Application of the 3-PGS model to assess carbon accumulation in forest ecosystems at a regional level

A. Nolè, B.E. Law, F. Magnani, G. Matteucci, A. Ferrara, F. Ripullone, and M. Borghetti

Abstract: In this study we assessed carbon sequestration by Italian forest ecosystems at a regional level. We applied a monthly time-step process-based model (3-PGS), coupled with a modified soil respiration model, to predict both gross primary production ($GPP_{3\text{-}PGS}$) and net ecosystem production ($NEP_{3\text{-}PGS}$). To evaluate the general reliability of model estimates, we compared, at five different forest sites, monthly and annual $GPP_{3\text{-}PGS}$, $NEP_{3\text{-}PGS}$, and predicted total ecosystem respiration ($TER_{3\text{-}PGS}$) with averages of monthly and annual eddy covariance (EC) measures of GPP_{EC}, NEP_{EC}, and TER_{EC}. A strong correlation was found between annual $GPP_{3\text{-}PGS}$ and annual GPP_{EC} (r^2 = 0.77, RMSE = 1.28 Mg C·ha^{-1}·year^{-1}), and monthly (r^2 = 0.85, RMSE = 35 g C·m^{-2}·month^{-1}), as well as between $NEP_{3\text{-}PGS}$ and annual NEP_{EC} (r^2 = 0.76, RMSE = 0.21 Mg C·ha^{-1}·year^{-1}), and monthly (r^2 = 0.78, RMSE = 18 g C·m^{-2}·month^{-1}). The $TER_{3\text{-}PGS}$ also showed a high correlation with annual TER_{EC} (r^2 = 0.93). Furthermore, a sensitivity analysis showed that $GPP_{3\text{-}PGS}$ was highly sensitive to the satellite greenness index (normalized difference of vegetation index) and to the vapor pressure deficit. With general confidence in the models, we established a 30 year average meteorological grid of 8 km × 8 km resolution across Italy and created a map representing annual $NEP_{3\text{-}PGS}$ across Italian forests, based on the remotely sensed CORINE Land Cover forest classification.

Résumé : Dans cette étude, nous avons évalué la séquestration du carbone à l'échelle régionale par les écosystèmes forestiers en Italie. Nous avons appliqué un modèle basé sur les processus au pas de temps mensuel (3-PGS) couplé à un modèle modifié de respiration du sol pour prédire la production primaire brute ($PPB_{3\text{-}PGS}$) et la production nette de l'écosystème ($PNE_{3\text{-}PGS}$). Pour évaluer la fiabilité générale des estimations des modèles, nous avons, dans cinq stations forestières différentes, comparé les valeurs mensuelles et annuelles de la $PPB_{3\text{-}PGS}$ et de la $PNE_{3\text{-}PGS}$, ainsi que la valeur prédite de la respiration totale de l'écosystème ($RTE_{3\text{-}PGS}$), avec les moyennes mensuelles et annuelles des mesures de la PPB_{CT}, de la PNE_{CT} et de la RTE_{CT} par la méthode de corrélation turbulente (CT). Il y avait une étroite corrélation entre la $PPB_{3\text{-}PGS}$ annuelle et les PPB_{CT} annuelle (r^2 = 0,77, EQM = 1,28 Mg C·ha^{-1}·an^{-1}) et mensuelles (r^2 = 0,85, EQM = 35 g C·m^{-2}·mois^{-1}), ainsi qu'entre la $PNE_{3\text{-}PGS}$ et les PNE_{CT} annuelle (r^2 = 0,76, EQM = 0,21 Mg C·ha^{-1}·an^{-1}) et mensuelles (r^2 = 0,78, EQM = 18 g C·m^{-2}·mois^{-1}). La $RTE_{3\text{-}PGS}$ était également étroitement corrélée à la RTE_{CT} annuelle (r^2 = 0,93). De plus, une analyse de sensibilité a montré que la $PPB_{3\text{-}PGS}$ était très sensible à l'indice de végétation par différence normalisée et au déficit de pression de vapeur. Avec une confiance générale dans les modèles, nous avons établi un quadrillage météorologique des moyennes de 30 ans avec une résolution de 8 km × 8 km dans l'ensemble de l'Italie et nous avons généré une carte représentant la $PNE_{3\text{-}PGS}$ annuelle des forêts italiennes basée sur la classification des forêts de la base de données CORINE Land Cover obtenue par télédétection.

[Traduit par la Rédaction]

Introduction

The increase of atmospheric carbon dioxide due to anthropogenic emissions and the associated global warming are partly counterbalanced by active carbon sequestration by terrestrial vegetation (Magnani et al. 2007). Temperate and boreal forests, which cover an area of about 2 × 10^7 km^2, act as a substantial carbon sink of 0.6–0.7 Pg (Goodale et al. 2002). At the European level, terrestrial vegetation is thought to absorb 7%–12% of total anthropogenic carbon emissions (Janssens et al. 2003). There is an increasing demand for reliable estimates of carbon sinks by forest and agricultural ecosystems. Quantitative assessment of carbon sequestration by terrestrial vegetation at a local to regional

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scale represents basic information for recommending and evaluating policy and management decisions (IPCC 2001).

Recent studies have been focused on the interaction between ecosystems and changing climatic conditions, with particular attention on the feedback between the carbon cycle and climate change (Ciais et al. 2005; Friedlingstein et al. 2006). One of these interactions regards the changes in terrestrial carbon sinks in response to changes in temperature and precipitation patterns that may provide a positive feedback in a warming world (Heimann and Reichstein 2008). Quantifying and predicting actual and future magnitudes of terrestrial ecosystems carbon dynamics at both a regional and global scale represent major challenges for the scientific community.

The use of process-based models, which incorporate a basic understanding of plant physiology and soil processes, provides an effective way to assess terrestrial carbon sinks under varying environments over a range of spatial scales (Prince and Goward 1995; Kimball et al. 1997; Landsberg and Gower 1997; Cao and Woodward 1998; Cramer et al. 1999; Landsberg and Coops 1999; Veroustraeteet al. 2002; Medlyn et al. 2003; Yuan et al. 2007). These models summarize the fast leaf-level photosynthetic response at a longer (daily–monthly) time step, by scaling up the process analysis from the leaf level to the whole-canopy level (Mäkelä et al. 2008). In particular, these models are based on the light use efficiency (LUE) approach, which estimates the conversion efficiency of absorbed photosynthetically active radiation (APAR) into gross primary production (GPP) and assumes a linear dependence of GPP on APAR reduced by environmental constraints (McMurtrie et al. 1994; Landsberg and Waring 1997; Running et al. 2004).

The availability of CO_2 flux data from the worldwide network of eddy covariance (EC) towers (FLUXNET), covering a wide range of biomes, represents a fundamental support for the development, calibration, and evaluation of process- and satellite-based models, to better understand temporal and spatial variation in CO_2 fluxes. (Baldocchi and Meyers 1998; Law et al. 2000).

The 3-PGS model (physiological principles predicting growth - spatial) by Coops et al. (1998) is a simplified and spatially extended version of the well-documented 3-PG model (Landsberg and Waring 1997), with the exclusion of the stand-growth modeling routine. The model predicts net carbon accumulation in green plants (net primary production, NPP) using a limited number of input variables and parameters.

Previous applications of 3-PGS over a wide range of forest types in North America, New Zealand, and Australia have proved its effectiveness to predict forest productivity under different environmental and vegetation conditions (Coops and Waring 2001*a*, 2001*b*; Coops et al. 2001, 2005; Tickle et al. 2001). The effectiveness of the 3-PGS model depends mainly on a combination of generalized biophysical and physiological principles coupled with main assumptions based on empirical observations, while a major limitation for large-scale applications is the availability of spatial input information.

Although 3-PGS was not designed to estimate net ecosystem fluxes, we proposed to extend its application through the addition of a soil respiration model to predict total ecosystem respiration (TER) and then net ecosystem production (NEP).

Table 1. Parameterization of the soil respiration model T&P&LAI (Reichstein et al. 2003).

Parameter	Value
$R_{LAI=0}$ (g C·m^{-2}·day^{-1})	0.48
s_{LAI} (g C·m^{-2}·day^{-1})	0.31
Q (°C^{-1})	0.03918
K (mm)	2.15
P_0 (mm)	1.55

Note: $R_{LAI=0}$, soil respiration at LAI = 0; s_{LAI}, basal rate of soil respiration for LAI; Q, exponential relationship between soil respiration and temperature; P_0, non-water-limited soil respiration in months without rain, amounting to the fraction $P_0/(K + P_0)$ of non-water-limited soil respiration; K, half-saturation constant of the hyperbolic relationship of soil respiration with monthly precipitation.

