adjacent stations (minimum and maximum temperatures and precipitation) were utilised to preliminarily drive MT-CLIM.

The BIOME-BGC outputs were evaluated by comparison with the described reference data, which were monthly GPP data for Castelporziano and San Rossore taken in 1997 and 2000–2002, respectively, and daily transpiration measurements for Radicondoli, taken in 1998. In all cases the accordance between measured and estimated data was summarised by means of conventional accuracy statistics (correlation coefficient, r, and root mean square error, RMSE).

6. Results

6.1. *Calibration phase*

The mean monthly GPP estimates of the 10 study plots produced by C-Fix are shown in Fig. 2. Globally, Turkey

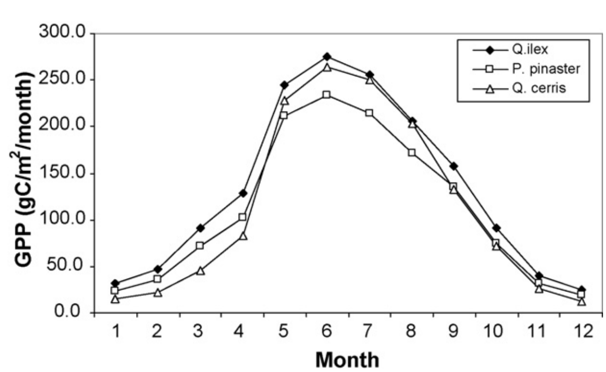

Fig. 2 – Mean monthly GPP values produced by C-Fix.

Table 1 – Default parameter setting of BIOME-BGC for the three forest species considered

Keyword	*Quercus ilex*	*Pinus pinaster* (ENF)	*Quercus cerris*
Woody/non-woody flag	1	1	1
Evergreen/deciduous flag	1	1	0
C3/C4 flag	1	1	1
Model phenology/user specified	1	1	0
ONDAY	0	0	100
OFFDAY	0	0	300
Transfer growth period as fraction of growing season (prop.)	0.2	0.3	0.2
Litterfall as fraction of growing season (prop.)	0.2	0.3	0.2
Annual leaf and fine root turnover fraction ($year^{-1}$)	0.5	0.33	1
Annual live wood turnover fraction ($year^{-1}$)	0.7	0.7	0.7
Annual whole plant mortality fraction ($year^{-1}$)	0.005	0.005	0.005
Annual fire mortality fraction ($year^{-1}$)	0.002	0	0
Allocation new fine root C:new leaf C (ratio)	1	1.4	1.2
Allocation new stem C:new leaf C (ratio)	2.2	2.2	2.2
Allocation new live wood C:new total wood C (ratio)	0.16	0.071	0.16
Allocation new coarse root C:new stem C (ratio)	0.22	0.29	0.22
Allocation current growth proportion (prop.)	0.5	0.5	0.5
C:N of leaves (kgC/kgN)	42	42	25
C:N of leaf litter (kgC/kgN)	49	93	55
C:N of fine roots (kgC/kgN)	42	58	48
C:N of live wood (kgC/kgN)	42	58	48
C:N of dead wood (kgC/kgN)	300	730	550
Leaf litter labile proportion (dim)	0.32	0.31	0.38
Leaf litter cellulose proportion (dim)	0.44	0.45	0.44
Leaf litter lignin proportion (dim)	0.24	0.24	0.18
Fine root labile proportion (dim)	0.34	0.34	0.34
Fine root cellulose proportion (dim)	0.44	0.44	0.44
Fine root lignin proportion (dim)	0.22	0.22	0.22
Dead wood cellulose proportion (dim)	0.76	0.71	0.77
Dead wood lignin proportion (dim)	0.24	0.29	0.23
Canopy water interception coefficient (1/LAI/d)	0.045	0.045	0.045
Canopy light extinction coefficient (dim)	0.7	0.51	0.54
All-sided to projected leaf area ratio (dim)	2	2.6	2
Canopy average specific leaf area (m^2/kgC)	8.2	8.2	32
Ratio of shaded SLA:sunlit SLA (dim)	2	2	2
Fraction of leaf N in Rubisco (dim)	0.033	0.04	0.033
Maximum stomatal conductance (m/s)	0.006	0.006	0.006
Cuticular conductance (m/s)	0.00006	0.00006	0.00006
Boundary layer conductance (m/s)	0.01	0.09	0.01
Leaf water potential: start of conductance reduction (MPa)	−0.6	−0.65	−0.34
Leaf water potential: complete conductance reduction (MPa)	−3.9	−2.5	−2.2
Vapor pressure deficit: start of conductance reduction (Pa)	1800	610	1100
Vapor pressure deficit: complete conductance reduction (Pa)	4100	3100	3600

