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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

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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

(Battaglia and Sands, 1998). Its use requires the following information about the selected ecosystem:

- climate data: daily minimum and maximum temperature, precipitation, solar radiation and dew point temperature;
- environmental data and stand information: position, soil characteristics, etc.;
- species ecophysiological parameters, e.g. LAI specific leaf area (SLA m^{-2} $kg(C)^{-1}$), maximum canopy stomatal conductance ($m\ s^{-1}$), etc.

The basic assumption for the model application is that forests have to be homogeneous. Additionally crown cover is considered as a single layer described by LAI (corresponding to its height), so no information about its structure is required (Running and Hunt, 1993).

One of the most interesting characteristics of the model is that it works on two different temporal scales. The daily part of the model concentrates on the hydrologic balance, plant water availability, primary production and respiration. The yearly module is designed to simulate the allocation of the previously calculated production into the different parts of the plants, the nitrogen cycle and decomposition processes.

Another important characteristic is that FOREST-BGC can be initialised and driven by remotely sensed data (Running and Coughlan, 1988). More particularly, forest types can be obtained by processing high spatial resolution images, while multitemporal LAI values can be derived from low resolution NDVI images, as described for deciduous species in Chiesi et al. (2002).

3. Study area

The test site (43°36′–43°48′N, 10°15′–10°21′E; Fig. 1) covers the Regional Park of San Rossore. This protected area is limited by the Tyrrhenian sea on the

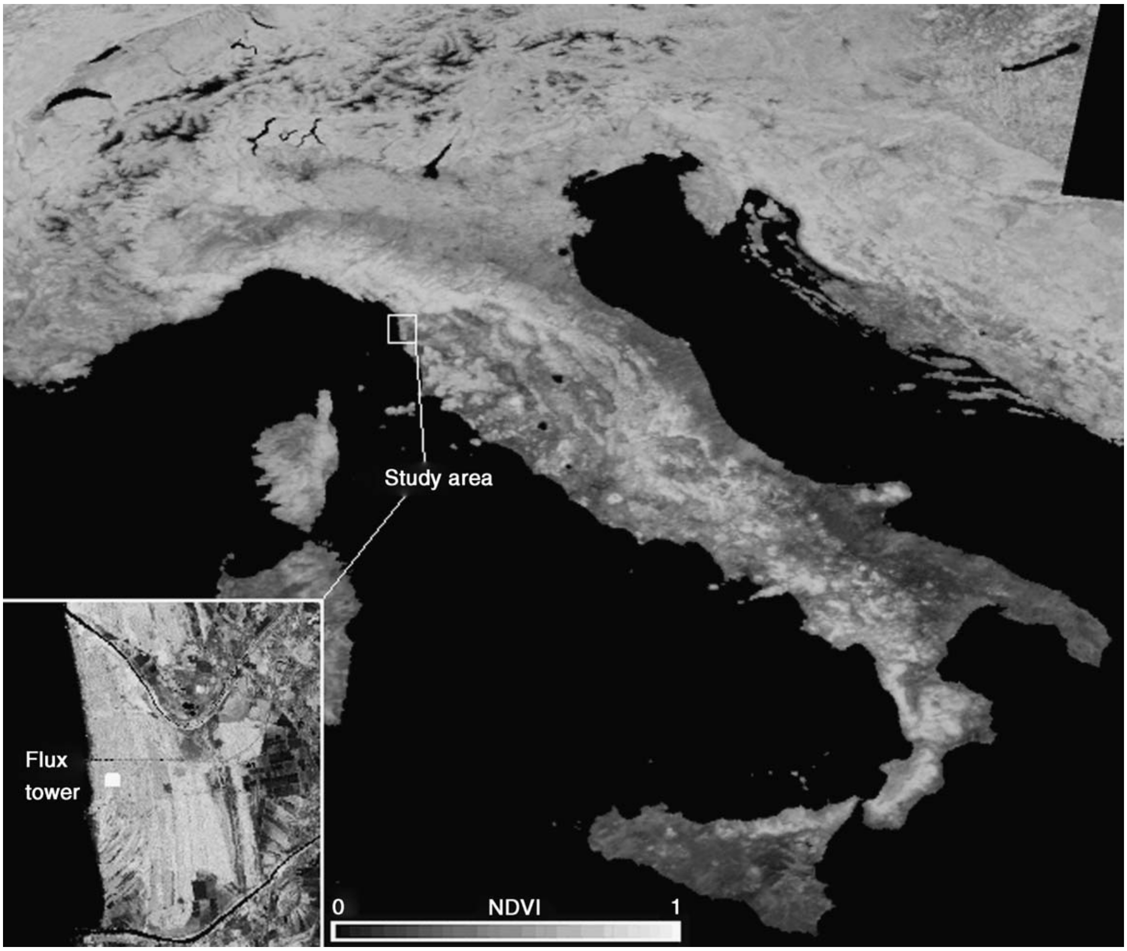

Fig. 1. NOAA–AVHRR normalised difference vegetation index (NDVI) image of August 2001 showing the position of the study area and corresponding Landsat-ETM + NDVI image with indication of the flux tower by the white square.

west and the rivers Arno and Serchio on the South and North, respectively. The climate is Mediterranean subhumid (Rapetti and Vittorini, 1995); the average yearly temperature is 14.8 °C and the average rainfall is 900 mm. The rainfall minimum coincides with the temperature summer maximum, usually originating a water stress period from June to September.

As other sites located near the sea, also San Rossore is characterised by the classical sea–land breeze regime. Being however, the site itself, the surrounding coastline and the internal landscape almost flat, the local circulation is not specifically altering the synoptic wind regime.

The soils of the area are prevalently sandy and are vulnerable to the infiltration of saline water particularly during the dry period (DREAM, 2003).

The land cover is dominated by the presence of a Mediterranean pine forest (both *Pinus pinaster* Ait. and *Pinus pinea* L.). In the most humid and inland areas, there are also hardwood species such as *Quercus robur* L., *Fraxinus angustifolia* Vahl., *Populus alba* L., *Alnus glutinosa* (L.) Gaith. and *Carpinus betulus* L. The most termophilous species are represented by *Quercus ilex* L. and other species from the Mediterranean maquis, which are also present in the under-storey layer of the pine forest (DREAM, 2003).

