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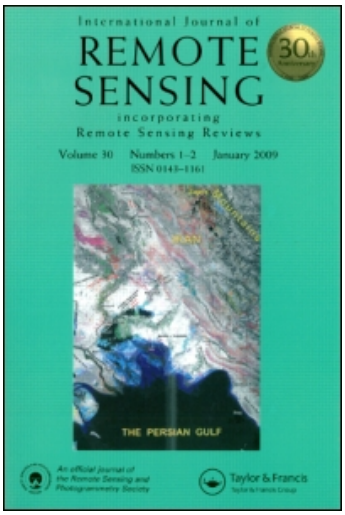

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713722504

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F. Maselli [a]; M. Chiesi [a]; L. Fibbi [a]; M. Moriondo [b]
[a] Institute of Biometeorology (IBIMET), National Research Council of Italy (CNR), 50019 Sesto Fiorentino, Firenze, Italy [b] Department of Agronomy and Land Management (DISAT), University of Florence, 50144 Firenze, Italy

Online Publication Date: 01 April 2008

To cite this Article Maselli, F., Chiesi, M., Fibbi, L. and Moriondo, M.(2008)'Integration of remote sensing and ecosystem modelling techniques to estimate forest net carbon uptake',International Journal of Remote Sensing,29:8,2437 — 2443
To link to this Article: DOI: 10.1080/01431160801894857
URL: http://dx.doi.org/10.1080/01431160801894857

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International Journal of Remote Sensing
Vol. 29, No. 8, 20 April 2008, 2437–2443

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Letter

Integration of remote sensing and ecosystem modelling techniques to estimate forest net carbon uptake

F. MASELLI*†, M. CHIESI†, L. FIBBI† and M. MORIONDO‡
†Institute of Biometeorology (IBIMET), National Research Council of Italy (CNR), Via Madonna del Piano 10, 50019 Sesto Fiorentino, Firenze, Italy
‡Department of Agronomy and Land Management (DISAT), University of Florence, P. le delle Cascine 18, 50144 Firenze, Italy

(*Received 29 May 2007; in final form 2 January 2008*)

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Estimates of forest gross primary production (GPP) can be obtained using a parametric model (C-Fix) that combines ground and remotely sensed data. A methodology is presented to convert these GPP estimates into values of net ecosystem exchange (NEE). The methodology is based on the use of a process model (BIOME-BGC) that, after proper calibration, simulates all main functions of forest ecosystems at the climax condition. The estimated photosynthesis and respirations are transformed into net carbon fluxes of actual forests by using a simplified approach that relies on the difference between actual and potential stand biomass. The methodology was applied to eight forest sites in Italy where flux measurements were available and GPP estimates had been previously produced. The comparison of the obtained NEE estimates to the ground data indicates the potential of the approach and the prospects for future investigation.

1. Introduction

The estimation of the main forest ecosystem processes is necessary to advance towards sustainable management of forest resources, both on local and regional scales (Waring and Running 1998). Several studies have demonstrated that the gross production of forest ecosystems can be estimated by the combination of remotely sensed optical images and ancillary data (Veroustraete *et al.* 2004, Maselli *et al.* 2006). The assessment of net carbon fluxes is more complex due to the necessity for the additional simulation of both autotrophic and heterotrophic forest respirations (Waring and Running 1998).

A recent investigation conducted in Italy has shown that a simple parametric model which combines satellite sensor and meteorological data (C-Fix) is capable of producing accurate estimates of forest gross primary production (GPP) (Maselli *et al.* 2006). A simplified methodology has been proposed to convert these GPP values into estimates of net ecosystem exchange (NEE), which expresses the actual forest net carbon uptake (Maselli *et al.* 2008). The methodology relies on the use of a process model (BIOME-BGC) to simulate all main forest functions at the climax condition. Photosynthesis and respiration estimates of real forests are produced by considering the difference between actual and potential volumes as an indicator of ecosystem distance from climax.