oak and Maritime pine had similar GPP integrals (1355 and 1325 gC/(m^2 year), respectively) which were lower than those of Holm oak (1594 gC/(m^2 year)). The seasonal variation of Turkey oak was higher than that of the other two species. Both these findings are in accordance with the eco-physiology of these trees, since Turkey oak is the only deciduous species and *Q. ilex* that living in warmest areas.

The results obtained during the first step of the performed BIOME-BGC calibration are summarized in Fig. 3. The curves show the highest correlations found for the three study

Table 2 – List of the eco-physiological parameters modified to correctly initialise BIOME-BGC

	Q. ilex	*P. pinaster*	*Q. cerris*
Fraction of leaf N in Rubisco	0.033	0.021	0.044
Maximum stomatal conductance (m/s)	0.0010	0.0015	0.0018
Cuticolar conductance (m/s)	0.000010	0.000015	0.000018
Leaf water potential: start of conductance reduction (MPa)	−0.48	−0.65	−0.272
Leaf water potential: complete conductance reduction (MPa)	−3.12	−2.5	−1.76
Vapor pressure deficit: start of conductance reduction (Pa)	1440	610	880
Vapor pressure deficit: complete conductance reduction (Pa)	3280	3100	2880

The PSI and VPD values of *Q. ilex* and *Q. cerris* were obtained by multiplying for 0.8 the default model parameters.

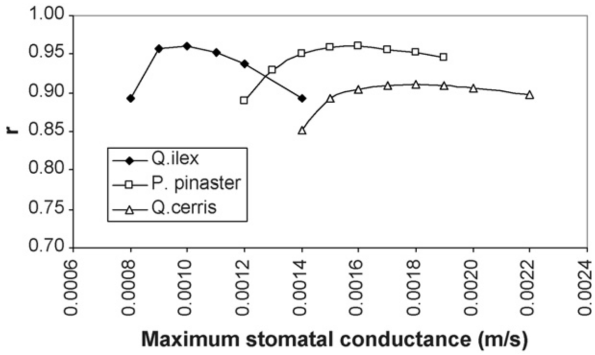

Fig. 3 – Correlation coefficients obtained by comparing the GPP estimates of C-Fix to those of BIOME-BGC obtained with different maximum stomatal conductances. The highest correlations were obtained with stomatal conductance equal to 0.0010 m/s for Holm oak, 0.0015 m/s for Maritime pine and 0.0018 m/s for Turkey oak (see text for details).

species using different values of maximum stomatal and cuticolar conductances. These correlations derive from the use of default VPD and LWP parameters for Maritime pine, and of VPD and LWP multiplied by 0.8 for Holm oak and Turkey oak. High correlation values were found in most cases, partly due to the expected similar reproduction of intra-year (seasonal) GPP patterns. More importantly, different correlation maxima were identified for the three species, which are summarized in Table 2. These values are generally in accordance with auto-ecological considerations, being Holm oak the most thermophilous and Turkey oak the most hygrophilous species (Anselmi et al., 2004).

The results achieved during the following identification of the correct fraction of leaf nitrogen in Rubisco are summarized again in Table 2. The scatter plots corresponding to the optimal agreements between C-Fix and BIOME-BCG monthly GPP estimates are shown in Fig. 4a–c. In general, good accordance can be observed for all three species, testified by correlation coefficients higher than 0.9 and RMSEs lower than 50 gC/(m^2 month).