In this paper, we add a heterotrophic component to 3-PGS, apply the two models at five distinct forest sites in Italy where EC flux measurements are available, perform a sensitivity analysis, and then expand the approach to map forest NEP across the entire country through the model implementation in a GIS environment.

Materials and methods

Application of the 3-PGS model

The 3-PGS model is the simplified spatial version of the LUE-based model 3-PG, which provides estimates of forest GPP and NPP, as well as transpiration, evaporation, and stand properties frequently measured by foresters (leaf area index, canopy cover, tree spacing, diameters, volume, and biomass). Details of the 3-PG model structure can be found in Landsberg and Waring (1997).

The main simplifications introduced by Coops et al. (2001) in 3-PGS are the use of satellite-derived data of vegetation greenness index at a regional scale instead of stand-level properties and the exclusion of the stand-growth modeling routine. Generally the model is based on a combination of biophysical and physiological principles, coupled with main assumptions based on empirical observations. The model also requires only few parameters that can be easily derived from literature or from field measurements.

In this study, we extended the model's application through the implementation of a soil respiration routine to predict NEP.

Integrated over a monthly time step, the GPP is assumed to be related to the photosynthetically active radiation (PAR) absorbed by the forest canopy (APAR) through ε_{max}, which represents LUE (g C·m^{-2}·MJ^{-1}), and reduced by the effect of the environmental constraints (f_x), following the general LUE model equation:

$$[1] \qquad \mathrm{GPP} = a\mathrm{PAR} \times \varepsilon_{max} \times f_x$$

The APAR reduced by the effect of the environmental constraints (f_x) is considered to be the usable APAR (APARu).

The fraction of PAR absorbed by the canopy (f_{PAR}) is estimated as a linear function of the normalized difference of

Table 2. Forest types defined from the original CORINE Land Cover 2000 with stomatal and maximum canopy conductance values for each forest type.

Index	Forest type	g_s ($mm \cdot s^{-1}$)	g_{cmax} ($mm \cdot s^{-1}$)	Source
1	Mediterranean maquis	4	33	Kelliher et al. 1995
2	Holm oak forest	4	21	Körner et al. 1979
3	Mediterranean pine forest	4	33	Loustau et al. 1996
4	Hygrophilous broadleaf forest	4	15	Breuer et al. 2003
5	Oak forest	3	20	Kelliher et al. 1995; Breuer et al. 2003
6	Beech forest	4	20	Kelliher et al. 1995; Breuer et al. 2003
7	Mountain pine forest	5	21	Sandford and Jarvis 1986; Kelliher et al. 1995
8	White fir – Norway spruce forest	2	20	Kelliher et al. 1995; Breuer et al. 2003

Note: g_{cmax}, maximum canopy conductance; g_s, stomatal conductance.

vegetation index (NDVI) (Sellers 1987; Law and Waring 1994; Prince and Goward 1995; Coops et al. 1998):

$$[2] \qquad f_{\mathrm{PAR}} = a \times \mathrm{NDVI} + b$$

In this study the empirical constants a and b have been set to 1.24 and –0.168, respectively, according to Yuan et al. (2007).

APAR is calculated as a function of incoming solar radiation and canopy properties:

$$[3] \qquad \mathrm{APAR} = \mathrm{PAR} \times f_{\mathrm{PAR}}$$

PAR was estimated as a constant fraction of global radiation (Landsberg and Waring 1997) estimated at a regional scale with the Thornton and Running model (Thornton and Running 1999).

The 3-PGS model reduces potential GPP by the effect of environmental constraints (f_x) represented by three environmental modifiers ranging between 0 (system "shutdown") and 1 (no constraint). The modifiers include the vapor pressure deficit (VPD) modifier (f_D), the frost modifier (f_τ), and the soil drought modifier (f_θ); between f_D and f_θ only the most limiting factor is used. The f_D and f_τ modifiers are calculated as in Landsberg and Waring (1997):

$$[4] \qquad f_D = \exp(-k_D \times D)$$

$$[5] \qquad f_\tau = 1 - \left(\frac{\mathrm{FD}}{30(\text{days per month})}\right)$$

In eq. 4 D represents VPD, and k_D is an empirical coefficient describing the relationship between stomatal and canopy conductance and D; in eq. 5 FD is the number of frost days per month.

To evaluate the soil drought modifier (f_θ), the model includes a single-layer soil water balance routine, assessing the soil water balance (WB) on a monthly time step as the difference between transpiration and precipitation. Monthly canopy transpiration is calculated using the Penman–Montheith equation with canopy conductance (g_c) modified by the forest leaf area index (LAI) and constrained by the monthly estimates of VPD (Landsberg and Gower 1997). In particular, in the case of LAI >3, g_c is estimated as the maximum canopy conductance (g_{cmax}) reduced by the effect of the VPD constraint, while in the case of LAI <3, g_c is estimated as stomatal conductance (g_s) multiplied by LAI and reduced by the effect of the VPD constraint.

The model is initialized with the available soil water content supposed to be half of the maximum soil available water (θ, mm) in the soil profile (Landsberg and Gower 1997). The moisture ratio (r_θ) for the stand is calculated as follows:

$$[6] \qquad r_\theta = \frac{\mathrm{ASW} + \mathrm{WB}}{\theta}$$

where ASW is the available soil water.

WB in any month will be negative if transpiration exceeds precipitation; if the numerator of the expression for r_θ exceeds θ, it is set to θ, and the excess water is assumed to run off or drain out of the system. With a negative value of the numerator, r_θ = 0; the soil water modifier f_θ is then calculated with the expression

$$[7] \qquad f_\theta = \frac{1}{1 + \left[\left(1 - r_{\theta(\mathrm{init})}\right)/c_\theta\right]^{n_\theta}}$$

where c_θ and n_θ are soil-type-related parameters (clay: c_θ = 0.4, n_θ = 3; clay loam: c_θ = 0.5, n_θ = 5; sandy loam: c_θ = 0.6, n_θ = 7; sand: c_θ = 0.7, n_θ = 9) as in Landsberg and Waring (1997), and $r_{\theta(\mathrm{init})}$ is the initial moisture ratio value.

To predict NEP, the model has been modified to predict total ecosystem respiration (TER), by introducing a soil respiration routine, starting from the generalized equation

$$[8] \qquad \mathrm{NEP} = \mathrm{GPP} - \mathrm{TER}$$

where TER is the sum of the autotrophic and heterotrophic respiration (R_A and R_H, respectively) and is evaluated as follows:

$$[9] \qquad \mathrm{TER} = R_A + R_H$$

$$[10] \qquad R_A = 0.53 \times \mathrm{GPP}$$

$$[11] \qquad R_H = 0.55 \times R_S$$

Soil respiration (R_S) is estimated with the T&P&LAI model (Raich et al. 2002; Reichstein et al. 2003).

Modeling soil respiration

The model routine has been modified by introducing the

Table 3. Main characteristics, maximum leaf area index (LAI), and maximum available soil water (ASW) measured at the five eddy covariance sites.

Site	Position (UTM WGS84 Z32N)	Forest species or type	Measurement year(s)	Max. LAI ($m^2 \cdot m^{-2}$)	Max. ASW (mm)	Forest class
Castelporziano	4622555.20N, 780906.28E	*Quercus ilex*	1997–1998	3.5	380	Holm oak forest
Collelongo	4643246.63N, 880911.42E	*Fagus sylvatica*	1997	3.78	383	Beech forest
Nonantola	4950614.08N, 665506.21E	Mixed deciduous forest	2001–2003	1.82	387	Hygrophilous broadleaf
Renon	5162236.65N, 686516.90E	*Picea abies*	1997	3.47	339	White fir – Norway spruce
San Rossore	4842578.89N, 603648.47E	*Pinus pinaster*	2000–2002	2.25	387	Mediterranean pine forest

Note: A complete description of the sites can be found at http://www.fluxnet.ornl.gov/fluxnet/.

T&P&LAI model proposed by Reichstein et al. (2003). T&P&LAI is a simple climate-driven empirical model based on the Raich et al. (2002) model, which employed monthly average air temperature and precipitation as predictors for monthly soil respiration rates, and modified with the inclusion of LAI, which could be considered a surrogate of site productivity and carbon input into soil (Reichstein et al. 2003). The soil respiration model has been calibrated and tested for different forest types over several European and North American study EC sites, including two of the five Italian EC sites used in this study (Nonantola and Castelporziano).