The test site was selected for its ecological representativeness, for the availability of data on forest conditions and for the presence of process studies at the ecosystem level. In particular, the work was focused on a homogeneous forest stand characterised by the dominance of *P. pinaster*, where canopy flux measurements are being collected by the eddy covariance technique since the end of 1998. The flux tower is located about 700 m east from the seashore in a pine plantation extending along the coastline, with exact coordinates of 43°43′40″N and 10°17′04″E. No cutting or thinning operation was carried out in this stand since its planting (middle 1950s). The average stand height is now 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*).

4. Study data

4.1. Land cover and soil information

The vegetation cover of the study area was characterised using a forest map produced within the local forest management plan (1984–1994). This map (1:10,000 scale) reported the land cover for the whole park and for the forest area, the dominant species at stand level. This was acquired in a digital format and used to assist the remote sensing data processing.

Information on the soil condition of the study stand was derived using the technique suggested by Saxton et al. (1986).

4.2. Meteorological data

Daily meteorological data were derived from a station of the Italian National Hydrological Service. This station is situated in Pisa (Facoltà di Agraria; 43°43′N and 10°25′E), which is less than 10 km from the experimental site in San Rossore. The dataset contains daily temperatures (minimum and maximum) and precipitation for the years from 1966 to 2002. Similar daily data were also collected within the study stand, but only for the year 1999.

4.3. LAI data

LAI measurements were collected during the growing seasons 2000, 2001 and 2002, using a LAI-2000 Plant Canopy Analyser (Li-cor Inc., Lincoln, NE, USA). Each sampling was carried out taking six measurements along a linear transect of about 30 m. As LAI-2000 generally underestimates real LAI values of coniferous forests due to the needle clumping effect (Leblanc and Chen, 2001), each measurement was corrected applying a factor (1.6) found experimentally by comparison between needle and shoot area index.

4.4. Dendrochronological data

In March 2003, 20 trees growing in the area surrounding the flux tower were selected and measured (DBH and height). Trees were cored at 1.3 m height with an increment borer 0.5 cm in diameter. To avoid reaction (compression) wood, two wood cores were taken at 180° to each other. Cores were transported to the laboratory, carefully mounted on channelled wood, seasoned in a fresh-air dry store and sanded a few weeks later. All the tree rings were dated. Some of the cores had false rings and were difficult to date. Ring-width measurements were made to the nearest 0.01 mm, using TSAP-measurement equipment and software package (Frank Rinn, Heidelberg, Germany). The raw ring-widths of the single curves of each dated tree were plotted, cross-dated visually and then cross-dated statistically by (a) the *Gleichläufigkeit* (there is no English equivalent to this term), which is the percentage agreement in the signs of the first differences of two time series and (b) Student's *t*-test, which determines the degree of correlation between the curves. Standard methods were used to build an averaged series for each tree and for the site (Fritts, 1976; Cook et al., 1990). For this purpose, 24 cores from 16 trees were used, since for the other cores not significant correlation coefficients between them and the average were found. In this way, annual ring-widths were estimated up to 2001, since the values of 2002, being very close to the data sampling, were considered too noisy.

4.5. Flux data

Ecosystem fluxes of carbon and water were measured over the study area by the eddy covariance technique. The technique measures the net ecosystem exchange of CO_2 above a plant canopy. NEE is given by the difference of plant photosynthesis and ecosystem respiration. During the night, only the latter flux is measured while, during the day, the measured flux is the balance of the two processes. In this Mediterranean climate conditions, photosynthesis is occurring along all year. The flux tower is an experimental site of the Institute of Environment and Sustainability, Joint Research Centre of European Commission, based in Ispra (Varese, Italy). Flux measurements started at the end of 1998 in the frame of the EU project MEDEFLU and between 2000 and 2003 were performed within the EU project CARBOEUROFLUX. The site is joining the FLUXNET network and the integrated project CarboEurope-IP.

Fluxes were measured according to the Euroflux methodology (Aubinet et al., 2000), using a Gill-R2 sonic anemometer (Gill, UK), installed at 23.5 m and a closed-path Li-6262 infrared gas analyser (Li-Cor, Lincoln, NE, USA). Fluxes were elaborated as half-hourly averages using the MASE software (Multi-Anemometer Software Eddy) (Giovanni Manca, personal communication).

The possibility of night-time underestimation of canopy fluxes was tested by checking the relationship of night-time storage-corrected fluxes against friction velocity (u^*, m s^{-1}), a parameter which estimates the degree of turbulence. Measured turbulent fluxes were corrected for storage of CO_2 within the canopy by using the discrete approach (Greco and Baldocchi, 1996; Tirone, 2003). Monthly night-time data were binned in temperature (air) classes of two degrees and u^* classes of 0.1 m s^{-1} and then plotted against u^*. In such a way, it was possible to assess at $u^* = 0.1$ m s^{-1} the threshold below which there is a night-time flux underestimation for San Rossore pine forest (Tirone, 2003). The resulting u^* threshold is in the low range of other thresholds reported for forest ecosystems. In this respect, it should be considered that the studied site is almost completely flat, which results in a reasonably good estimation of storage fluxes.

Concerning the closure of energy budget at the site, the comparison between available energy (net radiation and soil heat flux, Rn–G) and energy used in latent and sensible heat fluxes (LE + H) results in a closure close to 80% (78.4% in 2002), similar to other forest sites and in agreement with the possible footprint differences between the measurement of available energy (net radiometer and soil heat flux plates) and energy fluxes (eddy covariance). Apart from the potential different uncertainties in the measurements (the 80% closure includes all the conditions, day, night, rain, etc.), the consideration of other components, such as energy storage in biomass and a more precise soil heat flux evaluation would bring the percentage closure up.

