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# Assessing the ability of three land ecosystem models to simulate gross carbon uptake of forests from boreal to Mediterranean climate in Europe

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## Abstract

We evaluate three terrestrial biosphere models (LPJ, Orchidee, Biome-BGC) with respect to their capacity to simulate climate related trends in gross primary production (GPP) of forests in Europe. We compare simulated GPP and leaf area index (LAI) with GPP estimates based on flux separated eddy covariance measurements of net ecosystem exchange (NEE) and LAI measurements along a gradient in mean annual temperature from the boreal to the Mediterranean. The three models capture qualitatively the pattern suggested by the site data: an increase in GPP from boreal to temperate and a subsequent decline from temperate to Mediterranean climates. The models consistently predict higher GPP for boreal and lower GPP for Mediterranean forests. Based on a decomposition of GPP into absorbed photosynthetic active radiation (APAR) and radiation use efficiency (RUE), the overestimation of GPP for the boreal zone appears to be primarily related to too high simulated LAI - and thus light absorption (APAR) - rather than too high radiation use efficiency. On average, the models compare similarly well to the site GPP data (RMSE of ~30% or 420 gC/m<sup>2</sup>/yr) but differences are apparent for different ecosystem types. Given uncertainties about the accuracy in model drivers, a potential representation bias of the eddy covariance sites, and uncertainties related to the method of deriving GPP from eddy covariance measurements data, we find the agreement between site data and simulations acceptable, providing confidence in simulations of GPP for European forests.

## 1 Introduction

Continental to global scale simulations of the land carbon cycle are subject to uncertainties related to model structure, parameters, and input driver data (McGuire et al., 2001; Moorcroft, 2006; Morales et al., 2005; Zaehle et al., 2005). Confronting simulations with measurements allows assessing the model's performance, to gain confidence and/or identify major issues. Such comparisons have been repeatedly made

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for single or few intensively investigated eddy covariance flux measurement sites when it was possible to parameterise and drive the models with in-situ data (e.g. Churkina et al., 2003; Kucharik et al., 2006; Morales et al., 2005). These analyses revealed important insights regarding the credibility of the model's dynamics and simulated temporal variations. However, models designed for the continental to global scale should also be evaluated on that scale, i.e. investigating how well the broad patterns along large environmental gradients are reproduced. Such studies have rarely been presented, primarily due to a lack of consistent synthesis work of carbon flux measurements. Global data for net primary productivity (NPP) are available (Scurlock et al., 1999, [http://www-eosdis.ornl.gov/NPP/npp\\_home.html](http://www-eosdis.ornl.gov/NPP/npp_home.html)) but prove to be difficult to use as benchmarks (e.g. Cramer et al., 1999; Zaehle et al., 2005). Compilations of NPP measurements suffer from inconsistent methodologies and individual values from different sites and investigators are often not compatible (but see Luyssaert et al., 2007<sup>1</sup>). In addition, NPP data are known to be biased low to an unknown extent and there is strong indication that this bias can change substantially for different climate regions (Luyssaert et al., 2007<sup>1</sup>).

Consistent estimates of gross primary production (GPP) are now becoming available from the eddy covariance measurement community based on methods that separate measured net ecosystem exchange (NEE) into GPP and ecosystem respiration (Luyssaert et al., 2007<sup>1</sup>; Papale et al., 2006; Reichstein et al., 2005). In this study we

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evaluate simulations of GPP by three global biogeochemical models (LPJ, Orchidee, Biome-BGC) for forest ecosystems in Europe. Our study is consistent with, and complements a recent model intercomparison project within the Carboeurope-IP project that aims to understand, quantify, and reduce uncertainties of the European carbon budget (<http://www.carboeurope.org/>). We investigate the performance of the models to reproduce the broad pattern suggested by eddy covariance based GPP along a mean annual temperature gradient running from the boreal to the Mediterranean. We evaluate to what extent we can be confident with European scale simulations of forest GPP, and aim to identify consistent patterns of correspondence and mismatch with the data. We further propose a simple method of decomposing GPP into APAR and RUE that aids in the diagnoses of model performance using ancillary leaf area index (LAI) measurements.