*Corresponding author. Email: maselli@ibimet.cnr.it

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2008 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160801894857

The current work aims to test the applicability of this modelling approach to simulate the NEE of eight Italian forest sites where carbon fluxes are measured by the eddy-correlation technique. In particular, this letter reports preliminary results obtained by converting previously produced mean annual GPP estimates into NEE values, which are evaluated by comparison to flux tower measurements.

2. Modelling approach

The model C-Fix estimates the gross primary production of forest ecosystems as a function of photosynthetically active radiation (PAR) absorbed by vegetation (Veroustraete *et al.* 2004). Specifically, the estimation of GPP is made through the general equation:

$$\mathrm{GPP} = \varepsilon \sum_{i=1}^{N} T_{\mathrm{cor}\,i} \mathrm{FAPAR}_i \mathrm{Rad}_i, \tag{1}$$

where ε is the radiation use efficiency (set to 1.1 g C MJ^{-1} absorbed PAR, according to Veroustraete *et al.* 2004), N is the number of periods considered, T_{cor} is a factor accounting for the dependence of photosynthesis on air temperature T_i, FAPAR is the fraction of absorbed PAR, and Rad is the solar incident PAR, all referred to period i.

The forest FAPAR estimates needed to drive C-Fix are obtained through the quasi-linear relationship that links FAPAR to the normalized difference vegetation index (NDVI) (Myneni and Williams 1994). Since this relationship is applicable to top-of-canopy NDVI values, the basic remotely sensed data to compute the index must be calibrated radiometrically and corrected for atmospheric effects. This is the case for the NDVI imagery derived from the SPOT-VEGETATION (SPOT-VGT) sensor, which has a spatial resolution of 1 km^2 and is produced routinely each ten day period (Veroustraete *et al.* 2004).

BIOME-Bio-Geochemical-Cycles (BIOME-BGC) is a process model developed at the University of Montana to estimate the storage and fluxes of carbon, nitrogen and water within terrestrial ecosystems (White *et al.* 2000). It requires daily climate data, information on the general environment (i.e. soil, vegetation and site conditions) and parameters describing the ecophysiological characteristics of vegetation. The model works by finding a quasi-climax equilibrium with local ecoclimatic conditions through the spin-up phase.

Forest GPP computed by C-Fix and BIOME-BGC is an expression of total or potential ecosystem photosynthesis, respectively. The two GPP estimates are usually almost equivalent, since brushes and grasses can complement the photosynthesis that is not performed by incomplete tree canopies. This opens the possibility of integrating the two model outputs by merging the C-Fix photosynthesis estimates with the BIOME-BGC simulated respirations (Maselli *et al.* 2008). The latter, however, relate to a quasi-climax situation, which may be very different to that existing in real forest ecosystems, where woody biomass can be artificially kept much smaller than the potential level (Waring and Running 1998).

The approach proposed by Maselli *et al.* (2008) to correct for this factor is based on the consideration that forest NEE is mostly determined by the capacity of new carbon accumulation in woody components. Such capacity may be limited by both very low and high levels of existing woody biomass, due to reduced tree photosynthesis and increasing autotrophic and heterotrophic respirations,

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respectively. Tree volume, which is directly related to woody biomass, can therefore be taken as an indicator of ecosystem proximity to the equilibrium condition. Specifically, the ratio between actual and potential tree volume is considered as an index of such proximity and is used to correct for photosynthesis and respiration differences with respect to the BIOME-BGC simulations.