Data coverage from 1999 to 2002 was excellent, ranging from 85 to 97% of the annual half-hours. To calculate daily, weekly, monthly and annual sums, it was necessary to gap-fill the flux data series. The gap filling was performed in the following ways: (i) night time data measured below the u^* threshold estimated as reported above were replaced by using the monthly relationship between storage-corrected night-time fluxes measured at $u^* > 0.1$ m s^{-1} and air temperature; (ii) the missing half-hours were calculated by simple interpolation when the data gap was shorter than four consecutive hours; (iii) using functional relationships between NEE and photosynthetic active radiation (PAR) during the day and between NEE and air temperature during night for longer gaps.

Gross Primary Production, which is equal to the sum of NEE and ecosystem respiration (RE), was obtained by summing annual NEE and ecosystem respiration. RE comes from the summation of night-time fluxes and of the day-time respiration.

4.6. Remotely sensed data

Both high and low spatial resolution images were used in the study. The first were Landsat TM and ETM + images, which were acquired in six optical bands (from visible to middle infrared) with a spatial resolution of 30 m and a revisiting period of 16 days. Nine acquisitions were used in the present case, taken in spring and summer from 1992 to 2001. All these images were not affected by radiometric and atmospheric perturbations over the San Rossore area.

As regards the low spatial resolution data, NOAA–AVHRR NDVI images were derived from the archives of Nuova Telespazio (Rome) and of the University of Berlin, within the framework of the EU projects RESMEDES (Bolle, 1998) and RESYSMED (Bolle, 1999). These archives contained images from 1986 to 2002. The original data were all 10-day NDVI maximum value composite (MVC) images mapped in a geographic (Lat/Long) reference system with a 0.01° pixel size (Bolle et al., 1999). The standard procedure for the production of these data comprised the georeferencing of the original images by a nearest neighbour algorithm, the radiometric calibration of the first two bands to derive apparent reflectances following Bolle et al. (1999), and the computation of NDVI values to finally obtain MVCs on a 10-day basis (Holben, 1986). The final products were therefore 36 10-day NDVI MVC images for the whole study period (1986–2001).

Images taken by the VEGETATION (VGT) sensor onboard the French SPOT4 (*Système Probatoire d'Observation de la Terre*) satellite were also considered as additional low resolution data. These images were freely provided in a pre-processed NDVI format for the years 1999–2002 by the Flemish Institute for Technological Research (VITO), Belgium. The preprocessing steps applied comprised 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 were computed and composited on a 10-day basis (Holben, 1986).

5. Methodology

As previously explained, the current research aimed at developing a methodology to optimally configure FOREST-BGC for the estimation of the carbon budget within Mediterranean forest ecosystems. Such a budget, and particularly NPP and NEE values, are determined not only by total photosynthetic rates, but also by respiration and decomposition processes (Valentini et al., 2000). In turn, these processes are dependent upon the amount of living biomass, which is linked to the trophic conditions and age of the ecosystem (Song and Woodcock, 2003). Consequently, all respiration and allocation processes of a forest stand are strictly related to its trophic and edaphic conditions and age, which can be taken into consideration by FOREST-BGC (Kabeda, 1991; Ryan and Waring, 1992). This led us to formulate the hypothesis that the optimal model configuration could be identified by reproducing the development stage of the study forest. A calibration was therefore, performed by comparing the annual woody above-ground NPP simulated by the model during the stand growth (from 1960s up to present) to the same values derived from dendrochronological measurements. The model configuration found was then tested against recent GPP and NEE measurements from the flux tower.

5.1. *Pre-processing of meteorological data*

The application of the model to a long time period required the availability of relevant meteorological data. Daily meteorological data since the beginning of 1960s were reconstructed by adapting the Pisa weather measurements to the local conditions of the study stand. This was carried out by computing linear regressions between the minimum and maximum daily temperatures collected both in Pisa and in the study stand during 1999. The conversion formulas thus obtained were applied to the whole daily data series of Pisa, with the results evaluated by conventional statistics (correlation coefficient, R, and root mean square error, RMSE). The same inter-comparison was performed for rainfall considering the total amounts of annual precipitation recorded in both stations. Estimated daily temperatures and rainfall were then used to compute solar radiation using the algorithm proposed by Bindi and Miglietta (1991).

5.2. *Processing of dendrochronological data for the reconstruction of stand growth*

In order to compare the annual woody above-ground increments simulated by the model to the radius increments derived from dendrochronological measurements, the latter had to be transformed into carbon accumulated within the forest stems and branches. To this aim, a linear relationship was approximated between the present diameters derived by cores (thus excluding bark) and the measured tree heights. This relationship was applied to determine tree heights during the whole period 1966–2001. Next, annual measured diameters and estimated heights were used to determine tree volumes of all study years by means of the function given for *P. pinaster* by the Italian National Forest Inventory (Italian Ministry of Agricolture and Forestry, 1984). The volume values of the single trees were up-scaled to the entire stand by using the relevant density information. Such density was assumed to be constant during the whole study period: tree mortality was in fact almost completely concentrated during the first years after planting and no thinning operations occurred within the stand. Annual increments of stand stem biomass were then computed for the whole study period from the estimated stand volumes. Finally, using appropriate conversion tables (ISAFA, 1982), these increments were transformed into relevant woody above-ground carbon values which were comparable to the model outputs.

5.3. Comparison between measurements and model estimates of NPP

The calibration of FOREST-BGC was preceded by the setting of the stand soil water capacity. In particular, soil water capacity was set according to the local soil texture and initial soil water condition was high because winter rainfall usually recharges the soil layer (Rapetti and Vittorini, 1995).

Next, bearing in mind that FOREST-BGC was originally developed to simulate the behaviour of coniferous forest ecosystems, the calibration was oriented to modify only a minimal set of the model state variables and eco-physiological parameters. To reach this objective, the simulation was started in the year when the reproduced stem carbon value was most similar to the model default (Running and Coughlan, 1988). As regards leaf carbon, that is a driving variable provided on an annual basis, it was calculated assuming a logistic progression (Odum, 1971), which started from the middle 1950s (presumed planting year) and reached an asymptotic value derived from the presently measured LAI value (expressed as leaf carbon content by using SLA). This assumption is based on the fact that the current LAI value is close to the maximum for the selected stand. The slope of the logistic curve was adjusted in such a way that the simulated stem carbon peak approximately corresponded to the stem carbon peak derived from dendrochronological data. The model calibration was completed keeping all eco-physiological parameters (regarding both water and carbon budgets) equal to the model default and modifying only the maximum canopy mesophyll conductance for carbon dioxide, which is a major regulator of the model carbon balance (Running and Coughlan, 1988). Hence, the calibration phase consisted of running several model simulations with varying slopes of the logistic curve and different values of maximum canopy mesophyll conductance for carbon dioxide. The agreement between measured and simulated woody above-ground annual increments during the stand growth was quantified by correlation coefficient and root mean square error statistics.