## 2 Materials and methods

### 2.1 Site data

The observational site data we use originate from the recent data base of Luyssaert et al. (2007)<sup>1</sup>. We extracted all available data from sites with GPP (annual sums) or LAI measurements (annual maximum) for Europe. We excluded sites from mixed forests (mixed PFTs), manipulative experiments where the forest was fertilized or irrigated, as well as recently disturbed plots and clear cuts. Finally, 37 and 47 sites for GPP and LAI respectively are available of which 22 have both GPP and LAI estimates (Fig. 1).

The GPP data originate from Carboeurope eddy covariance tower sites that measure the net ecosystem CO<sub>2</sub> exchange (NEE). The data represent the time period from approximately 1996 to 2005 with a bias towards recent times. The NEE fluxes had been separated into GPP and ecosystem respiration ( $R_{\text{eco}}$ ) by subtracting  $R_{\text{eco}}$ .  $R_{\text{eco}}$  had been calculated based on its night time temperature sensitivities, the vast majority according to Reichstein et al. (2005).

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LAI measurements are partly based on different methods; indirect optical methods have been used primarily. We convert LAI to fAPAR (fraction of absorbed photosynthetic active radiation) using the Lambert-Beer's law since that is the crucial variable for light absorption and thus GPP (Eq. 1). The Lambert-Beer's law is also used in the three models to estimate light extinction.

$$\text{fAPAR} = 1 - e^{-k \times \text{LAI}} \quad (1)$$

where  $k$  denotes the light extinction coefficient, assuming  $k = 0.5$  for conifers and  $k = 0.58$  for broadleaf trees. The conversion of LAI to fAPAR implies larger discrepancy at low LAI values and smaller discrepancy at high LAI values. For example, the fAPAR difference between LAIs of 2 (fAPAR~0.63) and 4 (fAPAR~0.86) is much larger than between LAIs of 6 (fAPAR~0.95) and 8 (fAPAR~0.98).

## 2.2 Model simulations

We performed simulations at the locations of the measurement sites using three state of the art global biogeochemical models: LPJ, Orchidee, and Biome-BGC. The models are described in detail in Sitch et al. (2003), Krinner et al. (2005), and Thornton (1998, 2002) respectively. We used the same input data for each model, according to a modelling protocol that is consistent with model intercomparison studies by Vetter et al. (2007) and Jung et al. (2007)<sup>2</sup> to ensure comparability. We prescribed the PFT according to the prevailing vegetation type given in the database by Luysaert et al. (2007)<sup>1</sup>. No site history was prescribed that accounts for age and management related effects; the models simulate mature forest stands. Soil water holding capacity and meteorological model drivers originate from gridded data sets with a spatial resolution of 0.25°. Water holding capacity data are based on IGBP-DIS

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(2000) soil texture data. Meteorological model input from 1958–2005 is from a regional climate model (REMO, Jacob and Podzun, 1997) that was driven with NCEP reanalysis (Kalnay et al., 1996) at the boundaries of the European model domain (Feser et al., 2001). Details about model drivers and the modelling protocol are available in Vetter et al. (2007) and the Carboeurope-IP model intercomparison homepage ([http://www.bgc-jena.mpg.de/bgc-systems/projects/ce\\_i/index.shtml](http://www.bgc-jena.mpg.de/bgc-systems/projects/ce_i/index.shtml)).

For consistency, we matched simulated GPP and LAI with the site data on a site by site and year by year basis. Subsequently, the yearly data were aggregated (averaged) to the site level. In cases two or more measurement sites with the same PFT fell within the same 0.25° gridcell (i.e. identical model output), data on site level were further averaged to gain more representative values on the 0.25° gridcell level.

