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# Use of remotely sensed and ancillary data for estimating forest gross primary productivity in Italy

Fabio Maselli [a,*], Anna Barbati [b], Marta Chiesi [a], Gherardo Chirici [c], Piermaria Corona [b]

[a] *IBIMET-CNR, Via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy*
[b] *DISAFRI, University of Tuscia, Italy*
[c] *DISTAF, University of Florence, Italy*

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**Abstract**

The current paper describes the development and testing of a procedure which can use widely available remotely sensed and ancillary data to assess large-scale patterns of forest productivity in Italy. To reach this objective a straightforward model (C-Fix) was applied which is based on the relationship between photosynthetically active radiation absorbed by plant canopies and relevant gross primary productivity (GPP). The original C-Fix methodology was improved by using more abundant ancillary information and more efficient techniques for NDVI data processing. In particular, two extraction methods were applied to NDVI data, derived from two sensors (NOAA-AVHRR and SPOT-VGT) to feed C-Fix. The accuracy of the model outputs was assessed through comparison with annual and monthly values of forest GPP derived from eight eddy covariance flux towers. The results obtained indicated the superiority of SPOT-VGT over NOAA-AVHRR data and a higher efficiency of the more advanced NDVI extraction method. Globally, the procedure was proved to be of easy and objective implementation and allowed the evaluation of mean productivity levels of existing forests on the national scale.


*Keywords:* Forest ecosystems; Gross primary productivity; Carbon uptake; C-Fix model; NOAA-AVHRR; SPOT-VGT

## 1. Introduction

The assessment of forest productivity on wide areas is important for both scientific and practical purposes. Such an assessment is in fact necessary to study the global carbon cycle and can produce information useful for planning and managing forest resources (Waring & Running, 1998). Unfortunately, regional scale applications of field-based measurement techniques are economically expensive and time-consuming, due to the high spatial variability of the factors which affect forest production (climate, topography, soil fertility, management practices, etc.). Thus, a procedure mostly independent of field measurements and driven by remote sensing data would be extremely useful to yield spatial estimates of forest productivity (Running et al., 1999). Trials in this direction have already been made for some European countries, obtaining mixed results probably linked to the data sources utilized and the procedures applied (Veroustraete et al., 2002, 2004).

This situation calls for improvement and careful testing of remote sensing based procedures capable of evaluating forest productivity on regional to national scales. A research effort was recently conducted to respond to these needs for the Italian national territory. The basic consideration underlying this effort was that substantial improvements in the estimation of forest productivity over large areas was obtainable by suitably integrating multi-source remotely sensed and ancillary data. The research therefore aimed at developing and testing a methodology of relatively simple implementation capable of utilizing widely available earth observation and ancillary data. Such a methodology was based on a straightforward model of forest productivity (C-Fix) which uses the relationship between photosynthetically active radiation absorbed by plant canopies (APAR) and the productivity of those canopies. This approach was a modification of the C-Fix model originally proposed by Veroustraete et al. (1994), which has been applied over several European countries (Veroustraete et al., 2002, 2004). The

* Corresponding author. Tel.: +39 055 4483055.
*E-mail address:* maselli@ibimet.cnr.it (F. Maselli).

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additional value of the work performed by our group lay in a more efficient consideration of the ancillary information which was available for Italy.

The research effort first produced estimates of forest Net Primary Productivity (NPP), which were validated against destructive field measurements of wood increment. That experiment was presented in a paper (Chirici et al., submitted for publication), which, being addressed to a public mainly interested in forest topics, did not specifically consider all aspects related to satellite data processing. Also, that paper did not address the problem of estimating forest Gross Primary Productivity (GPP), which is equally interesting from both a scientific and an operational viewpoint (Waring & Running, 1998).

Our research was therefore directed to fully investigate the use of various normalized difference vegetation index (NDVI) data sets for forest GPP assessment. In particular, additional experiments were conducted using NDVI data from two satellite sensors (the NOAA-Advanced Very High Resolution Radiometer, AVHRR, and the SPOT-VEGETATION, VGT) and different NDVI extraction techniques in order to identify an optimal methodology to estimate forest GPP at the national scale. The produced annual and monthly GPP estimates were evaluated against reference values derived from eddy covariance flux towers positioned in eight Italian forest ecosystems.

The current paper, which fully documents this last part of the research effort, is organized as follows. The main features of Italian forests are introduced in the next section, followed by those of the ground and remotely sensed data utilized. Next, the basis of the C-Fix methodology and its current implementation are presented. This is followed by a description of the results obtained in comparison to existing GPP reference values. The paper is concluded by a section discussing the possibilities and limitations of the proposed approach.

## 2. Study area

Italy is geographically situated between 36° and 47°30′ North latitude and between 5°30′ and 18°30′ East longitude. Its orography is quite complex due to the presence of two main mountain chains, the Alps in the north and the Apennines in the centre-south. Italian climate is also very variable along the latitudinal and altitudinal gradients and the distance from the sea. In general, it ranges from Mediterranean warm to temperate cool and Alpine.

The land is mostly covered by agricultural areas, forests and pastures. The total extent of forest areas varies around 80,000–90,000 $km^2$, depending on the relevant definition (Corona et al., 2004). 95% of forest land is on hills and mountains. 32% of the forest formations are included in the Alpine biogeographical region, 16% in the Continental region and 52% in the Mediterranean region (sensu Habitat Directive of the European Commission 43/92). Due to such a pronounced biogeographical variability, forest ecosystems in Italy are characterized by a high biodiversity (e.g. 117 native forest tree species). The most widespread forest formations are dominated by various oak species (*Quercus* spp.) and beech (*Fagus sylvatica*). Among conifers, the most abundant are fir (*Abies alba*) and spruce (*Picea abies*), followed by various pines (*Pinus*). 53% of forest land is managed as coppices, 43% as high-stands, and 4% is Mediterranean maquis. Even-aged stands represent 60% of the total high-stands (Corona et al., 2004).

## 3. Input data

### 3.1. Ancillary data

A Digital Elevation Model (DEM) of Italy with a pixel size of 1 $km^2$ was derived from a previous work (Blasi, 2005). This DEM was projected into the UTM 32-North reference system, which was taken as standard for processing all other information layers.

The same work (Blasi, 2005) provided digital maps of mean monthly temperatures (minimum and maximum) and rainfall. These maps were produced by extrapolating climatic data measured over 30 years at about 400 stations distributed over the whole national territory. The extrapolation was performed by applying a locally calibrated regression procedure to the mentioned DEM. The principles and properties of such procedure are described in Maselli (2002).

Finally, a digital forest map was derived from the original CORINE Land Cover 2000 map of Italy (Maricchiolo et al., 2004). This map was produced at a nominal scale of 1:100,000 by manual photointerpretation of Landsat imagery supported by ancillary information (Bologna et al., 2004). The map classified forests and other wooded land in 26 types on the basis of the dominant species, maintaining the geometric and thematic congruency with the original data set. In the current case the original vector data set was used, grouping the classes into 12 main forest types with expected homogeneous NDVI responses (Table 1); a view of the obtained forest map of Italy is given in Fig. 1.