5.4. Validation of FOREST-BGC with NEE and GPP data

The optimal configuration identified was used to run the model during the years for which measured NEE and GPP values were available (1999, 2000, 2001 and 2002 for NEE and 2000, 2001 and 2002 for GPP). The simulated monthly NEE and GPP values were compared to the measurements collected by the eddy covariance technique using the same accuracy statistics as above (R and RMSE).

5.5. Integration of satellite data

As previously mentioned, FOREST-BGC can accept as input multitemporal LAI values derived from NDVI data (Chiesi et al., 2002). Being however, the study ecosystem characterised by the presence of coniferous evergreen species showing moderate intra-year LAI variations, the utilisation of such variable LAI values was deemed inappropriate.

An alternative, more direct method to estimate forest GPP is provided by the mentioned linear relationship between NDVI and FAPAR (e.g. Waring and Running, 1998; Veroustraete et al., 2002). FAPAR (F) can in fact be derived from NDVI data using a linear relation of the form:

$$F = a\mathrm{N} + b \tag{1}$$

where N is NDVI given on top of canopy and the two empirical coefficients a and b are 1.1638 and -0.1426, respectively (Myneni and Williams, 1994). This is a generalised equation applicable to the top-of-canopy NDVI values of most vegetation types, and is therefore, suited to transforming NDVI data corrected for the atmospheric effect.

From this, GPP (P) can be computed as (Prince, 1991; Waring and Running, 1998):

$$P = \varepsilon \sum_{i=1}^{t} (F_i G_i) \tag{2}$$

where ε is the light use efficiency (also called dry-matter yield; g(C) MJ^{-1} (APAR)), F represents the FAPAR and G corresponds to the photosynthetically active solar radiation (MJ m^{-2} day^{-1}) both during the time interval i. As can be seen, this straightforward equation could be used in our case by simply calibrating the coefficient ε to the specific pine wood ecosystem.

The extraction of multitemporal NDVI data for the study stand was carried out by processing the available high and low resolution satellite data. While in fact the former can provide the spatial detail suited to local studies, the latter are unique in supplying the temporal resolution needed for properly following vegetation processes (Maselli, 2004).

All low resolution AVHRR and VGT images were first pre-processed as described in Maselli et al. (2003) to remove residual cloud contaminations. Next, NDVI values of the pine wood were extracted by applying the locally calibrated end-member identification method proposed by Maselli (2001) to all these images. This procedure is capable of extracting the pure NDVI values of cover classes whose distribution is known from a higher resolution map. In the present case, four vegetation classes were derived from re-grouping the categories of the described land use map of San Rossore (i.e. coniferous and broadleaved forests, grassland and bare soil/water). The application of the end-member identification method produced pine wood NDVI values for the study stand, which were however, quite noisy probably due to the radiometric and spatial inaccuracies inherent in the low spatial resolution data used.

In order to reduce this problem and enhance the spatial detail of the information, a normalisation of the extracted NDVI data over the higher spatial resolution TM/ETM + images was applied. All available TM/ETM + images were therefore, geometrically corrected by a nearest-neighbour resampling algorithm trained on ground control points, obtaining a final error of about 1 pixel. The images were then atmospherically corrected by the method of Gilabert et al. (1994). From the reflectance images, NDVI values were extracted for the study stand. The averages and standard deviations of these values were finally used to normalise the same statistics from the low resolution data. This also allowed an approximate correction of the AVHRR NDVI data for the atmospheric effect (while this correction was not strictly necessary for VGT NDVI data, which were derived from atmospherically corrected imagery, see Maisongrande et al., 2004).

Once computed corrected NDVI values, these were inserted into Eqs. (1) and (2) to determine the suitable ε coefficient. This operation was performed by comparison to the GPP values provided by the previous model simulations for the calibration years (1986–2001). The identified ε was then used to compute, together with relevant NDVI and radiation data, monthly GPP estimates for the test years (1999–2002), which were first directly compared to the relevant ground measurements. Next, these GPP values were substituted to those previously computed by FOREST-BGC in order to estimate new monthly NEE values, which were again compared to the flux tower measurements. All comparisons were performed using the same accuracy statistics as above (R and RMSE).

Table 1
Relations between daily values collected at San Rossore (Y) and Pisa (x) for maximum (T_x) and minimum (T_n) temperatures and precipitation for 1999

Parameter	R	Equation
T_x (C°)	0.958	$Y = 0.83x + 0.64$
T_n (C°)	0.969	$Y = 0.92x - 0.07$
Precipitation (mm)	0.418	$Y = 1.0x$

All correlation coefficients are highly significant ($P < 0.01$).

6. Results

6.1. Evaluation of meteorological data

The results of the comparison between temperature and rainfall measurements taken at Pisa and San Rossore are summarised in Table 1. The daily data show a very high similarity, with correlation coefficients higher than 0.9. This finding allowed the use of the data from the former station to accurately simulate the measurements of San Rossore by the application of the two relevant linear equations. As regards precipitation, the correlation between the daily data was obviously much lower, due to the higher spatial variability of this parameter ($R = 0.418$). In spite of this, the use of no conversion factor was justified by the almost identical total annual amounts of rainfall (933 mm for Pisa against 925 mm for the pine stand) and the absence of topographical features between the two stations than can modify their precipitation distributions.