## 2.3 Decomposing GPP into APAR and RUE

We decomposes GPP [ $\text{gC m}^{-2} \text{yr}^{-1}$ ] into absorbed photosynthetic active radiation (APAR [ $\text{MJ m}^{-2} \text{yr}^{-1}$ ]) and radiation use efficiency (RUE [ $\text{gC MJ}^{-1}$ ]). This procedure provides further information about possible causes of mismatch between simulated and site eddy covariance based GPP.

$$\text{GPP} = \text{APAR} \times \text{RUE} \quad (2)$$

We calculate APAR according to a standard method used in model intercomparisons from monthly mean leaf area index and radiation (e.g. Bondeau et al., 1999; Ruimy et al., 1999) (Eq. 3). LAI measurements represent approximately the annual maximum and are not commonly available with a monthly resolution. In order to still estimate annual APAR for sites with a LAI measurement that is consistent with the models we simply use the modelled phenology but correct for the wrong magnitude of maximum LAI. We introduce a correction factor CF which scales the simulated annual maximum fAPAR to match the observed fAPAR (which we assume corresponds to the annual

maximum).

$$APAR = \sum_{m=1}^{12} fAPAR_{sim\ m} \times PAR_m [\times CF] \quad (3)$$

$$\text{with } CF = \frac{fAPAR_{obs}}{fAPAR_{max\ sim}} \quad (4)$$

Where, APAR denotes the absorbed photosynthetic active radiation [ $MJ\ m^{-2}\ yr^{-1}$ ],  $m$  is an index for the month,  $fAPAR$  is the fraction of absorbed photosynthetic active radiation, calculated according to Eq. (1),  $sim$  denotes the simulation,  $PAR$  is photosynthetic active radiation [ $MJ\ m^{-2}\ month^{-1}$ ] from REMO, assuming  $PAR = 0.48 \times$  global (short wave) radiation and  $CF$  is a correction factor that was only activated for the estimation of site APAR based on a LAI measurement.

Using Eq. (3), we estimate APAR for the models and the measurement site in a consistent way. The calculation is performed for sites where both GPP and LAI measurements are available and for all years with GPP measurements with subsequent averaging over the years. This procedure yields a site APAR for each model, since we use the model specific phenology. The differences between the site APARs for different models are then entirely related to differently simulated phenology not due to the maximum reached LAI. Site and modelled RUE can now be calculated based on Eq. (2), i.e. using eddy covariance flux separated GPP and site APAR, and simulated GPP and simulated APAR respectively.

Our method to decompose GPP into APAR and RUE for both, the simulations and real world data is a first order approximation. The retrieved values are not comparable to field measurements of APAR or RUE since we integrate over the entire year not over the growing season and we ignore factors like albedo, diffuse radiation, and complex canopy structure. The models use internally partly different representation of the energy budget (e.g. albedo), differ slightly in the PFT specific light extinction coefficients

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and assumptions about scaling up from tree to grid cell level. Therefore, absolute numbers of APAR and RUE by our decomposition approach do not fully comply with the model parameters. Given that our method to estimate site APAR relies on the modelled phenology, we apply it only for evergreen coniferous forests. Using the method for deciduous vegetation would require a priori confidence in the simulated timing of leaf onset, maximum LAI and leaf senescence for all three models. However, the consistency of our approach suggests that results can be interpreted and compared in terms of patterns such as changes along large climatic gradients, while the absolute numbers may not be compatible among models and site data.

### 3 Results and discussion

#### 3.1 GPP

All three models capture qualitatively the general pattern of GPP changes along the MAT gradient across Europe, which is characterized by an increase from boreal to temperate and a subsequent decrease from temperate to Mediterranean (Fig. 2). However, the models consistently predict higher GPP for the boreal and lower GPP for the Mediterranean zone than suggested by eddy covariance based GPP. Variations of GPP by the LPJ model are smaller than indicated by eddy covariance based GPP and the other two models Orchidee, and Biome-BGC.