Table 1
Forest types in Italy derived from regrouping the original CORINE classes, with relevant area extents

| Index | Forest type | Area ($km^2$) | Prevalent distribution in high/low altitudinal belt in Italy |
|---|---|---|---|
| 1 | White fir/Norway spruce forest | 7742 | H |
| 2 | Chestnut forest | 8437 | L |
| 3 | Exotic conifer forest | 146 | L |
| 4 | Beech forest | 11602 | H |
| 5 | Exotic broadleaf forest | 1692 | L |
| 6 | Hygrophilous broadleaf forest | 1246 | L |
| 7 | Mediterranean broadleaves | 9711 | L |
| 8 | Holm oak | 7025 | L |
| 9 | High maquis | 2019 | L |
| 10 | Mediterranean pine forest | 3071 | L |
| 11 | Mountain pine forest | 4130 | H |
| 12 | Other oaks | 21,347 | L |
| Total | | 78,168 | |

The division between forests distributed prevalently on high or low altitudinal belts, shown in the last column, served for computing different temperature correction factors.

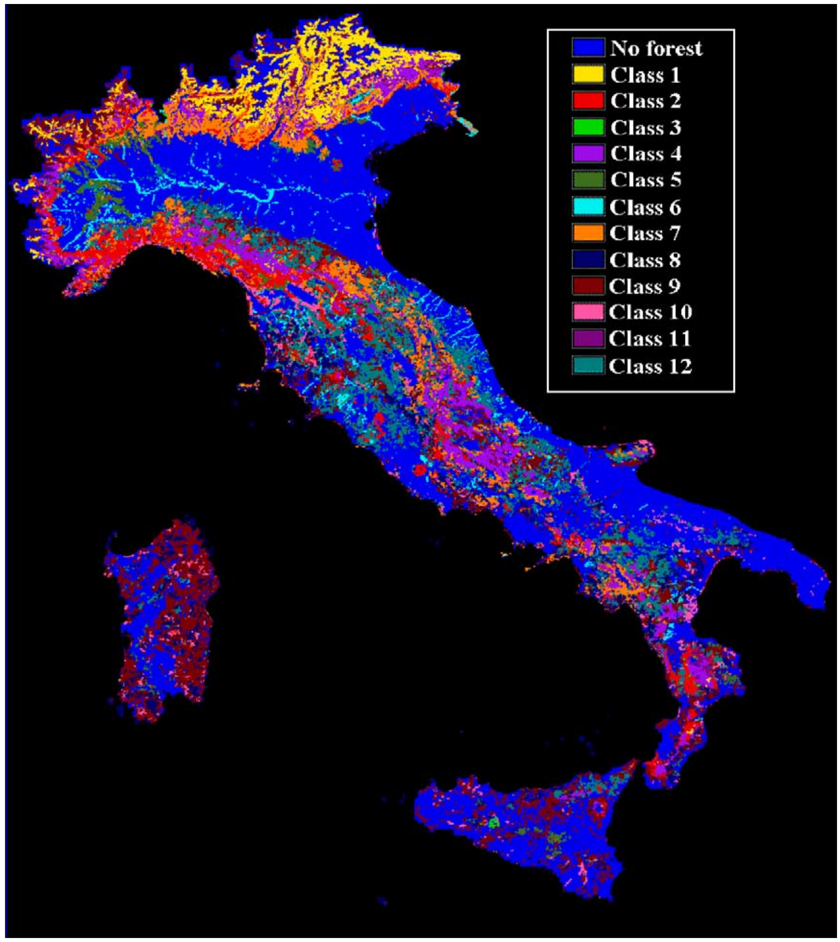


Fig. 1. Forest map of Italy in raster format with pixel size of 1 $km^2$. The nomenclature used is an aggregation of the original CORINE one as reported in Table 1.

### 3.2. Forest GPP data

Reference photosynthesis values of some Italian forests were derived from the existing towers measuring carbon fluxes by the eddy correlation technique. Most of these flux towers belong to the FLUXNET network, and are completely described on the relevant web-site (http://www.fluxnet.ornl.gov/fluxnet/).

The Italian network comprises 10 flux towers located in forest ecosystems. Out of these, only the eight towers listed in Table 2 were considered. The flux measurements at these towers were taken in the years from 1997 to 2003, approximately coincident with those of the satellite data acquisitions. On the contrary, the first excluded tower (Lavarone) was installed in 2000, but was moved in 2002 and presented some problems of data inconsistency (Marcolla and Manca, personal communication). The second excluded tower (Bonis) was installed in the summer of 2003 and has not yet produced complete reliable annual measurements (Matteucci, personal communication).

The main features of the 8 sites considered are summarized in Table 2. As can be derived from their geographical positions, these eight sites are characteristic for most of the national territory, from the centre to the north of the peninsula and from the sea level up to the mountains. Unfortunately, no GPP measurement covers the whole period 1997–2003, due to different years of tower installation and to problems of acquisition continuity (Table 2).

Table 2
Main characteristics of the 8 sites from which flux tower measurements were derived for evaluating the performances of the current procedure

| Test site | Position | Forest species | Measurement period | Forest class |
|---|---|---|---|---|
| Renon | 46.59°N, 11.44°E | *Picea abies* (L.) Karst. | 1997 | White fir/Norway spruce |
| Parco del Ticino | 45.20°N, 9.06°E | *Populus alba* I 214 | 2003 | Hygrophilous broadleaves |
| Parco La Mandria | 45.19°N, 7.53°E | *Quercus robur* L. | 2002–2003 | Other oaks |
| Nonantola | 44.68°N, 11.12°E | Mixed deciduous forest | 2001–2003 | Hygrophilous broadleaves |
| San Rossore | 43.7°N, 10.5°E | *Pinus pinaster* Ait. | 2000–2002 | Mediterranean pines |
| Collelongo | 41.85°N, 13.59°E | *Fagus sylvatica* Mill. | 1997 | Beech |
| Castelporziano | 41.71°N, 13.63°E | *Quercus ilex* L. | 1997–1998 | Holm oak |
| Roccarespampani | 42.39°N, 11.92 °E | *Quercus cerris* L. | 2002–2003 | Other oaks |

All available mean annual GPP values of the eight towers were considered to assess the accuracy of the current estimation methodology. Additionally, the monthly GPP data which were available for three of these sites (San Rossore, Collelongo, Parco del Ticino) were used for a more refined evaluation.

### 3.3. Satellite data

NOAA-AVHRR NDVI images were obtained from the archive of the University of Berlin. 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). Their pre-processing sequence comprised the geo-referencing of the original imagery by a nearest neighbor algorithm, the radiometric calibration of the first two bands to derive top-of-atmosphere reflectances following Bolle et al. (1999), and the computation of NDVI values to finally obtain Maximum Value Composites (MVC) on a 10-day basis (Holben, 1986).