6.2. Calibration of FOREST-BGC

The temporal curve of stem carbon derived from the dendrochronological measurements is shown in Fig. 2. As previously explained, the simulation starting year was set to 1966, when this development curve had a stem carbon of 10,716 kg(C) ha^{-1}, close to the model default. Using the described criterion of maintaining also leaf carbon close to the model default in this year and adapting the slope of the logistic LAI curve, LAI started from a value of 2.5 and asymptotically tended to the maximum measured in the stand (i.e. 4.2). In this way, the reconstructed LAI curve tended to reach its asymptotic value earlier than that of stem carbon (Fig. 2).

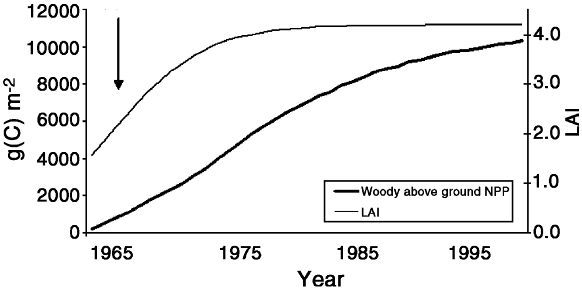

Fig. 2. Cumulative values of stem carbon (g(C) m^{-2}) derived from dendrochronological data and reconstructed leaf area index (LAI) (m^2 m^{-2}). The arrow indicates the first simulation year (1966).

The annual woody above-ground NPP increments corresponding to these stem carbon values are shown in Fig. 3. It can be noted that such increments reached a maximum at the middle of 1970s, corresponding to the increasing phase of the previously seen logistic curve. This indicates that at that time the ecosystem, which was about 20 years old, reached its maximum growth, which was then limited by an increasing competition for environmental resources due to a lack of thinning operations.

The previously described calibration led to identifying an optimal carbon dioxide maximum mesophyll conductance of 0.001 m s^{-1} (instead of the default value of 0.0008 m s^{-1}). As can be seen again in Fig. 3, by using this value, the model simulated the woody above-ground NPP in an optimum way ($R = 0.946$ and RMSE = 42.4 g(C) m^{-2} $year^{-1}$).

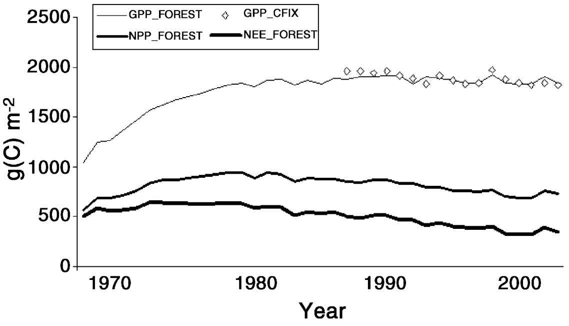

Fig. 4. Trends of gross primary production (GPP), net primary production (NPP) and net ecosystem exchange (NEE) derived by the model for the whole study period and additional estimates of GPP (C-FIX) by including AVHRR NDVI data for the period 1986–2002.

The annual patterns of GPP, NPP and NEE simulated by the calibrated model during the study period are shown in Fig. 4. It is worth noting that while GPP asymptotically tended towards an almost stable maximum similarly to the input LAI, NPP and NEE reached a peak during the middle 1970s and then began to decrease as a consequence of increased respiration and decomposition processes. This led to simulated ratios NPP/GPP and NEE/GPP which had a clearly decreasing trend, as highlighted by the values reported for example years in Table 2. This decrease was particularly evident for the second ratio, which passed from a value of 0.475 in 1966 to a value 0.188 in 2002.

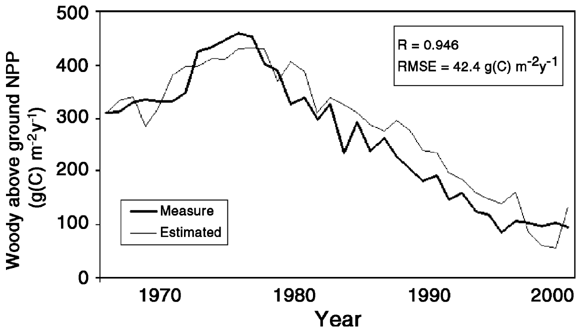

Fig. 3. Net primary production allocated in the above-ground woody compartments as derived from the measured dendrochronological data and estimated by the model for the period 1966–2001. The correlation coefficient is highly significant ($P < 0.01$).

6.3. Validation of FOREST-BGC

As is visible in Fig. 5a and b, the annual carbon budget measured by the tower was not changing significantly from year to year (coefficient of variation 5.4%), with a minimum in 1999 (397 g(C) m^{-2} $year^{-1}$) and a maximum in 2000 (442 g(C) m^{-2} $year^{-1}$).

The estimates of GPP obtained by the optimal model configuration are also shown in Fig. 5a. The model tended to overestimate GPP variations, which yielded a quite good correlation coefficient (0.895) but a relatively high RMSE (51.4 g(C) m^{-2} $month^{-1}$).

The same comparison of measured and simulated monthly NEE values gave the results visible in Fig. 5b. In this case, a fairly good agreement between the measured and estimated NEE values can be clearly appreciated in terms of both statistics used ($R = 0.924$, RMSE = 18.8 g(C) m^{-2} $month^{-1}$).

Table 2
Ratios NPP/GPP and NEE/GPP simulated by the model for four example years

Ratio	1966	1978	1990	2002
NPP/GPP	0.544	0.514	0.435	0.401
NEE/GPP	0.475	0.346	0.245	0.188

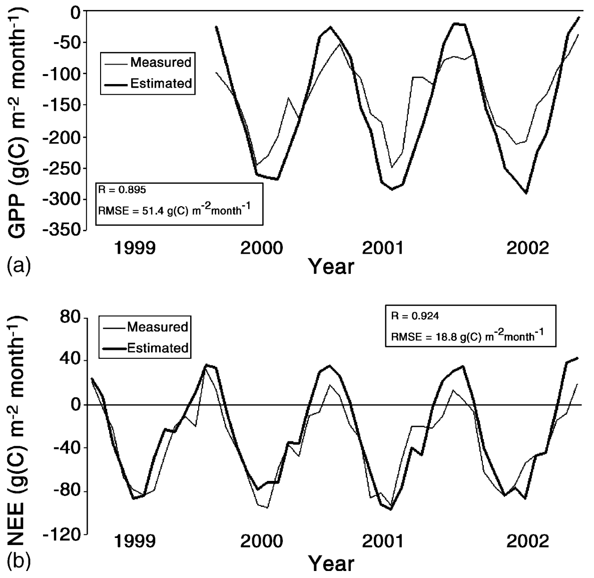

Fig. 5. Comparison of (a) monthly GPP and (b) NEE measured at the site and estimated by the model for the years 1999, 2000, 2001 and 2002. Both correlation coefficients are highly significant ($P < 0.01$).