In Table 1 we compare eddy covariance based and modelled GPP using the mean and the root mean square error of prediction (RMSE) relative to the mean of the eddy covariance based GPP (relative RMSE). The RMSE is the standard measure to estimate the deviation of simulations to independent observational data (Tedeschi, 2006). Including all sites, the three models predict on average lower GPP than the eddy covariance based (not significant for Orchidee and Biome-BGC), and agree similarly well with the eddy covariance based GPP (RMSE of  $\sim 30\%$  or  $420\ gC/m^2/yr$ ). The stratification by ecosystem types reveals differences among models as well as among forest

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types and reveals individual contributions to the overall RMSE. On average, the RMSE is smallest for temperate coniferous sites (16–25%) and largest for Mediterranean forest ecosystems (21–61%). The three models consistently predict higher GPP for the boreal forest by 10 to 23%, lower GPP for temperate deciduous broadleaf forest and Mediterranean sites by 15 to 31% and 21 to 45% respectively. Between the models, LPJ is closest regarding the boreal forests (RMSE of 24%), Orchidee for temperate sites (RMSE of 16 and 27% for conifers and broadleaves respectively), and Biome-BGC for Mediterranean evergreens (RMSE of 21 and 28% for conifers and broadleaves respectively). The latter statement is somewhat ambiguous, given the small number of data points in the Mediterranean.

Our results match several findings from Morales et al. (2005) who studied the performance of LPJ-GUESS, Orchidee, and RHESSyS (Biome-BGC is part of RHESSyS) in simulating seasonal and interannual variations of NEE and evapotranspiration at Carboeurope eddy covariance sites: (1) model errors tend to be lowest in the temperate zone and highest in the Mediterranean, and (2) model errors tend to be lower for evergreen coniferous forests than for deciduous broadleaf forests. Morales et al. (2005) attributed the large deviations for Mediterranean sites to the ability to simulate water stress and its physiological consequences, and suggested that issues related to phenology may cause the discrepancy for deciduous sites.

Our primary goal is to assess the general correspondence of European scale simulations and eddy covariance based GPP along the MAT gradient. Thus we used the same driver data as previous modelling studies of Carboeurope-IP (Jung et al., 2007<sup>2</sup>; Vetter et al., 2007). This approach has the advantage that model evaluation is facilitated at their scale of application. However, it trades-off to some extent with the identification of model structural uncertainties and unambiguous identification of which model performs best since input data effects can not be separated. Substantial deviation between the rather coarse soil and meteo input data and in situ conditions at the measurement sites can be expected due to small scale variability (esp. convective rainfall, cloudiness, soil structure and depth) and general uncertainties regarding the quality of the coarse scale

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model input. Since the models are sensitive to their input data (e.g. Hicke, 2005; Jung et al., 2007<sup>2</sup>; Zhao et al., 2006), these input data related uncertainties together with uncertainties of the eddy covariance method (e.g. Loescher et al., 2006; Oren et al., 2006; Rannik et al., 2006; Richardson et al., 2006), subsequent data processing (Papale et al., 2006) and flux separation (Reichstein et al., 2005) would be sufficient to explain the apparent model-data mismatches. Particularly the discrepancy for Mediterranean forest sites may result to a large extent result from input data effects, given that the landscape is very heterogeneous, and moisture conditions resulting from localised rainfall and soil characteristics control photosynthesis. From this point of view, we can be confident about the European simulations of GPP for forests as the general pattern is qualitatively reproduced. Deviations among site data and models as well as among models are apparent but robust quantification of model performance and identification which model performs best would be very speculative at this stage. Ongoing research aims to understand real and model world controls of GPP variations using simulations based on in-situ input data for a few selected sites.

In the next section we compare simulated maximum LAI with measurements in order to gain more information about the model performances and what may cause some of the consistent discrepancy between eddy covariance based and modelled GPP.

### 3.2 LAI

LPJ and Orchidee simulate hardly any changes of LAI (expressed as fAPAR, see Sect. 2.1) from the boreal to the temperate zone which results in substantial overestimation of fAPAR in the boreal zone but reasonable agreement for temperate forests (Fig. 3). Biome-BGC captures the pattern qualitatively and does simulate an increase of LAI from boreal to temperate but not as strong as suggested by the measurements. The simulated LAI of boreal conifers is still too high while LAI of temperate conifers appears too low. In addition, deciduous forests exhibit far too low leaf area in Biome-BGC, most likely indicating a problem with the parameterisation. The measurements and all three models suggest decreasing LAI when moving from temperate to Mediterranean

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climate.