NDVI images taken by the SPOT-VGT sensor were downloaded from the archive of VITO (http://free.vgt.vito.be), which freely distributes pre-processed 10-day MVC imagery for the entire globe acquired since April 1998. The applied pre-processing steps comprised the radiometric calibration of the original channels and their geometric and atmospheric corrections (Maisongrande et al., 2004). The final products of these steps were 10-day NDVI MVC images having a pixel size of about 1 $km^2$.

For both AVHRR and VGT, only 10-day MVC images acquired from April 1998 (start of VGT data distribution) to March 2003 were considered. Data from 5 years were in fact deemed sufficient to depict the mean environmental situation of the study forests, while the consideration of the same period for the two sensors allowed the correct inter-comparison of their properties for GPP estimation.

## 4. Modelling approach

C-Fix is a Monteith type parametric model driven by temperature, radiation and fraction of APAR (fAPAR), quantified through its generalized relationship with the NDVI (the ratio between the difference and the sum of the reflectances in the red and infrared wavelength bands) (Veroustraete et al., 2002, 2004). Satellite-derived fAPAR is combined with field based estimates of incoming solar radiation and air temperature, which are jointly used to simulate first total photosynthesis and then net carbon accumulation by subtracting autotrophic and heterotrophic respiratory fluxes. Estimates of GPP can therefore be obtained, together with those of NPP and net ecosystem exchange (NEE), which are, however, more imprecise due to the more complex estimation of autotrophic and heterotrophic respiratory fractions (Veroustraete et al., 2002).

Given its conceptual simplicity and general applicability, C-Fix only requires the tuning of a few coefficients, and can use inputs averaged over different time periods (most commonly 10-day to monthly). In the current case, annual GPP (g C $m^{-2}$ $year^{-1}$) of each forest type was computed by summing monthly estimates:

$$\mathrm{GPP}_i = \varepsilon_i \sum_{z=1}^{12} \mathrm{Tcor}_{zi} \mathrm{fAPAR}_{zi} \mathrm{Gpar}_z \qquad (1)$$

where: $i$ = index of the forest type = 1...12; $\varepsilon_i$ = radiation use efficiency for the $i$th forest type (g C $MJ^{-1}$(APAR)); $z$ = index of the month = 1...12; $\mathrm{Tcor}_{zi}$ = temperature correction factor of the $z$th month for the $i$th forest type; $\mathrm{fAPAR}_{zi}$ = fraction of the photosynthetic active radiation absorbed by the $i$th forest type in the $z$th month; $\mathrm{Gpar}_z$ = incoming photosynthetically active radiation in the $z$th month (MJ $m^{-2}$).

The current procedure took into account the presence of different forest types and was raster-based, with 1-$km^2$ pixels, which is the scale of the NDVI imagery considered (NOAA-AVHRR and SPOT-VGT). The following sections describe the production of all data layers needed for applying Eq. (1) on national scale.

## 5. Data processing

### 5.1. Estimation of global radiation

Monthly radiation images were computed by processing the available DEM and climatic data. More particularly, monthly theoretic radiation $G_0$ was first computed by applying relevant astronomic formulas to the slope and aspect images derived from the DEM (Iqbal, 1983). Next, the correction of these images for actual monthly cloud cover was carried out by an empirical relationship between a climatic index and the real/theoretic radiation ($G/G_0$) ratio. The definition of this relationship was based on the observation that monthly $G/G_0$ decreases with increasing rainfall and decreasing thermal gradient (the difference between maximum and minimum temperatures). Thus, using the climatic data provided by Benincasa et al. (1991) for 10 Italian sites, the following relationship was defined:

$$G/G_0 = 0.6735\mathrm{e}^{-0.02255\frac{P}{T_{\max}-T_{\min}}} \qquad (2)$$

where: $P$ = monthly rainfall (mm); $T_{\max}$ = monthly average of maximum daily temperatures (°C); $T_{\min}$ = monthly average of minimum daily temperatures (°C).

This formula was applied to correct all theoretic radiation images by using the previously described monthly temperature and radiation maps. Modelled $G$ values were then transformed into incoming photosynthetically active radiation, Gpar by the formula (Iqbal, 1983):

$$\mathrm{Gpar} = 0.464G \qquad (3)$$

### 5.2. Estimation of fAPAR

#### 5.2.1. Image pre-processing

A preliminary visual examination of the available 10-day NOAA-AVHRR and SPOT-VGT NDVI images indicated that they contained a variable number of pixels with erroneous values. A specific procedure was therefore applied for the reduction of all these defects, which is fully described in Escadafal et al. (2001). This procedure 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, since the original MVC process was ineffective to remove all atmospheric contaminations for periods with high cloud cover, the same algorithm was re-applied to compose the corrected 10-day images on a monthly basis (Holben, 1986). This yields monthly MVC imagery for both data series (AVHRR and VGT).

The AVHRR imagery was produced from atmospherically uncorrected data, which required an additional transformation aiming at making the NDVI values compatible with top-of-canopy estimates. This was done by applying a normalization factor equal to 1.35, derived from the works of Maselli (2004) and Bolle et al. (in press). Moreover, a further correction factor (0.936) was applied to the AVHRR NDVI imagery after 2000, when a transition from NOAA-14 to NOAA-16 acquisitions was performed. The NDVI values from the latter satellite were in fact found to be consistently higher than those from the previous ones (Bolle et al., in press).

The obtained monthly AVHRR and VGT NDVI imagery were averaged over the same five study years (April 1998–March 2003) to compute 12 mean monthly NDVI images. These images were then re-projected into the reference system as all other information layers (UTM 32-North).

#### 5.2.2. Computation of forest NDVI data

The extraction of forest NDVI values from the two data sets was carried out with two levels of increasing complexity. First, the original monthly values of each pixel were considered, as proposed by Veroustraete et al. (2002). To this aim, pixels covered by more than 50% of forestry species were isolated by using the higher spatial resolution CORINE map. Only these pixels were used for subsequent processing and validation.

This “hard” use of the original NDVI values was prone to possible inaccuracies. It must in fact be recalled that most VGT and AVHRR pixels were mixed, i.e. contained different cover types in various proportions, which were currently derivable from the CORINE reference map. A second procedure was therefore tested to estimate, on a pixel basis, the potential NDVI values that could be measured if the pixel was fully covered with a single forest type. To this aim, the vector database of the 12 main forest types (Table 1) was rasterized with the same resolution (1 $km^2$) and reference system (UTM 32-North) as the other available layers, producing fraction (or abundance) images for all considered forest types (i.e. images whose grey values were proportional to the fractions of the cover types). These 12 images were used to extract the per-pixel NDVI values of each forest type by applying the methodology proposed by Maselli (2001). That method is based on locally calibrated multivariate regression analyses, which can determine spatially variable NDVI end-member values of all land cover types derived from a higher resolution map. In summary, the method estimates for every image pixel a different multi-spectral (or multi-temporal) end-member, which represents the signature of each pure class considered (Maselli, 2001). As demonstrated in the same work, these spatially variable end-members can reproduce within-class NDVI variations and are therefore more suitable than the original values for the description of local vegetation properties.