6.4. Integrated satellite data

The comparison of remote sensing and model GPP estimates led to identify an ε coefficient equal to 1.1 g(C) MJ^{-1} (APAR), which is quite close to those reported in the literature for similar forest ecosystems (Running and Hunt, 1993; Veroustraete et al., 2002). As can be seen from Fig. 4, the accordance between annual GPP values simulated by the calibrated model and computed by Eqs. (1) and (2) was quite good, yielding an R of 0.687 (highly significant correlation, $P < 0.01$) and a RMSE of 42.0 g(C) m^{-2} year^{-1}.

Table 3
The root mean square errors (RMSE) of comparisons of simulated against measured (a) annual gross primary production (GPP) and (b) annual net ecosystem exchange (NEE) using the FOREST-BGC model and normalised difference vegetation index derived from NOAA–AVHRR and SPOT-VGT data for the years 1999 to 2002

(a) GPP	R	RMSE (g(C) m^{-2} month^{-1})
FOREST-BGC	0.895	51.4
AVHRR	0.893	41.9
VGT	0.897	39.4

(b) NEE	R	RMSE (g(C) m^{-2} month^{-1})
FOREST-BGC	0.924	18.8
AVHRR	0.893	18.4
VGT	0.896	18.4

All correlation coefficients are highly significant ($P < 0.01$).

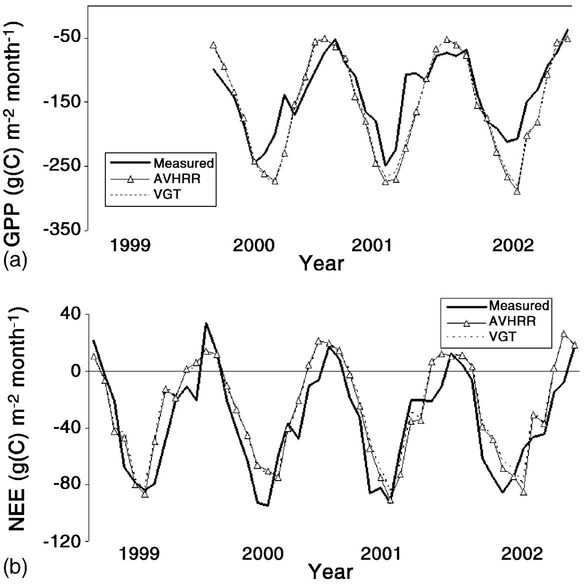

Fig. 6. Comparison between (a) monthly GPP and (b) NEE measured and estimated by NDVI data integration for the years 1999, 2000, 2001 and 2002. The values obtained with both AVHRR and VGT NDVI data are shown.

The monthly GPP and NEE values of the test years computed using the described integration procedure are shown in Fig. 6a and b together with the measured data. Summary accuracy statistics for all trials are given in Table 3a and b. As can be noted, the additional use of satellite data markedly increase the accuracy of the GPP estimates. In particular, the use of NDVI values within Eqs. (1) and (2) led to reduce the previously seen overestimation of real GPP values, thus consistently decreasing the RMSE found (39.4 g(C) m^{-2} month^{-1}). Slightly better results for both GPP and NEE were obtained using VGT instead of AVHRR data.

7. Discussion

The current work is part of a project which aims at using remotely sensed and ancillary data to routinely feed a model of forest ecosystem simulation processes, FOREST-BGC. Before applying the model to each specific study environment, two main issues must be addressed. The first is the collection of the suitable input data to drive the model, and the second is its calibration for simulating local ecosystem conditions. These issues were sequentially addressed in the current simulation of a Mediterranean pine forest, which started with a series of preparatory steps that are here briefly reviewed and discussed.

The characterisation of the study forest stand was performed mainly using existing information on local plants (tree type, age, density, etc.) and soils (depth, texture, etc.). Similar information is generally available for most forests in Europe, which, having usually artificial origin, are almost all controlled and managed.

As regards weather data, only one year of continuous meteorological measurements was available at the study site. Thus, the reconstruction of a long-term data series required an extrapolation from a nearby station, located in Pisa. This operation was quite efficient thanks to the spatial adjacency of the two stations and to the flatness of the surrounding area. For applications on a regional scale, however, the availability of an efficient method to extrapolate the input meteorological data would be essential (Phillips et al., 1992).

Using these data, the calibration of FOREST-BGC was possible with only minor modifications of the original model configuration. This was due to the fact that the study stand was dominated by evergreen coniferous species, for the simulation of which the model was originally developed. On the contrary, greater difficulties could be expected when considering broadleaved deciduous species, which would probably require a more complex tuning phase (see for example Chiesi et al., 2002).

A remarkable experimental finding was that the identification of the growing phase and trophic conditions of the study stand was essential to properly calibrate the model for simulating present carbon fluxes. Photosynthesis, respiration and allocation processes are in fact strictly related to the stand age and to how its trophic status is close to the equilibrium with local environmental conditions (Waring and Running, 1998). As these processes are strongly variable during the growth of the stand, the knowledge of its actual conditions is essential for properly simulating the correct ratios between GPP, NPP and NEE. The reconstruction of past forest carbon accumulation was therefore a decisive step to find the optimal model configuration for the study ecosystem, which was obtained by processing dendrochronological data combined with ground forestry measurements.