Leaf area is constrained by the availability of resources (Cowling and Field, 2003). In LPJ and Orchidee, the main resource limitation is plant available water while Biome-BGC includes nitrogen limitation. In a global NPP model intercomparison, Bondeau et al. (1999) suggested that models that include only water limitation tend to overestimate light harvesting when nitrogen limitation is present. The boreal zone is known to be nitrogen limited and this limitation decreases as nitrogen availability increases towards the temperate zone due to higher turnover but also anthropogenic deposition. The lack of an explicit nitrogen cycle may cause that LPJ and Orchidee do not simulate increasing LAI from boreal to temperate. On the other hand, the observed increase of LAI from boreal to temperate is partly an effect of a change in the prevailing conifer species from pine to spruce the latter being known to exhibit very high LAI (e.g. Breda, 2003) while global models cannot account for such species related effects. In the following section we investigate to what extent the overestimation of LAI for the boreal forests may be responsible for the overestimation of GPP.

### 3.3 Decomposing GPP into APAR and RUE

Figure 4 shows APAR and RUE along MAT for boreal and temperate conifers. Because the modelled phenology was used to estimate site APAR, a site APAR for each model is presented (see Sect. 2.3). Site and modelled APAR is significantly ( $p < 0.05$ ) correlated with MAT, but the site APARs show a larger slope (see also Table 4). As shown above, the models cannot reproduce the increase of fAPAR (i.e. LAI) from boreal to temperate so that their slope of APAR vs MAT simply represents increasing radiation, while the larger observed slope is due to additionally increasing fAPAR.

Site and modelled RUE is not significantly correlated with MAT. Despite the considerable scatter there is a trend of increasing RUE with MAT suggested by the site data (no significant correlation). This trend is reproduced by Orchidee while LPJ and Biome-BGC show essentially no change. Increasing RUE may result from increasing rubisco concentrations in the needles as nitrogen becomes more available, or due to

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more favourable temperature conditions for photosynthesis. Decreasing water stress would also lead to increasing RUE but this is unlikely to be the case here. The Orchidee model shows increasing RUE with MAT likely because different optimum temperatures are assigned for boreal and temperate coniferous trees.

Site APAR and RUE for LPJ are different than “site” for Orchidee and Biome-BGC, the latter two being almost identical (Fig. 4). This difference can only result from different phenological curves. The assumption in LPJ that leaf area is constant over the year for evergreens seems to have a significant effect. Modelling small increases of fAPAR during summer (fresh needles) when radiation is high seems to be important for the magnitude of absorbed radiation.

We showed above that both site APAR and RUE increase more strongly with MAT than predicted by the models. The question is which of the two factors has the larger effect in explaining increasing GPP from boreal to temperate forests. Since GPP is the product of APAR and RUE, the answer to the question can be inferred from the coefficient of variation (standard deviation divided by mean) of both factors. The factor that varies more also controls more the variations of GPP. Site data and the models agree that changes of APAR is the dominant factor that explains increasing GPP from boreal to temperate coniferous forests in Europe, while changes of RUE are of secondary importance (Fig. 5). The variation of APAR is more than twice as high as the variation of RUE and it is therefore likely that the data-model mismatch for boreal conifer forests is primarily caused by overestimating LAI.

## 4 Conclusions

Based on a simple method that allows decomposing GPP into APAR and RUE for simulations and site data, we suggest that consistent overestimation of GPP for boreal forests results primarily from simulating too high LAI. Accounting explicitly for nitrogen limitation should therefore improve the model performance substantially for the boreal zone. The method of GPP decomposition may be useful for future evaluations of large

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scale carbon cycle simulations based on global measurement databases that include also LAI data. The method can be used to compare variations of APAR and RUE as suggested by site data and the models and therefore helps to interpret what process or factor could explain variations of GPP and data-model mismatch.

5 We find the agreement of eddy covariance flux separated and simulated GPP by process-oriented biogeochemical models across Europe acceptable. The models were run in a typical mode for continental to global scale applications, i.e. based on PFT parameterizations and using relatively coarse scale meteorological and soil input data without accounting for site specific peculiarities such as management, age, and  
10 species effects. Since the models reproduce the general pattern of GPP variations from boreal to Mediterranean climate, we can gain confidence in simulations of forest GPP for Europe by global biogeochemical models from our analysis.