Following this approach, the actual forest volume is normalized over the maximum (climax) volume computed by BIOME-BGC. Normalized actual volume (NV_A) is then converted into actual LAI (LAI_A) using the maximum leaf area index (LAI) simulated by BIOME-BGC. Next, LAI_A is utilized to compute actual forest cover (FC_A) through Beer's law. The parameter FC_A represents the fraction of photosynthetic radiation actually intercepted by the tree canopy and can be used to convert BIOME-BGC GPP into the GPP of the existing tree compartment. The respirations of this compartment are instead considered to be quasi-linearly dependent on NV_A. Accordingly, actual NEE (NEE_A) can be approximated by:

$$NEE_A = (GPP \times FC_A) - (Rgr \times FC_A) - (Rmn \times NV_A) - \left(Rhet \times NV_A^2\right), \quad (2)$$

where GPP is the total ecosystem production calculated from equation (1), and Rgr, Rmn and Rhet are growth, maintenance and heterotrophic respirations, respectively, all simulated by BIOME-BGC and rescaled to conform to C-Fix GPP (Maselli *et al.* 2008). Figure 1 reproduces schematically the dependence of NEE_A on normalized volume. Increasing volume increases NEE_A up to a certain value (30%–40% of maximum volume), above which NEE_A tends to return to 0 (corresponding

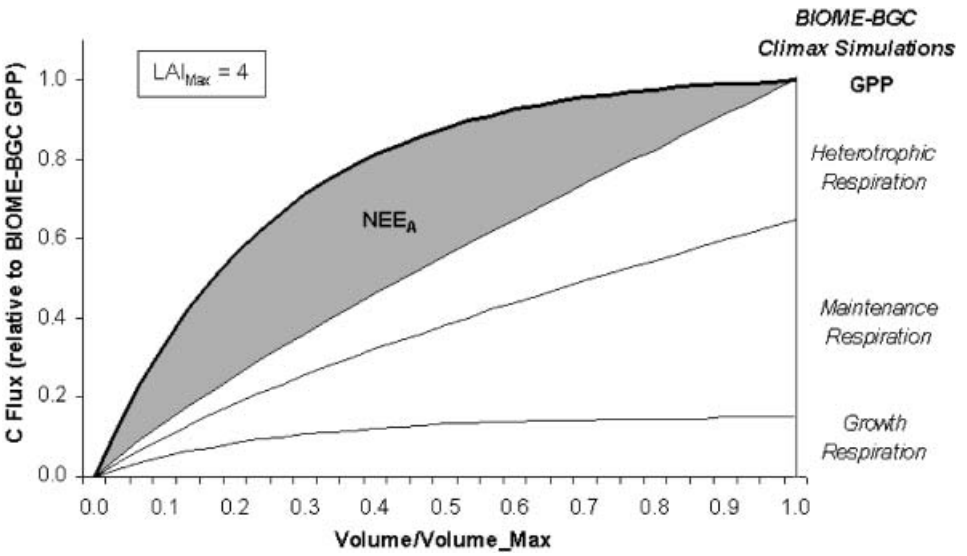

Figure 1. Scheme of the simplified methodology applied to correct BIOME-BGC NEE estimates on the basis of existing volume. Forest GPP and growth respiration are assumed to vary with actual forest cover, while maintenance and heterotrophic respirations are assumed to vary with actual normalized volume. The different dependences of photosynthesis and respirations on actual forest volume determine the variation of NEE_A (grey area), which starts from 0 when NV_A is 0 (no forest), reaches a maximum when NV_A is approximately 0.3–0.4 (young, dense forest) and returns to 0 when NV_A approaches 1 (climax forest).

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to the BIOME-BGC climax simulation). The assumptions and approximations involved in such a scheme are fully discussed in Maselli *et al*. (2008).

3. Materials and methods

The eight forest sites considered are the same as used in Maselli *et al*. (2006). All these sites belong to the FLUXNET network, and are described on the relevant website (http://www.fluxnet.ornl.gov/fluxnet/). The mean annual NEE values currently used were computed using eddy-correlation data taken in the same years as the previous work (from 1997 to 2003). The NEE values reported on the FLUXNET website were completed and confirmed through personal contacts with the scientists responsible for the management of the eight flux towers.