The efficiency of such an approach was demonstrated by the model validation, where the simulated monthly GPP and NEE were compared to measured data. The calibrated model yielded in fact GPP and NEE estimates that were in reasonable accordance with the measured values. This can only be explained with a good simulation of forest respiration and decomposition processes, which are responsible for the differences in the two productivity parameters. On the contrary, previous simulations (not currently reported), performed without taking into account the actual growing phase of the study stand, produced very inaccurate NEE estimates.

The accuracy of the model estimates was particularly good if considering that the calibration was carried out using annual stem increments, which depended on NPP and allocation processes, while the validation was performed against NEE measurements, which also included ecosystem respiration. From an ecological point of view, such results are a confirmation that the model can work efficiently also in Mediterranean environments, which are very different from those for which FOREST-BGC was originally created.

As regards the use of remote sensing data, it relied on the well-known general relationship between NDVI and FAPAR values. The efficient extraction of NDVI data descriptive of the study stand was therefore essential for computing GPP with a temporal resolution comparable to that of the ground measurements. Also due to the geographical position of the study stand (close to the sea-shore) and to its limited extension (a few hectares) this operation was possible only by the integration of high and low spatial resolution data, which circumvented the problems related to the scarce temporal resolution of the former and the lack of spatial detail of the latter (Maselli, 2004). The GPP estimates obtained in this way were even more accurate than those from FOREST-BGC and have the additional advantage of being more easily extendable over wider forest surfaces. As previously noted, however, similar remote sensing techniques can produce NPP and NEE estimates only through integration with ecosystem model functions, due to the described relevance of respiration and decomposition processes in determining net forest carbon fluxes (Valentini et al., 2000).

8. Conclusions

From the experimental results obtained in the current work the following conclusions can be drawn:

1. Dendrochronological methods combined with ground measurements of forest parameters provide a plausible history of past forest carbon accumulation.
2. This information cannot be directly converted into estimates of GPP, NPP and NEE due to the importance of respiration, decomposition and allocation processes.
3. Simulations of such processes are therefore, necessary, which can be efficiently carried out by forest

ecosystem models such as the well-known FOREST-BGC.

4. The calibration of the model against past carbon accumulation is a rapid and efficient way to identify the current growing phase and trophic conditions of a forest, whose knowledge is essential for correctly simulating the relevant carbon budget.
5. After such calibration, FOREST-BGC can actually simulate GPP and NEE values which are in accordance with flux tower measurements in a Mediterranean pine forest ecosystem.
6. Due to point two, optical remote sensing data, which are directly linked to FAPAR, can be used to estimate forest GPP, but not NPP and NEE.
7. Remotely sensed GPP estimates can however be merged with the model functions for a correct assessment of NPP and NEE values.

These considerations imply that forest carbon fluxes can be simulated by driving models of forest ecosystem processes like FOREST-BGC with:

- standard measurements of forest parameters;
- common daily meteorological data;
- historical estimates of carbon accumulation;
- suitably integrated high and low spatial resolution satellite data.

Such information allows the virtually complete characterisation of forest ecosystem processes by merging the respiration simulation functions of the calibrated model and the direct GPP estimates from suitably processed remote sensing data. This characterisation would be a decisive step towards the development of an integrated system suitable for monitoring applications at regional scale also in complex and heterogeneous Mediterranean environments. Within such a system, the importance of direct eddy covariance measurements should not be neglected, since, in addition to being the only means for soundly validating GPP and NEE estimates in specific cases, they can also give essential insights on ecosystem functions for improving future model simulations.

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References

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, Ch., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T., 2000. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. Adv. Ecol. Res. 30, 113–175.

Battaglia, M., Sands, P.J., 1998. Process-based forest productivity models and their applications in forest management. For. Ecol. Manag. 102, 13–32.

Bindi, M., Miglietta, F., 1991. Estimating daily global radiation from air temperature and rainfall measurements. Climate Res. 1, 117–124.

Bolle, H.J., 1998. Remote sensing of Mediterranean desertification and environmental changes. Final report of RESMEDES-ENV4-CT95-0094, Firenze.

Bolle, H.J., Billing, H., Brummer, Ch., Eckardt, M., Koslowsky, D., Langer, I., Tonn, W., 1999. University of Berlin contribution to final report of RESYSMED-ENV4-CT97-0683.

Bolle, H.J., 1999. Synthesis of change detection parameters into a land-surface change indicator for long term desertification studies in the Mediterranean area. Final report of RESYSMED-ENV4-CT97-0683, Firenze and Munchen.

Chiesi, M., Maselli, F., Bindi, M., Fibbi, L., Bonora, L., Raschi, A., Tognetti, R., Cermak, J., Nadezhdina, N., 2002. Calibration and application of FOREST-BGC in a Mediterranean area by the use of conventional and remote sensing data. Ecol. Model. 154, 251–262.

Cook, E.R., Shiyatov, S., Mazepa, V., 1990. Estimation of the mean chronology. In: Cook, E.R., Kairiukstis, L.A. (Eds.), Methods of Dendrochronology. Applications in the Environmental Sciences. Kluwer Academic, Dordrecht, pp. 123–132.

DREAM, 2003. Tenuta di San Rossore. Note illustrative della carte forestale e della fruizione turistica. Published by S.E.L.C.A. Firenze, Italy, may 2003.

Franklin, S.E., Lavigne, M.B., Deuling, M.J., Wulder, M.A., Hunt, E.R., 1997. Estimation of leaf area index using remote sensing and GIS data for modelling net primary production. Int. J. Remote Sens. 18, 3459–3471.

Fritts, H.C., 1976. Tree Rings and Climate. Academic Press, London, UK, p. 567.

Gilabert, M.A., Conese, C., Maselli, F., 1994. An atmospheric correction method for the automatic retrieval of surface reflectances from TM images. Int. J. Remote Sens. 15, 2065–2086.

Greco, S., Baldocchi, D.D., 1996. Seasonal variation of CO2 and water vapour exchange rates over a temperate deciduous forest. Global Change Biol. 2, 183–197.

Griffis, T.J., Black, T.A., Morgenstern, K., Barr, A.G., Nesic, Z., Drewitt, G.B., Gaumont-Guay, D., McCaughey, J.H., 2003. Ecophysiological control on the carbon balances on three southern boreal forests. Agric. For. Meteorol. 117, 53–71.