Table 3 reports the correlation coefficients (r) computed considering separately the different sources of GPP variations (spatial, intra and inter-annual). As expected, fairly good agreements were achieved in the case of intra-annual variation for all species, mostly due to a similar reproduction of the seasonal GPP profile by the two models. Lower and only partly significant correlations were instead found in the case of inter-annual and spatial variations, which are more difficult to simulate. This indicates that BIOME-BGC is globally capable of reproducing GPP patterns estimated by C-Fix in Mediterranean environments. This is true mainly for intra-annual

Table 3 – Correlations obtained between C-Fix and BIOME-BGC intra-annual, inter-annual and spatial GPP variations

	Q. ilex	*P. pinaster*	*Q. cerris*
Intra-annual variation (12 points)	0.983**	0.980**	0.944**
Inter-annual variation (five points)	0.958**	0.710	−0.085
Spatial variation (10 points)	0.666*	0.898**	0.525

*Significant correlation, $P < 0.05$; **highly significant correlation, $P < 0.01$

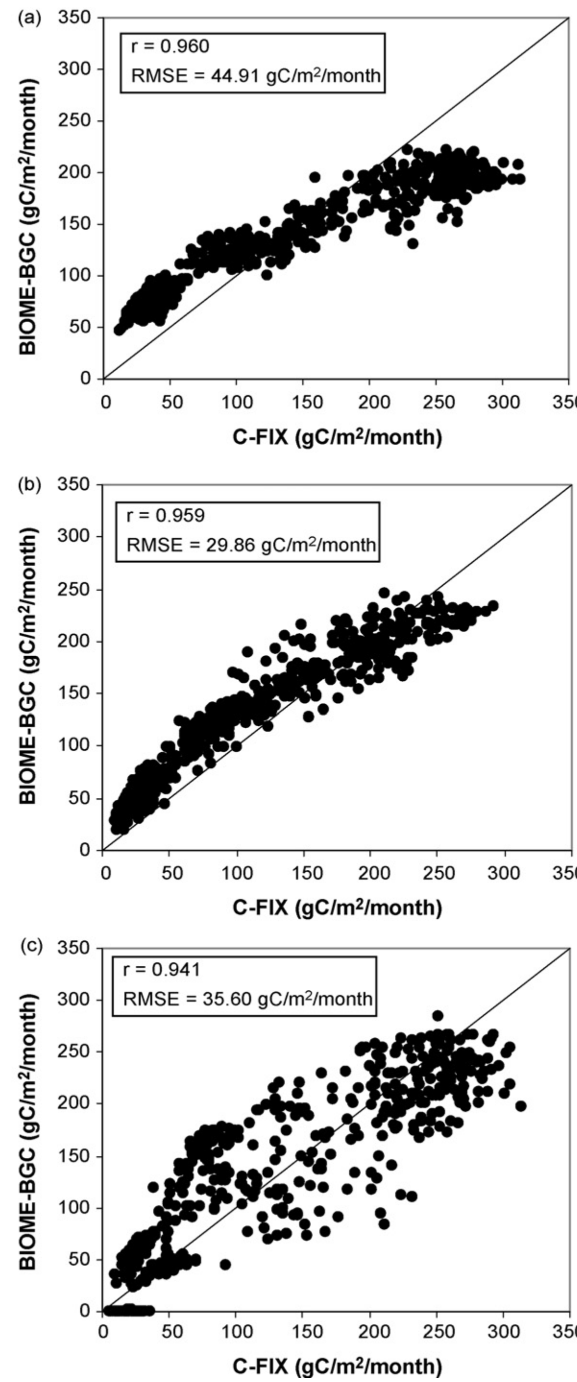

Fig. 4 – (a–c) Comparisons of monthly GPP values obtained by using C-Fix and calibrated BIOME-BGC for *Q. ilex* (a), *P. pinaster* (b) and *Q. cerris* (c). All correlations are highly significant, $P < 0.01$.

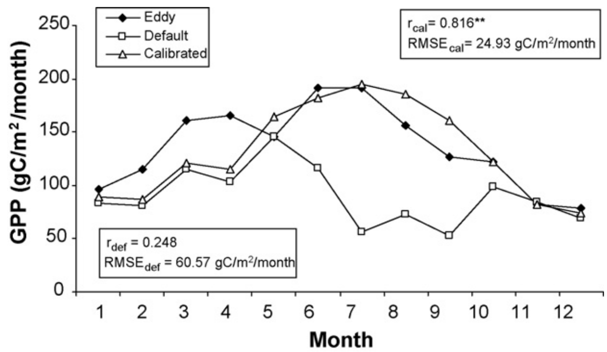

Fig. 5 – Castelporziano: comparison between monthly GPP values measured and estimated in 1997. The results and accuracy statistics are provided for the default (def) and the calibrated (cal) model configurations (**highly significant correlation, $P < 0.01$).