The T&P&LAI model predicts monthly R_S as a function of mean monthly air temperature (T_A), monthly precipitation (P), and LAI:

$$[12] \qquad R_s = (R_{LAI=0} + s_{LAI} \times \text{LAI}) \times e^{QT_a}[(P + P_0)/(K + P + P_0)]$$

where $R_{LAI=0} + s_{LAI} \times$ LAI represents the linear dependency of the basal rate of soil respiration on LAI; $R_{LAI=0}$ is soil respiration at LAI = 0; s_{LAI} is the basal rate of soil respiration for LAI; Q determines the exponential relationship between soil respiration and temperature; P_0 is the parameter representing the non-water-limited soil respiration in months without rain, amounting to the fraction $P_0/(K + P_0)$ of limited soil respiration; and K is the half-saturation constant of the hyperbolic relationship of soil respiration with monthly precipitation. We used the original model parameterization adopted by Reichstein et al. (2003) (Table 1).

The model estimates represent the contribution of both heterotrophic and autotrophic components to soil respiration. The introduction of the soil respiration model in the 3-PGS routine raises the problem of double accounting of the autotrophic component of soil respiration, which is already computed as constant fraction of GPP. On the basis of review studies summarizing data from different forest types under different climate conditions (Hanson et al. 2000; Bond-Lamberty et al. 2004) and of recent experimental results including Italian forest ecosystems (Rey et al. 2002; Tedeschi et al. 2006; Keith et al. 2009), soil heterotrophic respiration was assumed to account for 55% of soil respiration on an annual basis.

Input data sets

In the present application of 3-PGS for regional NEP assessment, the required input variables and parameters were obtained as follows: (*i*) climatic variables were derived from the LINK10' gridded climatology for 1961–1990 (New et al. 2002), including 1961–1990 monthly averages of air temperature, relative humidity, precipitation, and frost days per month; (*ii*) long-term averages of NDVI were retrieved from the GlobalNDVI data set (ClarkLabs/Idrisi Project, Clark University, Worcester, Massachusetts); (*iii*) soil texture classes were derived from the Soil Profile Analytical Database of Europe (SPADBE) (European Soil Bureau Network and the European Commissione 2004); (*iv*) soil water holding capacity was derived from the Global Gridded Surfaces of Selected Soil Characteristics (IGBP-DIS) (Global Soil Data Task Group 2000); (*v*) land cover types were obtained from the Corine Land Cover 2000 data-

Table 4. Results of the mean relative sensitivity (μ) of gross primary production predicted by 3-PGS to the variation of the main environmental factors across five eddy covariance sites.

	NDVI		T		P		VPD		FD	
	μ	SI	μ	SI	μ	SI	μ	SI	μ	SI
Castelporziano	1.61	3	–0.75	3	0.12	1	0.39	2	–0.07	0
Collelongo	2.65	3	–0.73	3	0.41	2	0.54	3	–0.11	1
Nonantola	2.29	3	–0.72	3	0.26	2	0.52	3	–0.10	1
Renon	2.81	3	–0.23	1	0.00	0	0.63	3	–0.45	2
San Rossore	1.61	3	–0.66	3	0.16	1	0.26	2	–0.07	0

Note: NDVI, normalized difference of vegetation index; T, temperature; P, precipitation; VPD, vapor pressure deficit; FD, frost days. Sensitivity index (SI) is based on the ranking categories proposed as follows: (Battaglia and Sands 1998): $|\mu| < 0.075$ SI = 0; $0.075 \le |\mu| < 0.25$, SI = 1; $0.25 \le |\mu| < 0.5$ SI = 2; $|\mu| \ge 0.5$ SI = 3.

base (http://terrestrial.eionet.eu.int/CLC2000); eight forest classes were defined, with homogeneous characteristics (Table 2).

LAI was derived from the NDVI data set, applying the well-established exponential relationship (Myneni et al. 1997), and evaluated as follows:

$$[13] \qquad \mathrm{LAI} = 0.09 \exp(5.5 \times \mathrm{NDVI})$$

The 3-PGS model was parameterized with respect to the forest classes and to the soil texture class. Different forest classes are characterized by a different canopy resistance, depending on g_s and LAI. Specific values of g_s and g_{cmax}, derived from literature, were assigned for each forest class as shown in Table 2 (Körner et al. 1979; Sandford and Jarvis 1986; Kelliher et al. 1995; Loustau et al. 1996).

Simulation procedures, data set validation, and sensitivity analysis

To predict regional GPP and NEP at a monthly time step and a spatial resolution of 8 km, the model was implemented in a GIS environment, using the ARC Macro Language of the ESRI™ ArcInfo software suite (ESRI 1997, 1999).

For validation purposes, model estimates were compared with EC flux data from five EC forest sites in Italy, within the frame of the CARBOEUROFLUX project (http://www.bgc-jena.mpg.de/public/carboeur/projects/). For each EC site, the average annual and monthly EC-estimated GPP (GPP_{EC}) and EC-measured NEP (NEP_{EC}) were calculated over the available years of EC measurements (Table 3). These were compared with the annual and monthly values of GPP and NEP predicted by the model ($GPP_{3\text{-PGS}}$ and $NEP_{3\text{-PGS}}$). The five EC sites represent different forest types among the Italian forest ecosystems: holm oak (*Quercus ilex* L.) forest, beech forest, hygrophilous broadleaf forest, white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.) – Norway spruce (*Picea abies* (L.) Karst.) forest, and Mediterranean pine forests.

A description of the EC sites' main characteristics is provided in Table 3. Further detailed information on site vegetation and climate is available at the FLUXNET network's Web site (http://www.fluxnet.ornl.gov/fluxnet/).

A sensitivity analysis of the model was performed with respect to the input climatic variables (T_A, VPD, P, FD) to the NDVI and maximum ASW, following the procedure described by Brylinsky (1972) to evaluate relative sensitivity (RS).

The original value of each variable was modified by ±5%, ±10%, ±15%, ±20%, and ±25%, except for maximum ASW, which was changed from 100 to 400 mm. RS, defined as the variation of model output produced by a disturbance of model input, was computed as follows:

$$[14] \qquad \mathrm{RS} = \frac{X_{+p\%} - X_{-p\%}}{X_0 \times p}$$

where X_0 is the model output under default conditions, and p is the coefficient of disturbance applied to the model input and is calculated as $p = |\Delta p_{\%}|/100$, while $X_{\pm p\%}$ represents the model output after the input percent variation. RS is positive or negative depending on whether an increase in $p_{\%}$ results in an increase or decrease in X.

At each site, mean RS (μ), evaluated for each variable, was ranked with a sensitivity index (SI), using the scheme in Table 4, as proposed by Battaglia and Sands (1998) and Esprey et al. (2004).