#### 5.2.3. Computation of fAPAR

The monthly AVHRR and VGT NDVI values of the forests extracted by the two methods were finally converted into relevant fAPAR values by means of the following formula, proposed by Myneni and Williams (1994):

$$\mathrm{fAPAR}_{zi} = 1.1638\mathrm{NDVI}_{zi} - 0.1426 \tag{4}$$

This is a generalized equation applicable to the top-of-canopy NDVI values of most vegetation types, and was therefore suited to transforming the available NDVI data which were corrected for the atmospheric effect (VGT) or normalized with respect to this factor (AVHRR).

### 5.3. Estimation of Tcor

The correction factor Tcor was computed on a monthly basis as suggested by Veroustraete et al. (2002):

$$\mathrm{Tcor}_{zi} = \frac{e^{\left(C_1 - \frac{\Delta H_{a,P}}{R_g T}\right)}}{1 + e^{\left(\frac{\Delta S T - \Delta H_{d,P}}{R_g T}\right)}} \tag{5}$$

where: $C_1$=constant equal to 21.9 (for mountain forests) or 21.6 (for plain/hilly forests); $\Delta H_{a,P}$=activation energy equal to 52750 J $mol^{-1}$; $R_g$=gas constant equal to 8.31 J $K^{-1}$ $mol^{-1}$; $T$=monthly air temperature (K); $\Delta S$=entropy of the denaturation equilibrium of $CO_2$ equal to 710 (for mountain forests) or 700 (for plain/hilly forests) J $K^{-1}$ $mol^{-1}$; $\Delta H_{d,P}$=deactivation energy equal to 211 J $mol^{-1}$.

Temperature correction images were computed for two main altitudinal belts, as proposed by Veroustraete et al. (2002). The division of the existing forest types into mountain and plain/hilly forests was made on the basis of ecophysiological considerations and is summarized in Table 1. In all cases the maps of monthly temperature were computed by applying the algorithm of Running et al. (1987) to the available maps of minimum and maximum temperatures.

### 5.4. Computation of mean annual GPP

According to Eq. (1), annual forest GPP imagery were computed by composing and summing on a yearly basis the mean monthly Gpar, fAPAR and Tcor images. To apply this equation on a spatial basis, the distribution of the forest types was derived again from the CORINE map. In the case of the “hard” extraction of the NDVI values, the forest type of each pixel was first found following a majority rule, which enabled the identification of the correct Tcor value. Subsequently, the sum of the composed monthly Gpar, fAPAR and Tcor images produced final GPP estimates for all forest pixels.

When instead the previously found end-member images were used, each forest type was treated separately again following the division of Table 1. An annual GPP image was thus obtained for each forest type, reporting the values which such forest type would have had if completely covering the land surface. Consequently, the computation of GPP for all existing forests was carried out by multiplying the images of the 12 forest types by the relevant cover fraction images and summing them up.

In all cases, radiation use efficiency was set equal to 1.1 g C $MJ^{-1}$ (APAR) for both conifers and broadleaved species, according again to the proposal of Veroustraete et al. (2002).

## 6. Data evaluation and validation

### 6.1. Evaluation of input data

The monthly maps of minimum and maximum temperatures and precipitation of Italy were validated in a previous investigation (Blasi, 2005). The global radiation imagery derived from these maps was currently evaluated against the monthly data of 10 stations given by Benincasa et al. (1991).

The CORINE Land Cover database applied was the subject of a specific accuracy assessment (Chirici et al., 2004). With regard to the low spatial resolution satellite data, the efficiency of the pre-processing steps applied was also assessed in a previous investigation (Maselli, 2004).

### 6.2. Validation of output data

The C-Fix GPP estimates derived from the two data sets applying the two NDVI extraction methods were first evaluated by comparison with the available annual measurements of the eight flux towers. To this aim, forest GPP estimates were taken from the corresponding pixels of the produced imagery and simply compared to the measured data. This operation relied on the assumption that the footprint of the towers was approximately 1 $km^2$ and that both measured and estimated values referred to whole ecosystem GPP. The validity of both these assumptions will be discussed in the concluding section.

A further accuracy assessment was made using the monthly data collected at San Rossore, Collelongo and Parco del Ticino. For each of these sites, comparisons were made between the monthly GPP reference values and the estimates obtained applying the two extraction methods to the two data sets.

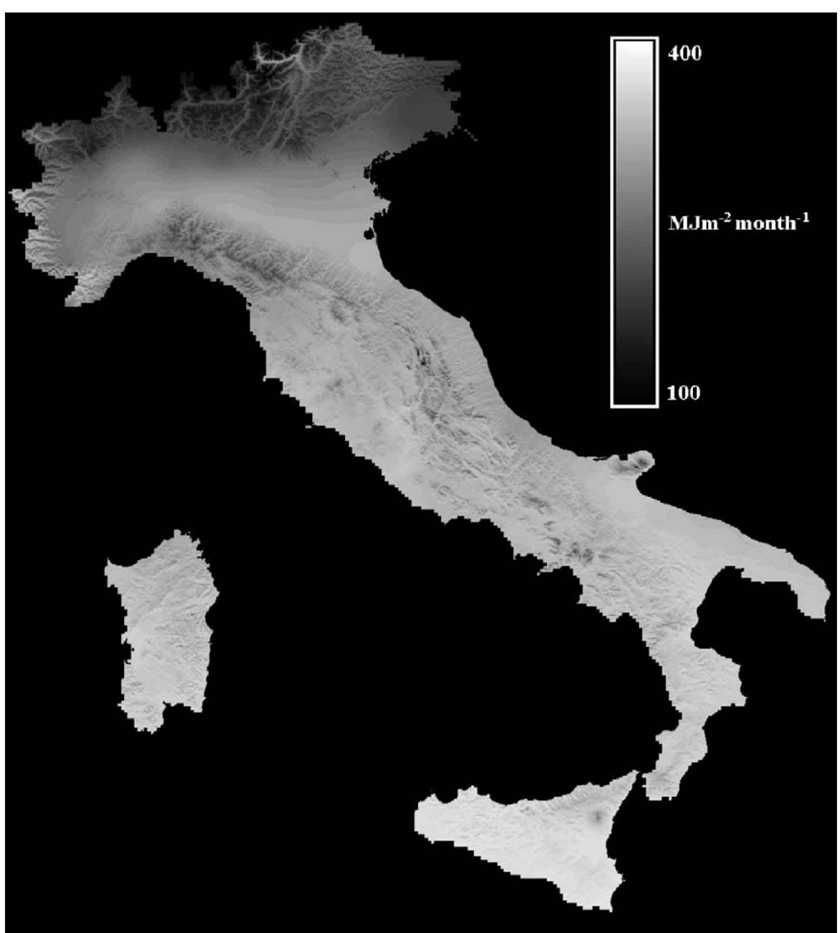


Fig. 2. Map of modelled PAR of August.

Correlation coefficients ($r$) and root mean square errors (RMSE) were the accuracy statistics used to summarize the results of both annual and monthly comparisons.