Holben, B.N., 1986. Characteristics of maximum-value composite images from temporal AVHRR data. Int. J. Remote Sens. 7, 1417–1434.

Hunt Jr., E.R., Martin, F.C., Running, S.W., 1991. Simulating the effects of climatic variation on stem carbon accumulation of a Ponderosa pine stand: comparison with annual growth increment data. Tree Physiol. 9, 161–171.

ISAFA, 1982. Tavole stereometriche ed alsometriche costruite per i boschi italiani. Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura, Trento.

Italian Ministry of Agricolture and Forestry, 1984. Inventario forestale nazionale italiano-Tavole di cubatura a doppia entrata, in: Castellani, C., Scrinzi, G., Tabacchi, G., Tosi, V. (Eds.) (a cura di), I.S.A.F.A., Trento.

Kabeda, O., 1991. Above-ground biomass production and nutrient accumulation in an age sequence of *Pinus caribaea* stands. For. Ecol. Manag. 41, 237–248.

Lacaze, B., Caselles, V., Coll, C., Hill, H., Hoff, C., de Jong, S., Mehl, W., Negendank, J.F., Riesebos, H., Rubio, E., Sommer, S., Teixeira Filho, J., Valor, E., 1996. De Mon-Integrated Approaches to Desertification Mapping and Monitoring in the Mediterranean Basin, Final Report of De-Mon I Project. Joint Research Centre of European Commission, Ispra (VA), Italy.

Leblanc, S.G., Chen, J.M., 2001. A practical scheme for correcting multiple scattering effects on optical LAI measurements. Agric. For. Meteorol. 110, 125–139.

Liu, J., Chen, J.M., Cihlar, J., Park, W.M., 1997. A process-based boreal ecosystem productivity simulator using remote sensing inputs. Remote Sens. Environ. 62, 158–175.

Maisongrande, P., Duchemin, B., Dedieu, G., 2004. VEGETATION/SPOT: an operational mission for the earth monitoring; presentation of new standard products. Int. J. Remote Sens. 25, 9–14.

Maselli, F., 2001. Definition of spatially variable spectral endmembers by locally calibrated multivariate regression analyses. Remote Sens. Environ. 75, 29–38.

Maselli, F., Romanelli, S., Bottai, L., Zipoli, G., 2003. Use of NOAA-AVHRR NDVI images for the estimation of dynamic fire risk in Mediterranean areas. Remote Sens. Environ. 86, 187–197.

Maselli, F., 2004. Monitoring forest conditions in a protected Mediterranean coastal area by the analysis of multi-year NDVI data. Remote Sens. Environ. 89, 423–433.

Myneni, R.B., Williams, D.L., 1994. On the relationship between FAPAR and NDVI. Remote Sens. Environ. 49, 200–211.

McLeod, S.D., Running, S.W., 1988. Comparing site quality indices and productivity in Ponderosa pine stands of western Montana. Can. J. For. Res. 18, 346–352.

Nemani, R.R., Running, S.W., 1989. Testing a theoretical climate-soil-leaf area hydrologic equilibrium of forests using satellite data and ecosystem simulation. Agric. For. Meteorol. 44, 245–260.

Odum, E. P., 1971 Fundamentals of Ecology, third ed. W.B. Saunders, Philadelphia.

Phillips, D.L., Dolph, J., Marks, D., 1992. A comparison of geostatistical procedures for spatial analysis of precipitation in mountainous terrain. Agric. For. Meteorol. 58, 119–141.

Prince, S.D., 1991. A model of regional primary production for use with coarse resolution satellite data. Int. J. Remote Sens. 12, 1313–1330.

Rapetti, F., Vittorini, S., 1995. Carta climatica della Toscana, Pacini Editore, Pisa (Italy).

Running, S.W., Coughlan, J.C., 1988. A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes. Ecol. Model. 42, 125–154.

Running, S.W., Gower, S.T., 1991. FOREST-BGC, a general model of forest ecosystem processes for regional applications, II. Dynamic carbon allocation and nitrogen budgets. Tree Physiol. 9, 147–160.

Running, S.W., Hunt, E.R., 1993. Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In: Ehleringer, J.R., Field, C.B. (Eds.), Scaling Physiological Processes: Leaf To Globe. Academic Press, San Diego, pp. 141–158.

Running, S.W., Nemani, R.R., Peterson, D.L., Band, L.E., Potts, D.F., Pierce, L.L., Spanner, M.A., 1989. Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. Ecology 70, 1090–1101.

Ryan, M.G., Waring, R.H., 1992. Maintenance respiration and stand development in a sub-alpine lodgepole pine forest. Ecology 73, 2100–2108.

Saxton, K.E., Rawls, W.J., Romberger, J.S., Papendick, R.I., 1986. Estimating generalized soil-water characteristics from texture. Soil Sci. Soc. Am. J. 50, 1031–1036.

Schimel, D.S., 1995. Terrestrial ecosystems and the carbon cycle. Global Change Biol. 1, 77–91.

Song, C., Woodcock, C.E., 2003. A regional forest ecosystem carbon budget model: impacts of forest age structure and land use history. Ecol. Model. 164, 33–47.

Tirone, G., 2003. Stima del bilancio del carbonio di due ecosistemi forestali mediterranei. Confronto fra una lecceta e una pineta. Ph.D. Thesis, University of Tuscia, Department of Forest Envi., pp. 113+VII.

Valentini, R., Matteucci, G., Dolman, A.J., Schulze, E.-D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalski, A.S., Vesala, T., Rannik, Ü., Berbigier, P., Loustau, D., Gudmundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J.B., Montagnani, L., Minerbi, S., Jarvis, P.G., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861–865.

Veroustraete, F., Sabbe, H., Eerens, H., 2002. Estimation of carbon mass fluxes over Europe using the C-fix model and Euroflux data. Remote Sens. Environ. 83, 376–399.

Waring, H.R., Running, S.W., 1998. Forest Ecosystems. Analysis at Multiples Scales, second ed. Academic Press, San Diego, p. 55.