Results

Model evaluation

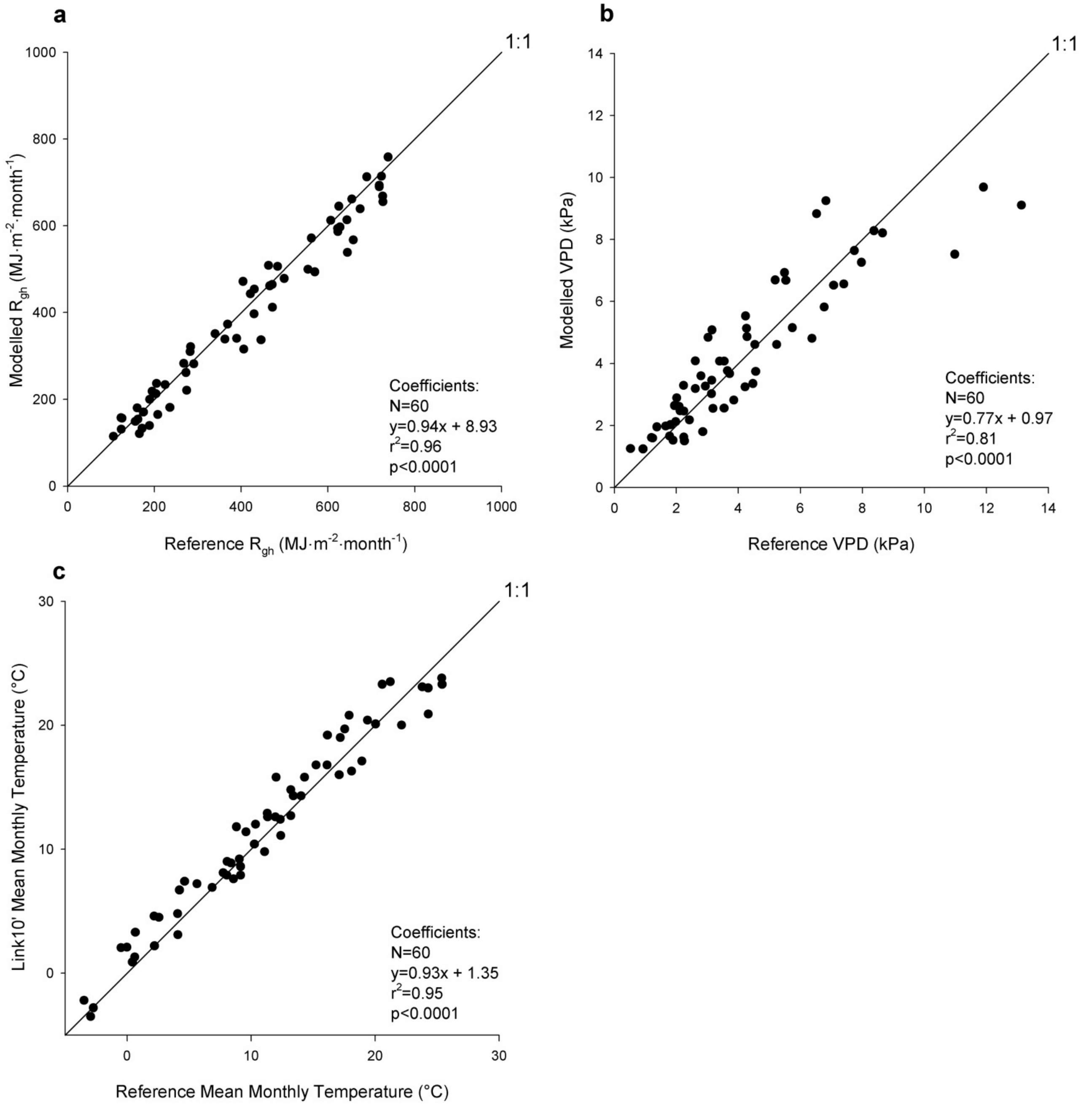
The predictions of the forest productivity model were compared with annual and monthly averages calculated over the available years of EC flux measurements from 1998 to 2005 at the five EC sites, as described in the methods.

The first output of the modeling process is global radiation (R_{gh}), using the model of Thornton and Running (1999). The regression of the modelled R_{gh} against the monthly averages of measured R_{gh} calculated over the available years at the EC sites was highly significant ($p < 0.0001$) and showed a good agreement between the two sets of values, with an $r^2 = 0.96$ (Fig. 1*a*).

To assess the reliability of the LINK10' climatic data set implemented in the modeling process, the long-term monthly averages of temperatures and estimated VPD (1961–1990) were regressed against the EC meteorology at each site as shown in Figs. 1*b* and 1*c*, for all the available measurement years. In both cases, for estimated VPD and mean monthly temperatures, we found a highly significant relationship ($p < 0.001$), with $r^2 = 0.95$ and 0.98, respectively (Figs. 1*b* and 1*c*).

Figure 2*a* shows the relationship between annual $GPP_{3\text{-PGS}}$

Fig. 1. Linear regressions of (*a*) the average monthly global radiation (R_{gh}) measured at the five eddy covariance (EC) sites against global radiation estimated with the Thornton and Running model (Thornton and Running 1999); (*b*) the average monthly vapor pressure deficit (VPD) estimated at the five EC sites again mean VPD from the LINK10' data set (1961–1990); and (*c*) the average monthly temperature measured at the five EC sites against mean temperature from the LINK10' data set (1961–1990).

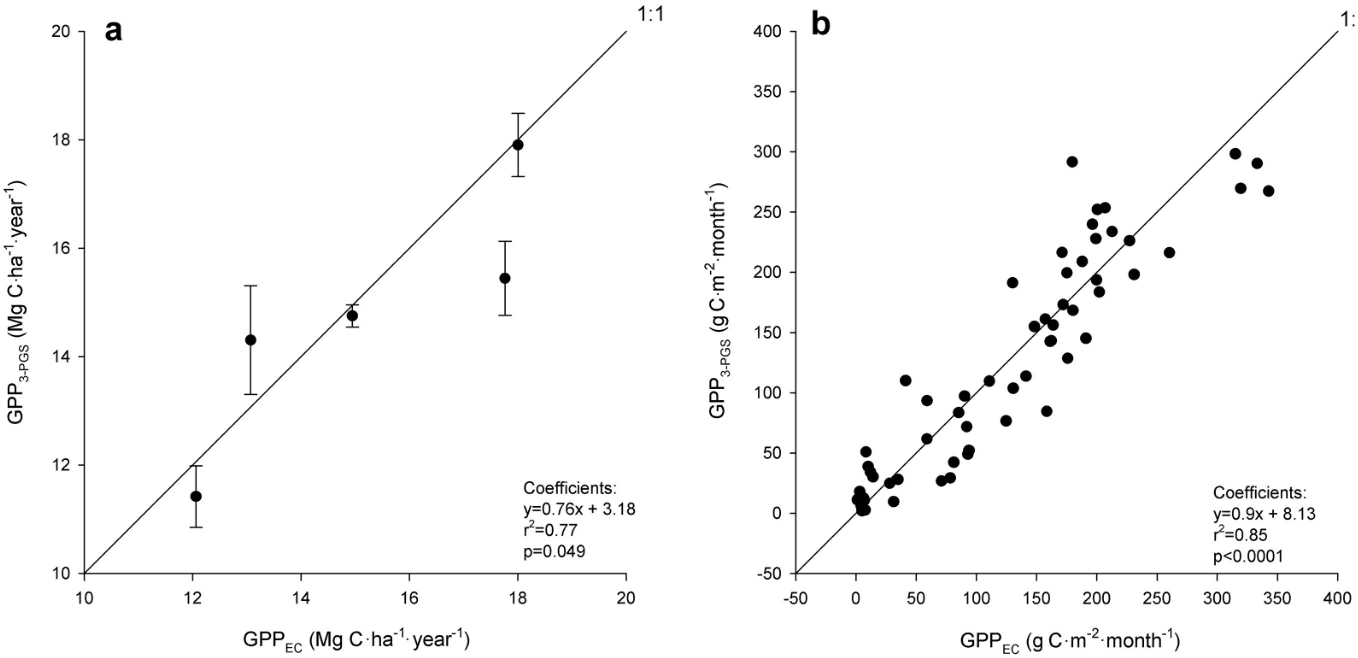


and the average annual GPP_{EC} for each EC site. For the annual values, we found a significant relationship (p = 0.049), with r^2 = 0.77 and RMSE = 1.28 (Mg C·ha^{-1}·year^{-1}). In Fig. 2*b*, the relationship between the monthly $GPP_{3\text{-}PGS}$ and average monthly GPP_{EC} shows a highly significant correlation ($p < 0.001$), with an increase in the correlation coefficient ($r^2 = 0.85$) and a RMSE = 35 (g C·m^{-2}·month^{-1}). The seasonal patterns of predicted and monthly GPP_{EC} at the flux sites were in good agreement, with distinct seasonal cycles (Fig. 3). In general, the model's behavior varies with forest types and climate. In the case of Renon (Fig. 3*d*), the model underestimated monthly $GPP_{3\text{-}PGS}$ during the summer, while it showed a strong agreement with measured values throughout the rest of the year (r^2 = 0.98, RMSE = 12 g C·m^{-2}·month^{-1}).

At another two sites, Collelongo and Nonantola (Figs. 3*b*, 3*c*), which are dominated by broad-leaved deciduous species, the model also underestimated GPP during the summer, but it produced overestimates the rest of the year. The correlation between measured and predicted GPP at these sites was significant, with r^2 = 0.93 and 0.94, RMSE = 33 and 37 (g C·m^{-2}·month^{-1}), respectively.

For the Mediterranean sites, Castelporziano and San Ros-

Fig. 2. Linear regression of (*a*) the average annual measured gross primary production (GPP) on annual 3-PGS-predicted GPP for the five eddy covariance (EC) sites; and (*b*) the average monthly measured GPP on monthly 3-PGS-predicted GPP for the five EC sites. Measured data are means ± SE.



sore, the 3-PGS model showed the opposite behaviour (Figs. 3*a* and 3*e*) — $GPP_{3\text{-}PGS}$ was overestimated during the summer months and underestimated the rest of the year. For San Rossore, a good agreement (r^2 = 0.87) was found between measured and estimated values, with RMSE = 29 (g C·m^{-2}·month^{-1}), while for Castelporziano, the model estimates showed a lower correlation with measured values (r^2 = 0.78), with the highest RMSE value (47 g C·m^{-2}·month^{-1}) among the EC sites.