## 7. Results

The accuracy assessments previously carried out on the climatic and land cover input data layers showed that their quality was sufficient to describe the features of the Italian territory at a national scale (Blasi, 2005; Chirici et al., 2004). As regards the radiation imagery produced by Eq. (2), the evaluation indicated an excellent agreement between measured and estimated $G$ values ($r$=0.990 and RMSE=15.9 MJ $m^{-2}$ $month^{-1}$). An example of the produced PAR maps is shown in Fig. 2 for the month of August, which approximately corresponds to the peak of the hot arid season in Italy.

The study conducted by Maselli (2004) indicated that the pre-processing steps applied to the low spatial resolution NDVI data are generally efficient in removing most of the radiometric errors and atmospheric contaminations contained in the original imagery. Consequently, the mean monthly NDVI imagery produced from both data series were considered to be of acceptable quality and useful to compute fAPAR. An example of these images, derived from SPOT-VGT data, is shown in Fig. 3.

A comparison of the annual GPP estimates with the mean measurements provided by the flux towers is shown in Fig. 4a–b. More particularly, these histograms show the results obtained using AVHRR (Fig. 4a) and SPOT-VGT NDVI data (Fig. 4b) extracted by the two described methodologies. Reasonably good agreements were found between the reference and simulated data in all cases.

Different patterns, however, derived from the application of the two NDVI extraction techniques to the two data types. The use of NDVI values conventionally extracted from AVHRR data produced a relatively high accuracy ($r$=0.758, RMSE=191.7 g C $m^{-2}$ $year^{-1}$). This accuracy was improved by the use of the end-member extraction procedure both in terms of $r$ (0.890) and RMSE (145.0 g C $m^{-2}$ $year^{-1}$).

The application of the two extraction methods to SPOT-VGT data led to a notable decrease of the mean errors and to an increase of the correlation. A correlation coefficient of 0.908 and an RMSE of 138.9 g C $m^{-2}$ $year^{-1}$ were in fact obtained with the simpler method, which were improved to $r$=0.921 and RMSE=123.0 g C $m^{-2}$ $year^{-1}$ with the more sophisticated one.

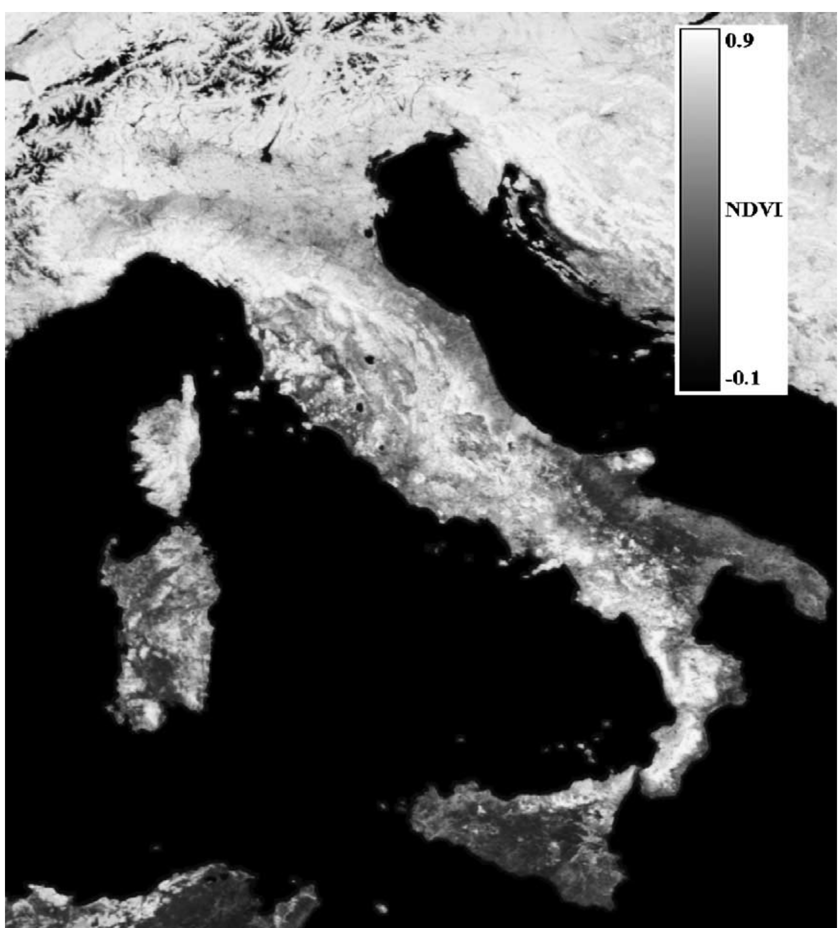


Fig. 3. Mean monthly SPOT-VGT NDVI image of August.