Mean annual GPP estimates for the eight towers were obtained by combining mean monthly meteorological data and SPOT-VGT NDVI imagery through C-Fix (Maselli *et al*. 2006). These estimates accurately reproduced the mean annual GPP measurements of the tower, as indicated by a correlation coefficient (r) of 0.921 and a root mean square error (RMSE) of $123.0\,\mathrm{g\,C\,m^{-2}\,y^{-1}}$.

Daily meteorological data (maximum and minimum temperatures and precipitation) for five years (1999 to 2003) were extrapolated to the eight study sites from measurements taken at adjacent weather stations (http://ww.ucea.it). The extrapolation was carried out using MT-CLIM, which also estimated the other variables needed to drive BIOME-BGC (air humidity and solar radiation) (Maselli *et al*. 2008). The versions of BIOME-BGC currently used were calibrated for six Mediterranean forest biomes, as described in Chiesi *et al*. (2007). The calibrated model versions were run at the eight sites to compute at-equilibrium carbon flux estimates. These were combined with the previously obtained C-Fix mean annual GPP estimates by applying the following steps to each flux tower site:

1. Computation of actual forest volume from the data descriptive of the site (http://www.fluxnet.ornl.gov/fluxnet/), complemented with information directly received from colleagues responsible for the tower management;
2. Derivation of maximum (climax) volume from BIOME-BGC stem carbon and normalization of actual volume to compute NV_A;
3. Conversion of NV_A into LAI_A by considering the BIOME-BGC maximum LAI estimate and use of LAI_A to compute actual forest cover (FC_A);
4. Rescaling of BIOME-BGC respirations using the ratios $GPP_{C\text{-}Fix}/GPP_{BIOME}$;
5. Computation of NEE of the tree compartment (NEE_A) by using C-Fix photosynthesis and rescaled BIOME-BGC respirations within equation (2).

Annual NEE_A estimates over five years (1999 to 2003) were thus obtained for each site. These estimates were averaged to compute eight mean annual values, whose accuracy was evaluated using the available flux tower measurements and conventional accuracy statistics (r and RMSE).

4. Results

The eight flux tower sites considered in the research are listed in table 1, together with the dominant forest species and the GPP estimates obtained by Maselli *et al*. (2006). The actual volumes derived from the site descriptions are also reported, followed by the maximum (potential) volumes estimated by BIOME-BGC. The

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Table 1. Main characteristics of the selected test sites. Existing species and actual volumes (VOL_A) were mostly derived from the descriptions of the towers (http://www.fluxnet.ornl.gov/fluxnet/), while GPP estimates were taken from Maselli *et al.* (2006) and maximum volumes (VOL_Max) were estimated through BIOME-BGC.

Site no.	Test site	Species	Estimated GPP ($g\,C\,m^2\,y^{-1}$)	VOL_A ($m^3\,ha^{-1}$)	VOL_Max ($m^3\,ha^{-1}$)
1	San Rossore	*Pinus pinaster* Ait.	1642	250	1379
2	Collelongo	*Fagus sylvatica* Mill.	1345	500	1482
3	Castel Porziano	*Quercus ilex* L.	1812	220	809
4	Nonantola	Mixed deciduous forest	1451	110	1465
5	Renon	*Picea abies* (L.) Karst.	759	350	1955
6	Ticino	*Populus alba* I 214	1376	270	1631
7	La Mandria	Mixed deciduous forest	1395	250	1796
8	Roccarespampani	*Quercus cerris* L.	1665	200	1261

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NV_A values computed from these volumes are generally small (from 0.07 for Nonantola to 0.34 for Collelongo). According to the proposed scheme (figure 1), these low NV_A values indicate great, variable distances of the study ecosystems from climax, and consequently determine tree photosynthesis and respiration estimates that are reduced with respect to those computed by C-Fix and BIOME-BGC.