The correlation between EC-measured and model-predicted annual NEP was slightly weaker than that obtained for annual GPP (Fig. 4*a*), with r^2 = 0.76, RMSE = 0.21 (Mg C·m^{-2}·month^{-1}), and p = 0.052. For monthly NEP, the relationship between average NEP_{EC} and $NEP_{3\text{-}PGS}$ was highly significant ($p < 0.001$), with an increase in the correlation coefficient ($r^2 = 0.78$) and RMSE = 18 (g C·m^{-2}·month^{-1}).

The correlation between annual average TER_{EC} for each EC site and the annual $TER_{3\text{-}PGS}$ in Fig. 5 is also high (r^2 = 0.93), mainly because of the similar modeling approach used to estimate both TER_{EC} and $TER_{3\text{-}PGS}$.

The annual predicted $NEP_{3\text{-}PGS}$ across the Italian forest ecosystems is shown in Fig. 6. The map clearly shows the spatial variability of annual $NEP_{3\text{-}PGS}$ along the Italian territory, ranging from Mediterranean to Alpine climate conditions.

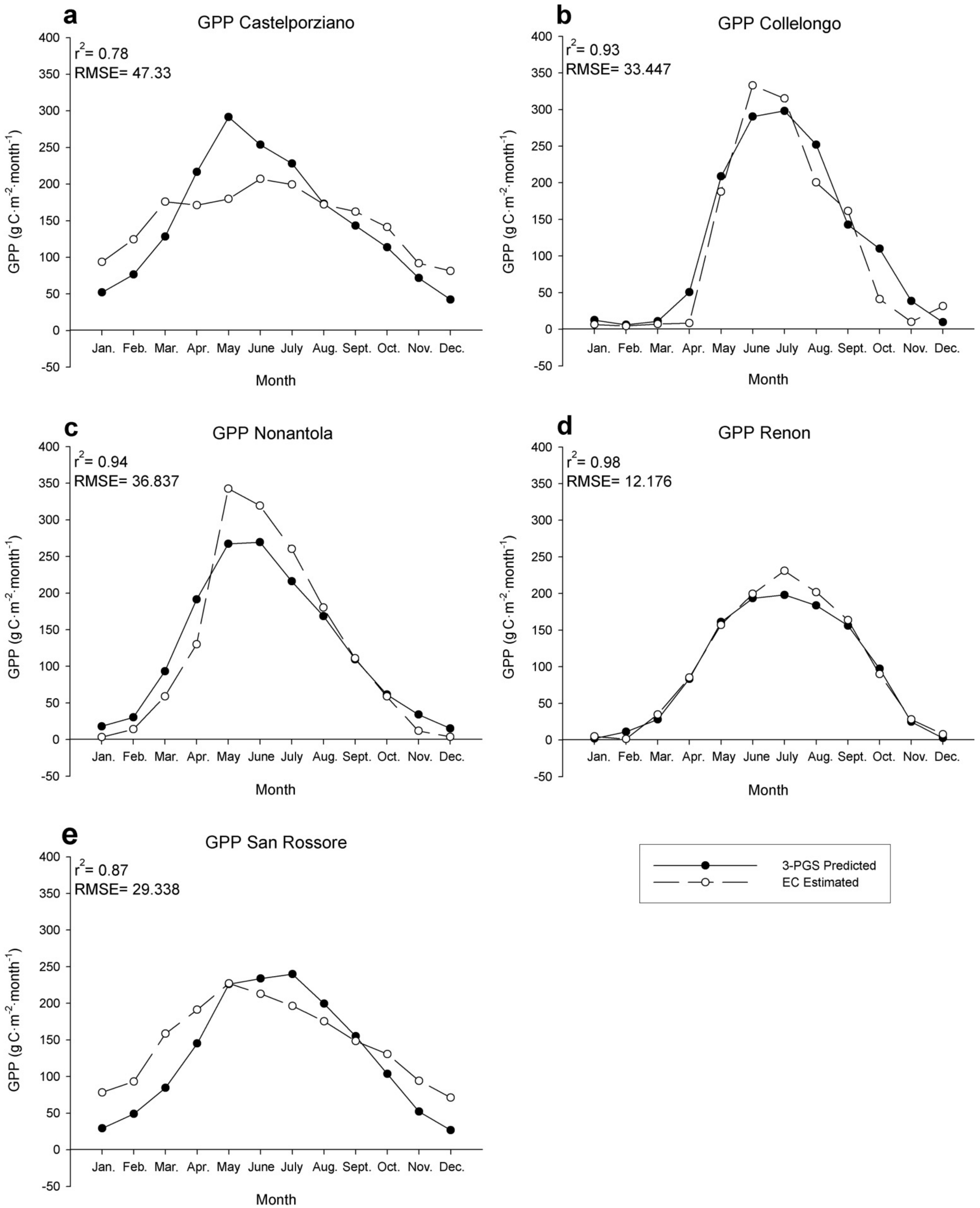
Figure 7 shows the seasonal patterns of monthly environmental modifiers that represent the constraints of climatic and edaphic factors on $GPP_{3\text{-}PGS}$, ranging from 0 (maximum constraint) to 1 (null), as predicted by the model, for each EC site (Figs. 7*a*–7*e*). This figure reveals that the model's behaviour is affected by the main site characteristics. In particular, the soil water modifier (f_θ) shows a similar pattern, but with a different amplitude, for all the EC sites, except for Renon, where no constraint occurs throughout the year. For all the other sites, f_θ starts affecting forest productivity in July and imposes a maximum constraint on $GPP_{3\text{-}PGS}$ in September, with a reduction ranging from 20% to 40%. During the autumn soil water content is fully recovered for all sites. The VPD modifier (f_D) imposes a maximum constraint in July, and its effect starts to decrease in August. At the Mediterranean sites (Figs. 7*a*, 7*e*), the constraint persist with a maximum value in August. The frost modifier for the number of subfreezing days (f_τ) represents the main constraint during winter for all sites. At two sites, Collelongo and Renon (Figs. 7*b*, 7*d*), the f_τ modifier also reduces productivity during late spring and early autumn and throughout the year, respectively. This seasonal pattern is explained by the terrain characteristics of the two sites, with altitudes reaching 1667 m a.s.l. for Collelongo in the central Apennines and 1997 m a.s.l. for Renon in the Alps. In Fig. 7*f*, the monthly patterns of APARu/APAR for each EC site represent the fraction of potential productivity each month. This ratio illustrates the multiplicative effects of environmental constraints on potential forest productivity.

Sensitivity analysis

A summary of the results from the environmental factors sensitivity analysis on $GPP_{3\text{-}PGS}$ is given in Table 4. Mean relative sensitivity (μ) and the sensitivity index (SI) describe the influence of each parameter on model output. The sensitivity analysis allows one to isolate the effect of a single input variable, ranking its effect with a sensitivity index from 0 (insensitive) to 3 (highly sensitive).

Table 4 shows the high sensitivity of $GPP_{3\text{-}PGS}$ to NDVI and to VPD at all the EC sites, while a high sensitivity to temperature was found at all sites but Renon. At the remaining sites, the $GPP_{3\text{-}PGS}$ shows the same sensitivity indexes among sites of the same forest type. At the two Mediterra-

Fig. 3. Comparison between seasonal patterns of monthly 3-PGS-predicted gross primary production (GPP) and the average monthly GPP measured at five eddy covariance (EC) sites.



nean sites, Castelporziano and San Rossore, the $GPP_{3\text{-}PGS}$ is insensitive to the number of frost days, moderately sensitive to precipitation, and strongly sensitive to VPD, temperature, and NDVI. At Collelongo and Nonantola, characterized by broad-leaved deciduous species, the $GPP_{3\text{-}PGS}$ shows a low sensitivity to the number of frost days a significant sensitiv-

Fig. 4. Linear regression of (*a*) average annual measured net ecosystem production (NEP) on annual 3-PGS-predicted NEP for the five eddy covariance (EC) sites; and (*b*) the average monthly measured NEP on monthly 3-PGS-predicted NEP for the five EC sites. Measured data are means ± SE.