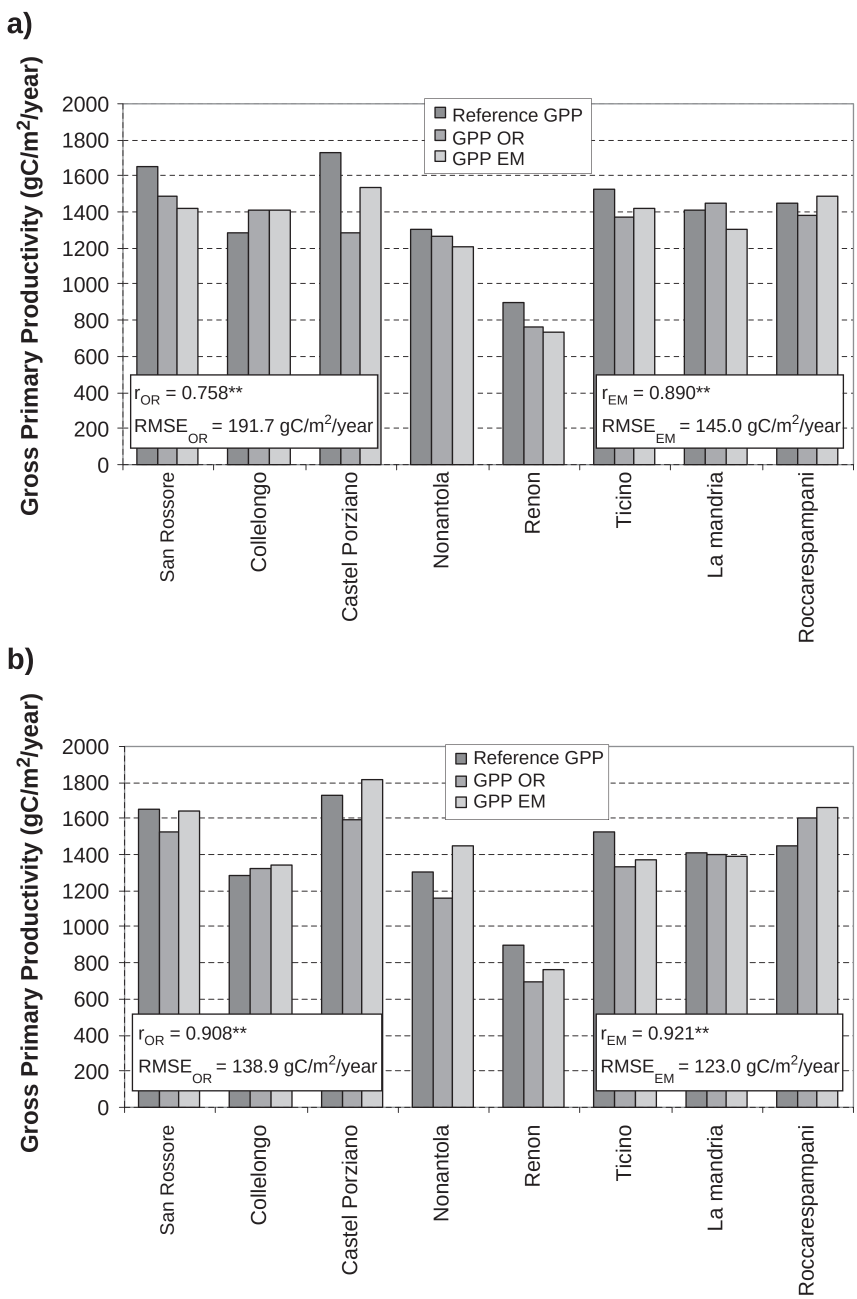


Fig. 4. Comparison of GPP values derived on the ground and estimated by C-Fix using the two NDVI extraction methods (OR = original and EM = end-member) and different satellites: (a) NOAA-AVHRR and (b) SPOT-VGT (** = highly significant correlation, $P < 0.01$).

In general, these results indicated that the use of VGT images outperformed that of AVHRR imagery, and the same was true for the more sophisticated NDVI extraction method with respect to the conventional one. Most of the errors found were related to varying underestimations of the reference GPP values, but also to the different ranges of the estimates. While in fact the mean reference GPP was equal to 1406.0 g C $m^{-2}$ $year^{-1}$, the mean GPP found by applying the two extraction methods to AVHRR data was 1301.3 and 1315.5 g C $m^{-2}$ $year^{-1}$, respectively. The mean estimated GPP increased to 1330.1 and 1430.8 g C $m^{-2}$ $year^{-1}$ by using the VGT data. Correspondingly, the reference GPP range was around 850 g C $m^{-2}$ $year^{-1}$, while the estimated ranges were of 700–800 g C $m^{-2}$ $year^{-1}$ with the AVHRR data and increased to 900–1000 g C $m^{-2}$ $year^{-1}$ with the VGT data.

The evaluation of the GPP estimates on a monthly basis gave the results presented in Figs. 5 and 6 for the three study sites (San Rossore, Collelongo, Parco del Ticino). The modelling approach was generally capable of reproducing the seasonal GPP patterns of these sites. In the case of San Rossore, however, where pine wood stands were present, the seasonal variability of the measured data was markedly lower than that of the simulated data. Higher accuracies were

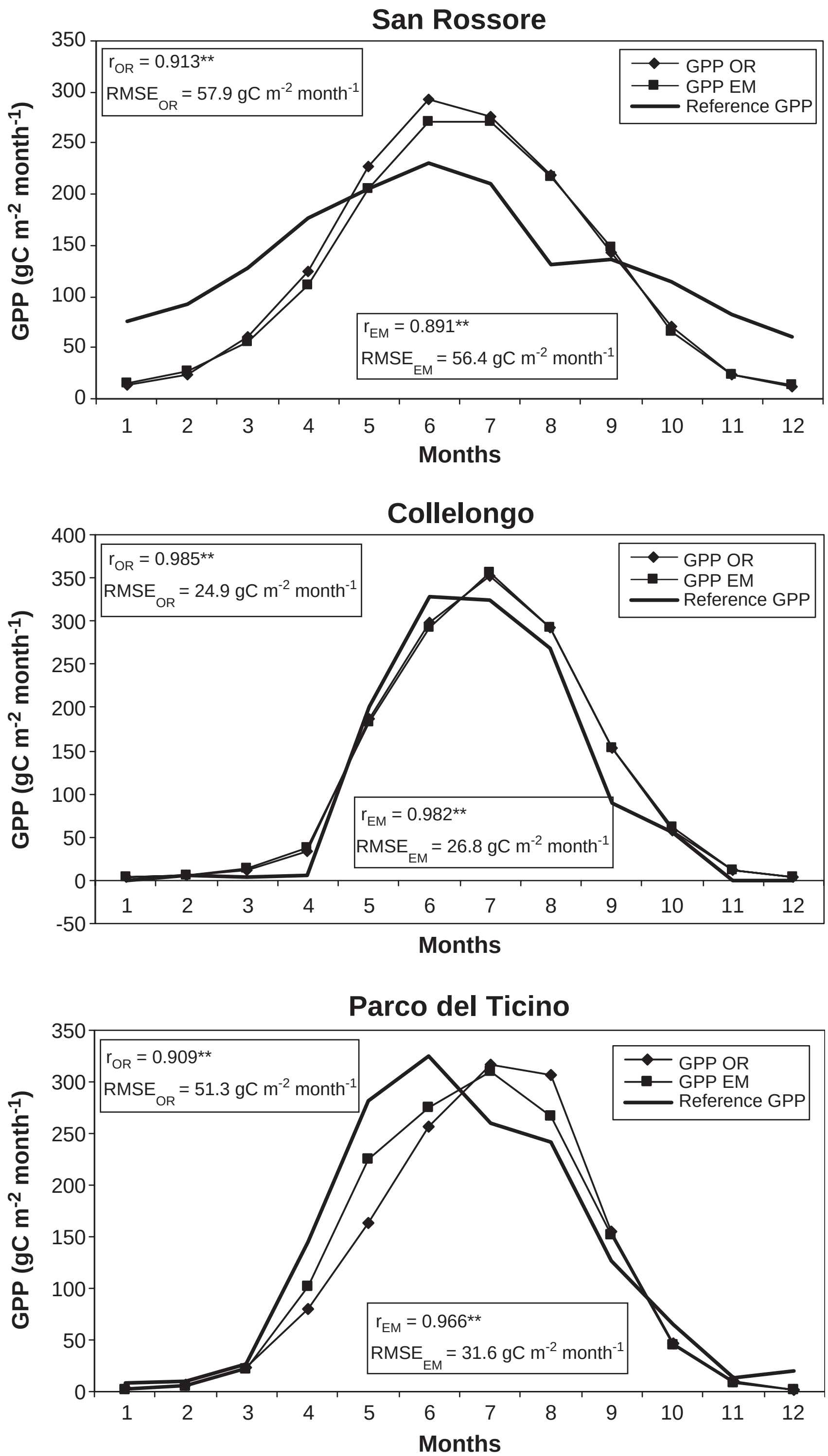


Fig. 5. Comparison of monthly GPP reference data at three different sites and estimated by C-Fix using AVHRR NDVI data (**=highly significant correlation, $P<0.01$).

obtained for Parco del Ticino and, above all, for Collelongo, where broadleaved deciduous species were dominant.