The NEE_A estimates obtained from equation (2) are compared to relevant measurements in figure 2. The correlation between measured and estimated NEE (0.777), although not very large, is significant at the 95% confidence level, and the mean error is $94.9\,g\,C\,m^{-2}\,y^{-1}$. Most of this accordance is due to the excellent accuracy of the original C-Fix GPP estimates, which obviously affect the estimated NEE. Part of the same accordance, however, is related to the approximated estimation of the NEE/GPP fractions at the eight study sites. The correlation between measured and estimated NEE/GPP fractions is in fact equal to 0.387, and the RMSE is 0.077.

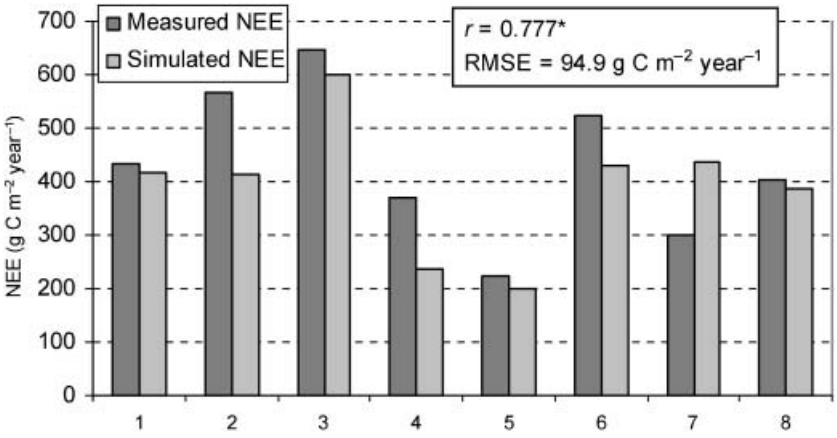

Figure 2. Measured and estimated mean annual NEE of the eight Italian flux towers. The sequential numbers of the towers on the *x*-axis are the same as reported in table 1 (*=significant correlation, $P<0.05$).

5. Discussion and future prospects

The accuracy obtained in the estimation of NEE through the described modelling approach is lower than that previously found for GPP. This is easily explainable considering the greater variability of NEE and, above all, the greater complexity in its simulation with respect to GPP. Forest NEE is, in fact, only partially dependent on total photosynthesis, which can be accurately estimated by using ground and satellite sensor data. Instead, NEE is mostly determined by autotrophic and heterotrophic respirations, which, depending on the biomass accumulated in the trees and in other ecosystem compartments, are very difficult to assess over wide land areas (Waring and Running 1998).

The approach proposed to circumvent this problem assumes a simplified dependence of tree photosynthesis and respirations on actual stand volume, which can be mapped with reasonable accuracy by the combination of ground and remotely sensed data (Katila and Tomppo 2001). This simplification renders the approach suitable only to simulate the functions of relatively wide forest ecosystems, but only to being applied on a regional scale. In spite of the approximations involved, the methodology was currently able to produce NEE estimates that were significantly correlated with the ground measurements. In addition to the previous observation on NEE estimation, this correlation is particularly relevant keeping in mind all the problems involved in the accuracy assessment performed (possible errors in the ground and satellite data used, different spatial supports and temporal coverages of the estimates with respect to the measurements, etc., see Maselli *et al*. 2006).

The full calibration and validation of the methodology proposed would require further experiment against a long-term series of ground NEE data. This is now becoming feasible due to the ongoing completion of an archive containing measurements taken in all Italian flux tower sites. Contacts with colleagues responsible for these data are being taken in view of a possible extended experiment.

Acknowledgements

The authors thank all colleagues who provided the ground data used in the research: Dr A. Cescatti, Dr G. Manca, Dr B. Marcolla, Dr G. Matteucci, Dr M. Meroni, Dr M. Migliavacca, Dr F. Rossi, Dr O. Facini, Dr G. Seufert, Dr L. Montagnani and F. Petrella. Thanks are also due to the colleagues who contributed to the calibration of the methodologies applied: Prof. M. Bindi, Prof. S.W. Running, Prof. H.J. Bolle, Prof. G. Chirici and Prof. P.M. Corona.

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