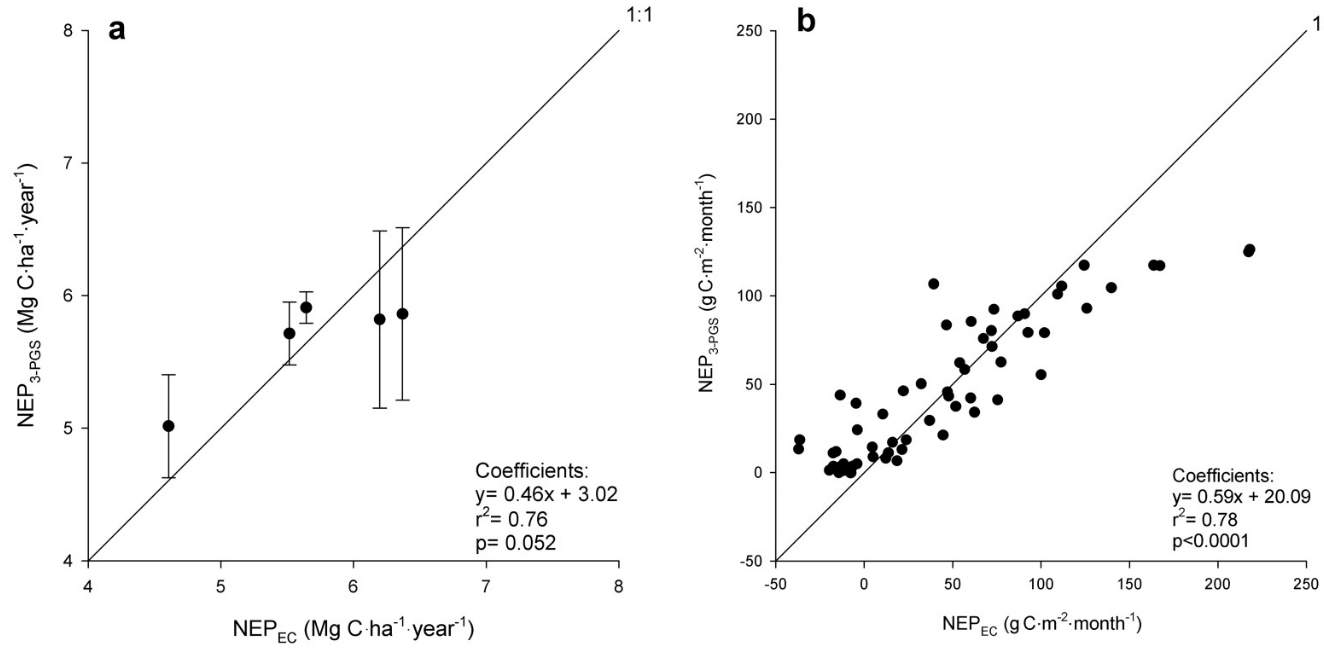
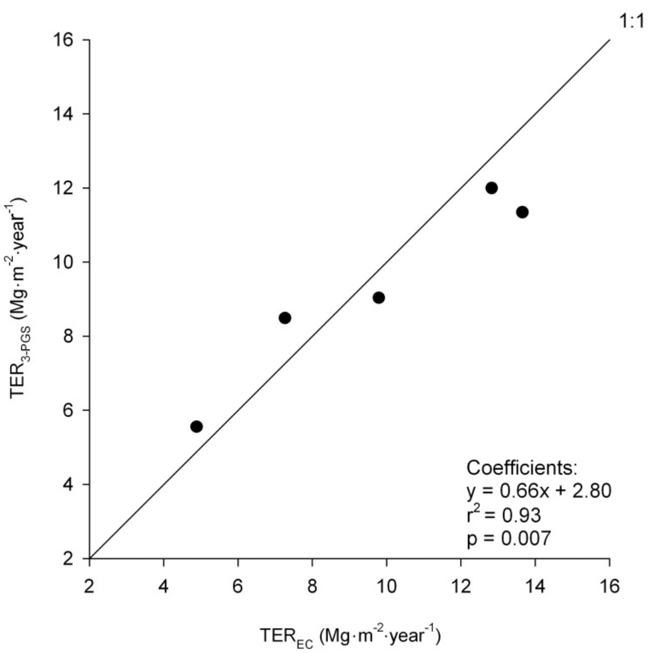


Fig. 5. Linear regression of the average annual measured total ecosystem respiration (TER_{EC}) on annual 3-PGS-predicted TER ($TER_{3\text{-}PGS}$) for the five eddy covariance (EC) sites.



ity to precipitation, and high sensitivity to the other parameters. At Renon, the model behaves differently, with a significant sensitivity to the number of frost days, no sensitivity to precipitation, and low sensitivity to temperature. Figures 8*a*–8*e* show how $GPP_{3\text{-}PGS}$ is affected by a variation in the value of selected parameters for each EC sites. Figure 8*f* shows the relationship between $GPP_{3\text{-}PGS}$ and maximum ASW, ranging from 100 to 400 mm, for each EC site. At two sites, Renon and Castelporziano, the $GPP_{3\text{-}PGS}$ is not sensitive to changes in soil water availability, while for the other sites, the model shows a significant sensitivity to changes in this parameter.

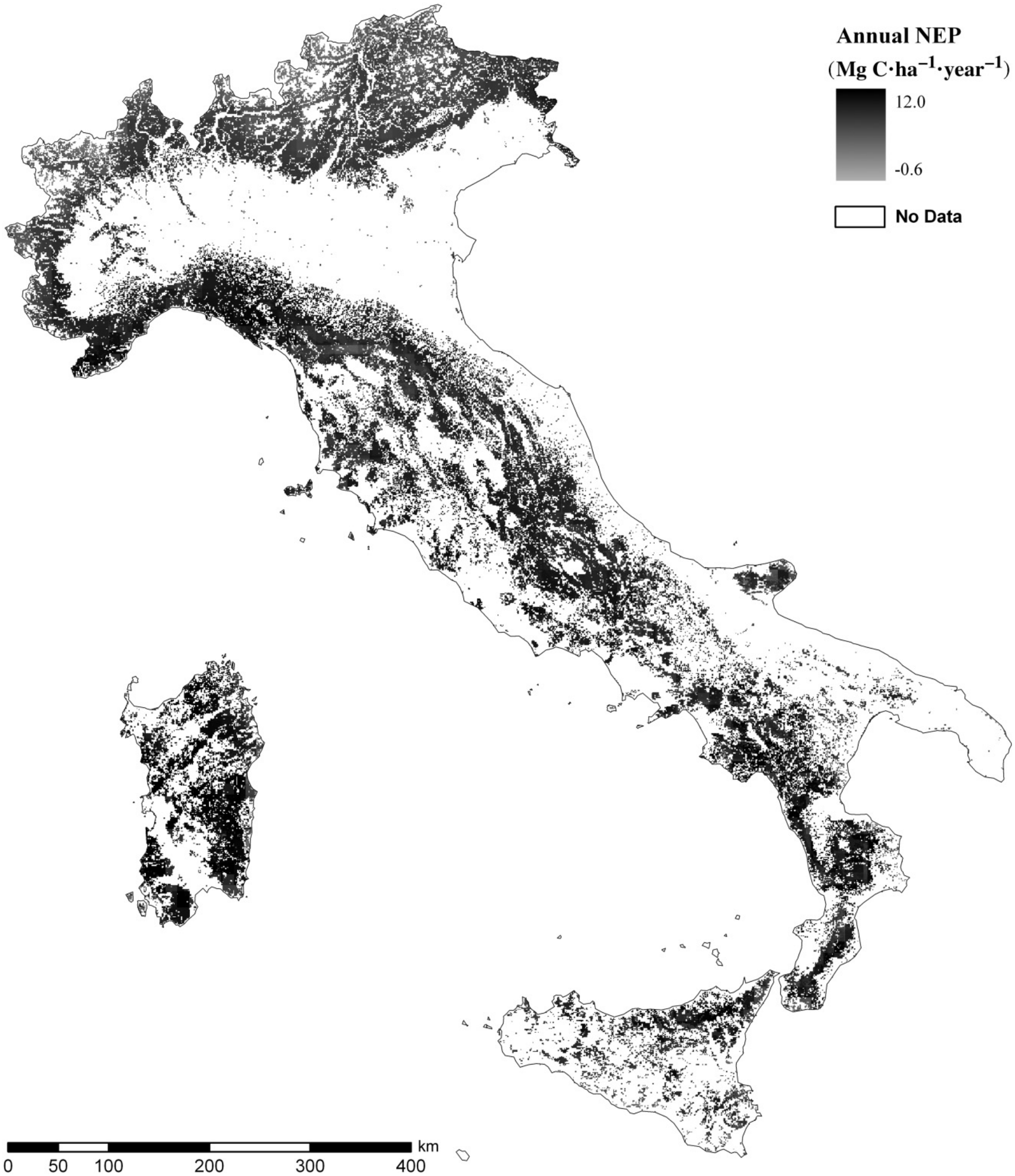
Discussion

The comparison of the 3-PGS model estimates with the flux measurements from five Italian forest types revealed a good agreement between $GPP_{3\text{-}PGS}$ and $NEP_{3\text{-}PGS}$ and actual GPP_{EC} estimates and NEP_{EC} observations at both annual and monthly time scales. This evaluation of the model's performance indicates that the model adequately reproduced forest GPP and NEP seasonal patterns.