Concerning the inter-comparison of the two data types and NDVI extraction methods, at Rossore the use of VGT data was slightly more efficient than that of AVHRR data, while the two extraction methods yielded similar accuracies. In the case of Collelongo, the agreement between reference and simulated data was always excellent in terms of correlation ($r>0.97$), but the use of VGT data led to slightly worse GPP underestimations with the AVHRR data. The two extraction methods performed in an almost identical way. As regards Parco del Ticino, the highest differences derived from the use of the two data types

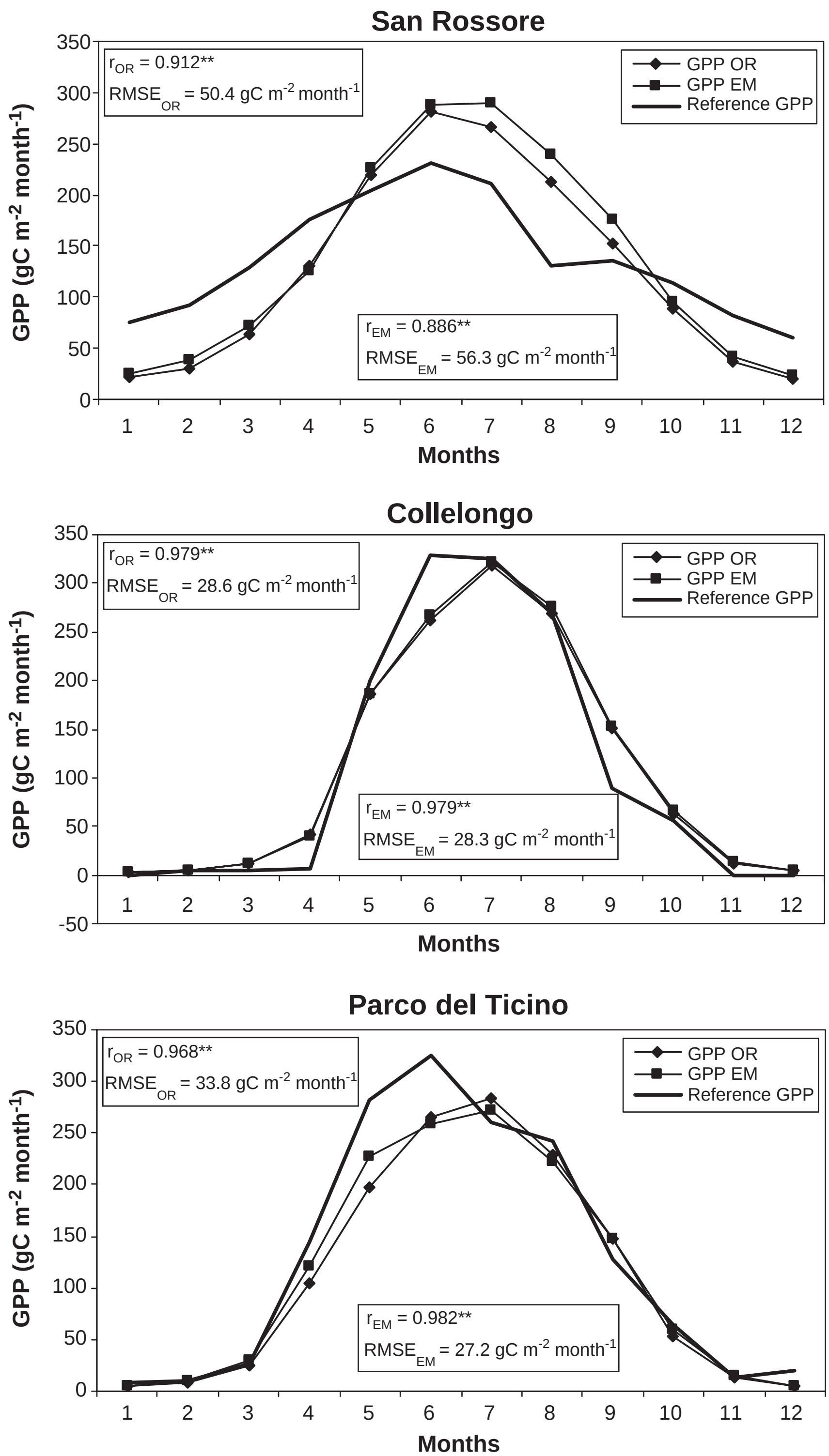


Fig. 6. Comparison of monthly GPP reference data at three different sites and estimated by C-Fix using SPOT-VGT NDVI data (** = highly significant correlation, $P < 0.01$).

and extraction methods. In particular, the utilization of VGT data clearly outperformed that of AVHRR data, and the same was true for the more complex extraction method.

Thus, in one case (Parco del Ticino) the use of VGT data clearly improved the accuracy in estimating monthly GPP values with respect to AVHRR data. For the same study site a major improvement was obtained by the more complex NDVI extraction procedure. In the other cases no consistent differences were attributable to the use of the two data types and extraction methods.

In summary, both accuracy assessments indicated that the estimates produced by the described approach realistically

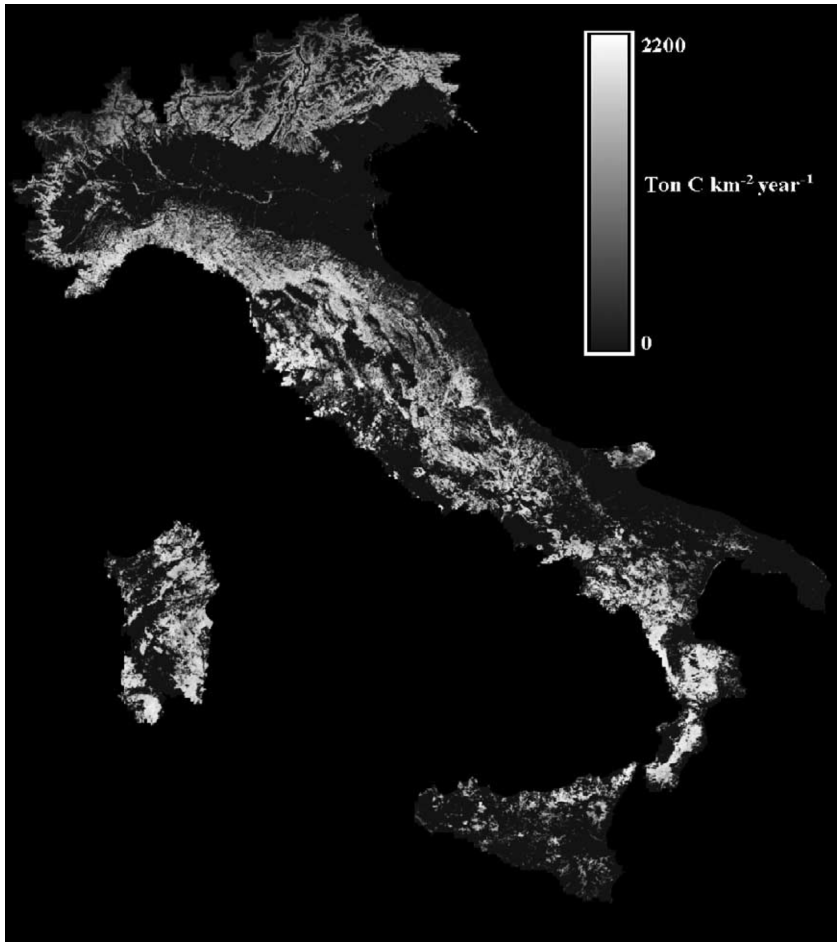


Fig. 7. Map of forest GPP in Italy obtained by applying the optimal integration approach to SPOT-VGT data.

represented the main features of forest GPP in Italy. Globally, the best results were obtained by the application of the more sophisticated NDVI extraction method at the VGT data. On the basis of these results, the estimation of forest GPP at the national level was deemed to be feasible. The forest GPP map obtained using the best NDVI data set (VGT) and extraction method (end-member) is shown in Fig. 7. Mean and total values of the single forest types were also derived from the GPP maps and are shown in Table 3. The best national estimate of all classes obtained by the current approach was of about 106 M t C $year^{-1}$.