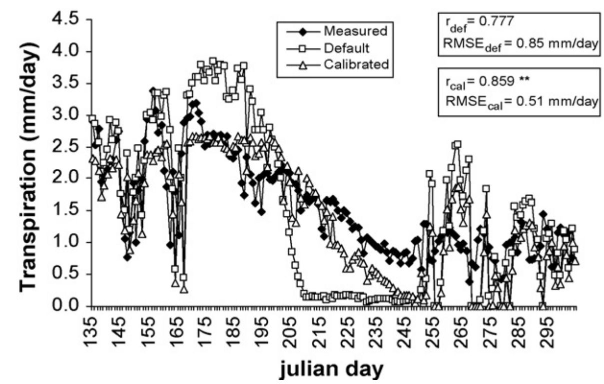

Fig. 7 – Radicondoli: comparison between daily transpiration values measured and estimated in the growing season 1998. Statistics are provided for the default (def) and the calibrated (cal) model configurations (**highly significant correlation, $P < 0.01$).

(seasonal) variations, but also, partially, for inter-annual and spatial (geographical) variations.

6.2. Validation phase

6.2.1. Castelporziano

The measured GPP annual profile for Holm oak is shown in Fig. 5 together with those obtained by both default and calibrated BIOME-BGC versions. The original model version was clearly incapable of simulating the correct GPP behaviour during summer, mostly due to an overestimation of the effect of water stress. Much better results were obtained by the calibrated model both in terms of correlation coefficient and of mean error ($r = 0.816$, RMSE = 24.93 gC/(m^2 month)). Also, the maximum LAI value estimated by the calibrated model (3.4) was very close to the measured value (between 3.2 and 4.0), while the original model produced a LAI estimate of 2.7.

6.2.2. San Rossore

The measured and estimated GPP profiles found in the pine forest are shown in Fig. 6. The original model highly overestimated the real GPP values, with a too pronounced effect of summer drought. On the contrary, the calibrated model provided quite accurate results ($r = 0.838$, RMSE = 35.89 gC/(m^2 month)), even if its sensitivity to late summer drought was excessively reduced. The maximum LAI estimated by using the calibrated BIOME-BGC (3.7) was much closer to the measured LAI (about 4.0) than the estimate from the original model Version (2.9).

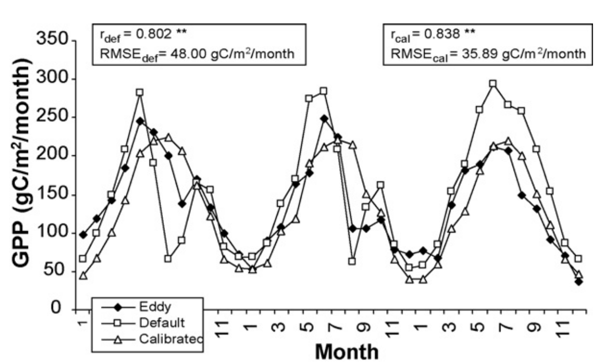

Fig. 6 – San Rossore: comparison between monthly GPP values measured and estimated in 2000–2002. Statistics are provided for the default (def) and the calibrated (cal) model configurations (**highly significant correlation, $P < 0.01$).

6.2.3. Radicondoli

The daily transpiration data measured and simulated in the Turkey oak forest are shown in Fig. 7. In its original configuration BIOME-BGC overestimated actual transpiration at the beginning of the study period and was ineffective to cope with the summer water stress period, when measured transpiration remained relatively high while simulated transpiration fell almost to zero. These deficiencies were markedly alleviated, even though not completely eliminated, by the use of the calibrated model, which produced rather accurate transpiration estimates ($r = 0.859$, RMSE = 0.51 mm/day). Also in this case the maximum LAI simulated by the calibrated model (4.1) was closer to the measured LAI (about 5.0) with respect to that from the original model configuration (1.9).

7. Discussion and conclusions

Recent studies have demonstrated that gross productivity features of forest ecosystems can be estimated by simple parametric models based on the use of remotely sensed data. In particular the model C-Fix, which relies on the well-known general relationship between NDVI and FAPAR, is able to estimate vegetation photosynthesis using commonly available satellite and meteorological data. This model has been recently applied in Italian forest areas, where it was proved to be capable of accurately reproducing annual and monthly GPP patterns measured by the eddy covariance technique (Maselli et al., 2006).