In general, the quality of the input data set, in terms of spatial resolution and model parameterization, and the assumptions made for model simulations should also be considered when evaluating a model's performance. On one hand, the use of the long-term averages of both the climatic data set (30 years) and the NDVI data set (18 years) with a coarse spatial resolution, 0.1 and 0.08 degree-days, respectively, limits the representation of the spatial heterogeneity of both Italian forest ecosystems and climate. On the other hand, the use of these data sets balances some of the key limitations of the model represented by the main assumptions based on long-term empirical observations that consider NPP a constant fraction of GPP and heterotrophic respiration a constant fraction of soil respiration on an annual basis. To assess the reliability of the climatic data set, monthly averages of *T* and VPD, calculated over the available years of EC flux measurements from 1998 to 2005 at the five EC sites, were compared with 1961–1990 monthly averages of *T* and VPD (Figs. 1*b*–1*c*), showing in both cases a highly significant correlation with $r^2 = 0.98$ and $r^2 = 0.95$, respectively.

Another source of uncertainty is related to the coarse res-

Fig. 6. Map of annual 3-PGS-predicted net ecosystem production ($NEP_{3\text{-}PGS}$) for the Italian forest ecosystems.



olution of the soil texture class map, which misidentified the soil texture class for two of the five EC sites (San Rossore with clay soil instead of sandy soil and Nonantola with sandy soil instead of clay soil). Although this misidentification introduces an uncertainty in the model estimates, it was not possible to investigate the effects of this error on predicted GPP and NEP, since we could identify only two sites within the entire Italian forest ecosystem.

Since we consider that soil texture class is an invariable site feature, we decided to correct the misidentification and use the actual soil texture class for the two sites, to run the model at a regional scale.

In general, the model tended to underestimate annual GPP except for Collelongo, where annual GPP is overestimated. However, the 3-PGS model tended to overestimate GPP during the summer months in Mediterranean sites with low precipitation (Castelporziano and San Rossore). These results are consistent with those of a previous study (Law et al. 2000) using the 3-PG model (parental site-specific version of the 3-PGS model) at the flux site in the eastern Cascades (Oregon, USA), which has a similar temperature and precipitation regime during the summer months. In Law et al. (2000), for the model calibration the soil water holding capacity had to be increased to match GPP_{EC}, while in the 3-PGS model application described in this study, soil water holding capacity was not modified to match GPP_{EC}. At the Mediterranean sites in Italy affected by severe summer drought, the model showed the same behaviour but with a

Fig. 7. (*a–e*) Seasonal patterns of monthly climate and soil modifiers and 3-PGS-predicted gross primary production ($GPP_{3\text{-}PGS}$) at each eddy covariance (EC) site. f_D, vapor pressure deficit modifier; f_τ, frost modifier; f_θ, soil water modifier; r_θ, soil moisture ratio. (*f*) Monthly patterns of the ratio of absorbed photosynthetically active radiation to usable absorbed photosynthetically active radiation (APARu/APAR), which represents the fraction of potential GPP each month for each of the five EC sites.

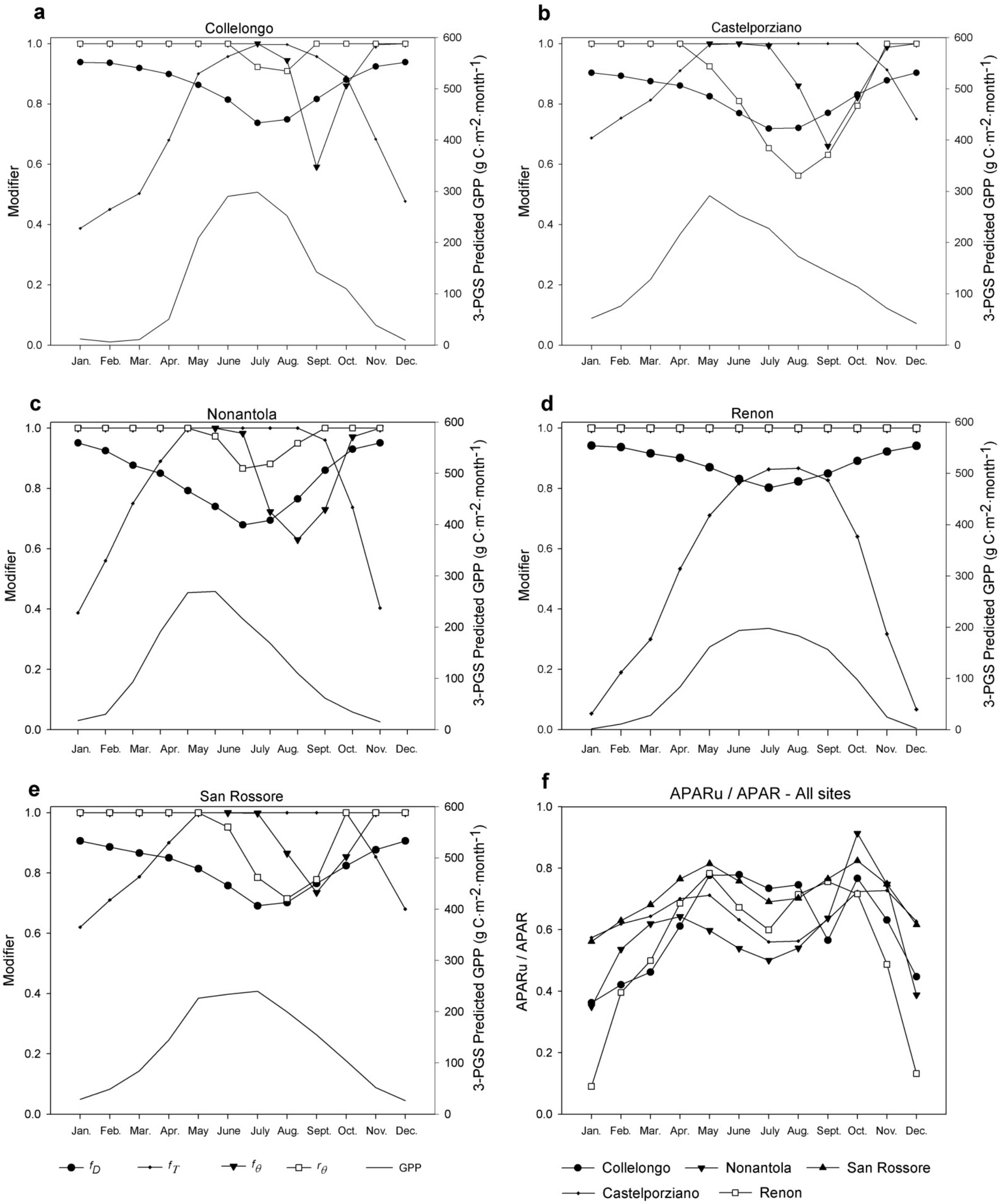
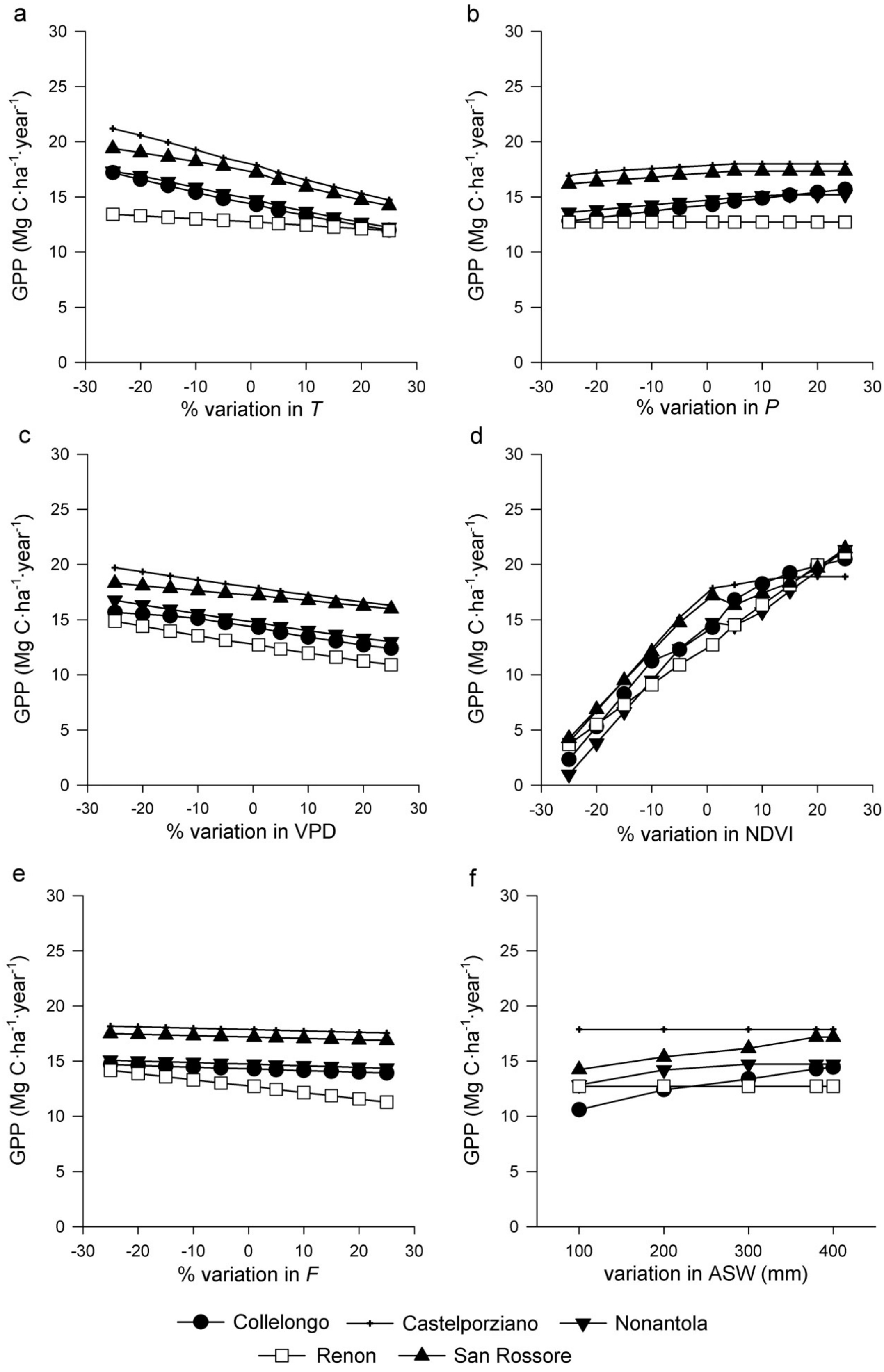