Table 3
GPP estimates obtained by the applied integration procedure for the 12 forest types considered

| Index | Forest type | Average estimated GPP (g C $m^{-2}$ $year^{-1}$) | Total GPP estimates per class (t C $year^{-1}$) |
|---|---|---|---|
| 1 | White fir/Norway spruce forest | 989.7 | 7,661,883 |
| 2 | Chestnut forest | 1393.1 | 11,753,472 |
| 3 | Exotic conifer forest | 1359.1 | 198,422 |
| 4 | Beech forest | 1318.8 | 15,300,519 |
| 5 | Exotic broadleaf forest | 1409.6 | 2,385,104 |
| 6 | Hygrophilous broadleaf forest | 1246.1 | 1,552,619 |
| 7 | Mediterranean broadleaves | 1232.5 | 11,968,304 |
| 8 | Holm oak | 1601.8 | 11,253,272 |
| 9 | High maquis | 1187.7 | 2,397,988 |
| 10 | Mediterranean pine forest | 1425.2 | 4,376,916 |
| 11 | Mountain pine forest | 1366.6 | 5,643,893 |
| 12 | Other oaks | 1465.6 | 31,286,119 |
| Total | | | 105,778,510 |

## 8. Discussion and conclusion

The C-Fix approach lies between complex process models requiring a large amount of field measurements and very simple semi-empirical models merely based on remotely sensed data. The approach relies on the premise that a quasi-linear relationship exists between fAPAR and biomass production. This assumption is actually not realistic over short time periods (e.g., hours–days), but it is justified when considering time periods of the order of months or years (Landsberg & Waring, 1997).

The relative simplicity of the model allows its application to large areas relying on remotely sensed and ancillary data which are generally widely available. In the present case DEM and climatic data layers were derived from previous research activities, together with land cover data recently produced for a European project (CORINE Land Cover). It can be reasonably supposed that similar data are equally available for many other areas, at least in developed countries.

With regard to satellite data, already processed archives of AVHRR images are now available in several parts of the globe, while VGT data are distributed for the whole land surface on a regular basis (Maisongrande et al., 2004; Townshend, 1994). This situation should permit a relatively easy replicability of the approach in other environments.

The use of the current satellite and ancillary data posed some theoretical and practical problems concerning the spatial and temporal resolutions of the investigation. Most data layers were in fact available at 1 km resolution, which was therefore selected as a reference for the study but might be not optimal to catch the spatial variability characterizing complex Italian landscapes (Lacaze et al., 1996; Maselli, 2004). Furthermore, the climatic data used covered a quite long time period (approximately 30 years) which was not coincident with that of the satellite data acquisitions (5 years). An assumption was therefore necessary that both data sets described the average environmental conditions of the forests under study. This implies that the current implementation of the approach is suited to estimating only mean productivity levels of existing forests at coarse spatial resolution.

With regard to GPP data measured at flux towers, the available sample was necessarily quite limited, which created an unavoidable constraint to a proper statistical assessment of the accuracy reachable by the various methods. Moreover, these data referred to few and often sparse measurement periods, which introduced a further source of error into the comparison with the above-mentioned averaged GPP estimates. Additional problems derived from the size of the footprint covered by each tower, which was variable mainly depending on the local environmental situation and land cover (Cohen et al., 2003). The assumption currently used was that, in temperate forest areas, such size was approximately comparable to that of the pixels under study (1 $km^2$). Relying on this assumption, the current accuracy assessment was made possible by the representativity of both measured and estimated values for whole ecosystem productivities, comprising the contribution of all photosynthesizing plants (trees, shrubs, grasses).

Considering all mentioned approximations and limitations, the obtained GPP estimates were demonstrated to be in good agreement with the GPP data derived from the flux towers. This was true for both mean spatial GPP variations due to climatic and edaphic factors and for temporal GPP variations of specific ecosystems during a growing season. The accuracy of the annual estimates, however, was found to be higher than that of the monthly values, probably due to their longer integration period which tended to smooth the effects of the various error sources. In particular, the tested procedure had problems when simulating the annual cycle of evergreen species, apparently due to an overestimation of the seasonal variability found with the eddy covariance technique. Consequently, the following conclusions on the different data types and NDVI extraction methods are derived from the analysis on an annual basis.

Concerning the data types, the use of SPOT-VGT images generally outperforms that of NOAA-AVHRR imagery. This is expectable considering the higher radiometric and geometric quality of the former data set, whose production also comprises an atmospheric correction module which could only be simulated for the AVHRR images (Maisongrande et al., 2004). More particularly, the poor GPP estimation caused by the use of AVHRR images can be partly attributed to the instability of the relevant NDVI values during the time period considered. As noted by Bolle et al. (in press), in fact, all corrections applicable to the AVHRR NDVI data can only reduce this instability, which is due to numerous factors varying in both space and time (sensor radiometric degradations, variations in atmospheric turbidity, differences in filter responses and varying times of image acquisition of the various NOAA satellites, etc.).

The inter-comparison between the two extraction methods indicates that the use of NDVI end-members generally produces more accurate annual GPP estimates. More specifically, the application of this method alleviates the GPP underestimation of the conventional procedure, likely due to its capacity of unmixing the forest spectral signatures from those of the surrounding areas which have generally lower NDVI values. Such a behavior testifies to a more efficient utilization of the available information on forest distribution, confirming again the results of previous investigations (Maselli, 2004).

A peculiar feature of the procedure applied is represented by its sound ecophysiological basis, i.e. the use of straightforward and well-documented functional relationships linking NDVI, fAPAR and GPP. This makes the method fundamentally different from those which simply extend carbon flux measurements on the land surface through semi-empirical statistical methodologies (Papale & Valentini, 2003). The current approach should in fact be applicable more easily and efficiently in other areas where the needed input data are available.

The results of the present experiment however need further confirmation. In particular, the validity of the approach should be tested in other regions also using different and more appropriate spatial and temporal resolutions. A decisive step in this direction would be the retrieval of a more adequate sample of test points, which is essential to definitively assess the general applicability of the methodology.

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