Similar remote sensing based methodologies, however, cannot estimate other major vegetation processes such as transpiration, respirations and allocations (Veroustraete et al., 2002; Maselli and Chiesi, 2005). The simulation of these processes in fact requires a more complex simulation of forest ecophysiology that must be carried out by sophisticated models of ecosystem processes. Among these, BIOME-BGC is one of the most widely known and applied, but has, up to now, found limited applications in Mediterranean environments, which are extremely different from those for which the model was developed. The current work aimed at filling this gap by using BIOME-BGC to simulate the main processes of Mediterranean forest ecosystems.

The application of the model required the preliminary creation of a spatially distributed dataset containing all necessary inputs. Among these, daily meteorological data are those which are generally more difficult to retrieve over relatively large areas for long-term periods. Moreover, since forest ecosystems are generally located in sparse, remote areas, meteorological data must be properly extended over the land surface by extrapolation/interpolation procedures. Such a problem was overcome by the sequential application of DAYMET and MT-CLIM, which enabled the production of daily weather data for the whole regional territory with a high (200 m) spatial resolution.

Next, a calibration of BIOME-BGC was necessary to adapt the model parameter settings to environments characterised by a marked summer drought. Relying on the previously exposed capacity of C-Fix to accurately depict the real photosynthetic status of the study ecosystems, GPP estimates produced by this model were used for the calibration of BIOME-BGC. The adoption of this calibration strategy permitted to circumvent the current scarcity of ground reference data describing the simulated forest processes. Since similar situations are quite common, such an approach could be proficiently extended to other cases. On the other hand, this strategy allows only an approximate adjustment of the model parameters related to global photosynthetic processes, and cannot yield an optimal complete parameterization of all model functions.

Furthermore, the parameterization of BIOME-BGC was carried out without considering factors additional to meteorology which are important in determining vegetation GPP. Among them, those related to soil structure and fertility are probably the most relevant. The model identification of an equilibrium with local eco-climatic conditions would in fact require the correct setting of soil parameters related to texture and depth. The current lack of these parameters on a regional scale could be soon overcome by the expected publication of the soil map of Tuscany (Gardin, personal communication). A further improvement of the model calibration could be produced by the use of longer series of meteorological and satellite data, which would allow a more complete characterization of inter-year GPP variability.

The calibrations performed might have yield suboptimal results also due to the incomplete representativity of the used reference points for all environmental conditions where the study biomes are present. The currently applied random selection of these points did in fact not guarantee the stability of the model in areas which are characterised by peculiar and/or extreme ecological conditions. These areas are obviously difficult to find out “a priori”, and their identification should be based on a spatially distributed application of the model. Such an application would allow the identification of areas where the discrepancies between C-Fix and BIOME-BGC GPP estimates are maximum, for which the parameterization process could be iterated until a sufficient stability of the parameter setting would be reached.

In spite of these limitations, the calibration phase actually made BIOME-BGC more resistant to summer drought by reducing the model sensitivity to water stress. The efficiency of the found parameter settings was confirmed by the validation phase, which consisted of applying both original and calibrated BIOME-BGC versions in three different forest ecosystems. The comparisons of the outputs to independent GPP and transpiration measurements indicated that the use of the calibrated model actually improved the simulation of both photosynthetic and transpiration processes, specially during the summer arid period. In particular, the calibrated BIOME-BGC yielded estimates whose accuracies are comparable to those obtained by specifically tuned models in similar Mediterranean environments. As regards photosynthesis, accuracies ranging from 25 to 60 gC/(m^2 month) were in fact previously found by the authors for various ecosystems in Central Italy (Chiesi et al., 2005; Maselli et al., 2006). Accuracy of 0.2–0.4 mm/day were obtained by Gash et al. (1999) and Chiesi et al. (2002) in the simulation of daily transpiration of coniferous and broadleaved ecosystems in Portugal and Italy, respectively.

The current approach could be easily replicated to calibrate BIOME-BGC for other forest species. Accurate estimates of photosynthesis and transpiration could thus be routinely obtained on local to regional scales. The substantial comparability of the GPP estimates obtained by C-Fix and BIOME-BGC also opens the possibility to integrate the two modelling approaches. In this way the capacity of the former model to accurately describe actual GPP features could be combined with the capability of the latter to simulate parameters like NPP and NEE, that play a fundamental role in view of the application of the Kyoto Protocol and related documents. Further studies are being directed to evaluate this possibility, which requires a comprehensive modeling of all main ecosystem functions.

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