Fig. 8. Annual 3-PGS-predicted gross primary production ($GPP_{3\text{-}PGS}$) as a function of site environmental factors: (*a*) temperature (*T*), (*b*) precipitation (*P*), (*c*) vapor pressure deficit (VPD), (*d*) normalized difference of vegetation index (NDVI), (*e*) number of frost days (*F*), and (*f*) available soil water (ASW).



smaller magnitude; in fact, high canopy conductance reduced modelled soil water content with a consequent reduction in $GPP_{3\text{-}PGS}$ during autumn. At Renon, soil water content does not limit photosynthesis during the summer months because precipitation is distributed throughout the year. With adequate water availability and high summer temperatures, the $GPP_{3\text{-}PGS}$ is only limited by VPD constraints, resulting in an underestimation of $GPP_{3\text{-}PGS}$ (Law et al. 2002). Another environmental constraint on $GPP_{3\text{-}PGS}$ is the number of frost days during the early and late summer months, which is determined by latitude and terrain characteristics.

The implementation of a soil respiration model in the 3-PGS routine enabled us to predict annual and monthly NEP. Although the annual predicted $TER_{3\text{-}PGS}$ showed a good agreement with TER_{EC}, on a monthly basis the correlation between $NEP_{3\text{-}PGS}$ and NEP_{EC} was weaker than that between $GPP_{3\text{-}PGS}$ and GPP_{EC}. This uncertainty related to monthly estimates is due to the assumption that the R_H-to-R_S ratio is a constant in the long term, while on a monthly and seasonal basis this ratio is more related to site phenology than temperature and soil water availability (Subke et al. 2006).

The good relationship between annual $TER_{3\text{-}PGS}$ and annual TER_{EC} is mainly due to the fact that the same modeling approach was applied for both estimates. In fact, TER_{EC} is modelled on the basis of the Lloyd and Taylor (1994) regression model, fitted to the scatter of nighttime measured ecosystem respiration versus either soil or air temperature (Reichstein et al. 2005). In this study, the evaluation of TER is based on two main long-term assumptions, i.e., that autotrophic and heterotrophic respiration are constant fraction of GPP and soil respiration, respectively (R_A = 0.53GPP and $R_H = 0.55R_S$). Soil respiration is estimated with the T&P&LAI model (Raich et al. 2002; Reichstein et al. 2003), as a function of average monthly air temperature, monthly precipitation, and LAI.

Nevertheless, the relationship between the average monthly NEP_{EC} and $NEP_{3\text{-}PGS}$ is still highly significant, indicating that the assumption made to separate soil autotrophic and heterotrophic respiration components does not reduce the model's effectiveness to compare monthly NEP_{EC} on the basis of a long-term analysis.

The results of the sensitivity analysis (Table 4) combined with monthly patterns of APARu/APAR ratio (Fig. 6*f*), which can be read as the fraction of potential productivity determined by environmental constraints, clearly show the influence of environmental modifiers on forest productivity, characterized by different behaviors at different sites.

In general, the model is more sensitive to VPD than to precipitation. This behaviour is due to a specific modeling approach that considers the minimum value between the VPD modifier and soil moisture modifier each month. In this way, the atmosphere humidity deficit plays a key role during most of the year, except for late summer months when drought occurs. Canopy and stomatal conductance are functions of the atmospheric evaporative demand and of available soil water content, positively affecting the photosynthetic carbon uptake at low VPD values (Law et al. 2002). According to this general relation, $GPP_{3\text{-}PGS}$ is more sensitive to lower rates of atmospheric humidity than to precipitation. At Renon, $GPP_{3\text{-}PGS}$ is mainly regulated by VPD. In fact, it is not sensitive to precipitation and shows a low sensitivity to temperature.

The high sensitivity to NDVI at all the sites can be easily understood by combining maximum LAI values at each site (Table 3) with the response of $GPP_{3\text{-}PGS}$ to changes in the value of NDVI shown in Fig. 6*d*. When NDVI is modified by a negative percentage value, the response of $GPP_{3\text{-}PGS}$ is near linear for all the sites, while when NDVI is modified by a positive percentage value, the response of $GPP_{3\text{-}PGS}$ differs among the sites. This behaviour can be explained by the near linear response of $GPP_{3\text{-}PGS}$ for LAI <3, while with LAI >3 this response approaches a plateau. In fact three of five sites have a maximum LAI >3, Collelongo, Catelporziano, and Renon (3.78, 3.5, and 3.47 $m^2 \cdot m^{-2}$, respectively), and a further increase in LAI due to positive percentage changes of NDVI determines a lower increase in $GPP_{3\text{-}PGS}$.

Conclusions

In agreement with previous studies, the results presented here corroborate the 3-PGS model's capability of predicting forest GPP at a regional scale, through the comparison with EC-estimated GPP. The implementation of a soil respiration routine in the 3-PGS model enabled us to predict annual and monthly NEP and supports the hypothesis to extend model predictions from the forest stand to the forest-ecosystem level. Model estimates of environmental modifiers represent a practical approach for efficiently quantifying the seasonal and spatial distribution of the environmental and edaphic constraints on forest productivity. Model performance can be improved significantly by introducing a more specific parameterization for each forest type and generally by introducing a finer resolution input data set with improved data accuracy, especially for the edaphic data set. Furthermore, the implementation of the model in a GIS environment, with the AML language makes the model a highly suitable tool for predicting GPP and NEP at a wide range of operating levels.

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