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**Table 1.** Relative RMSE and mean eddy covariance flux separated and modelled GPP, stratified by forest ecosystem type. The relative RMSE is calculated as RMSE divided by the mean of the eddy covariance flux separated GPP values. The model with smallest RMSE is underlined for individual forest types.

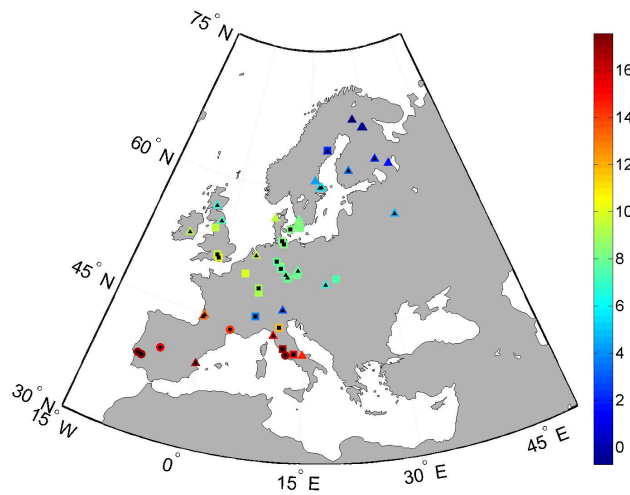
Forest ecosystem type	Number of sites	Mean GPP [gC/m <sup>2</sup> /yr]				Relative RMSE [%]		
		Observed	LPJ	Orchidee	Biome-BGC	LPJ	Orchidee	Biome-BGC
<b>All</b>	<b>37</b>	<b>1400</b>	<b>1097</b>	<b>1252</b>	<b>1243</b>	<b>32.34</b>	<b>29.56</b>	<b>29.65</b>
Boreal evergreen needleleaf	9	1003	1102	1225	1232	23.65	33.80	31.95
Temperate evergreen needleleaf	10	1643	1311	1537	1600	25.12	16.43	21.08
Temperate deciduous broadleaf	10	1534	1060	1305	1067	33.35	27.41	33.75
Mediterranean evergreen needleleaf	2	1586	879	894	1259	44.61	43.65	21.08
Mediterranean deciduous broadleaf	2	1197	811	558	665	42.35	60.84	51.32
Mediterranean evergreen broadleaf forest	4	1358	893	989	1097	41.03	32.59	28.29

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**Table 2.** Trends of APAR and RUE along MAT for boreal and temperate evergreen needleleaf forests.

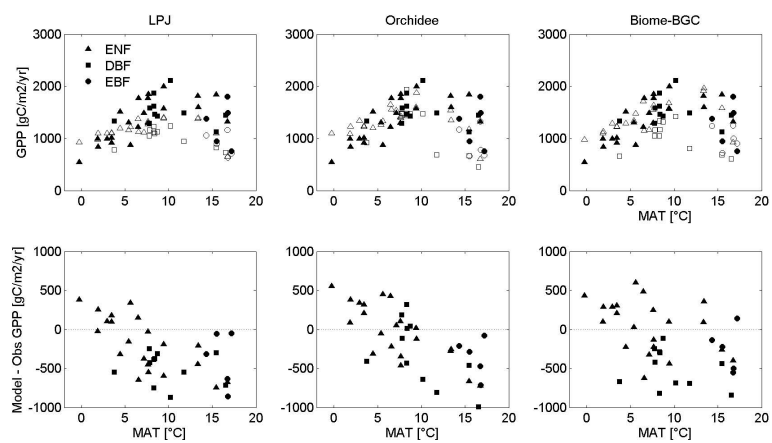
	Slope APAR vs MAT [MJ/°C]		Slope RUE vs MAT [gC/MJ/°C]	
	Modelled	Estimated from Observations	Modelled	Estimated from Observations
LPJ	34.58	82.78	0.003	0.033
Orchidee	42.11	99.65	0.016	0.023
Biome-BGC	40.1	97.87	0.002	0.017

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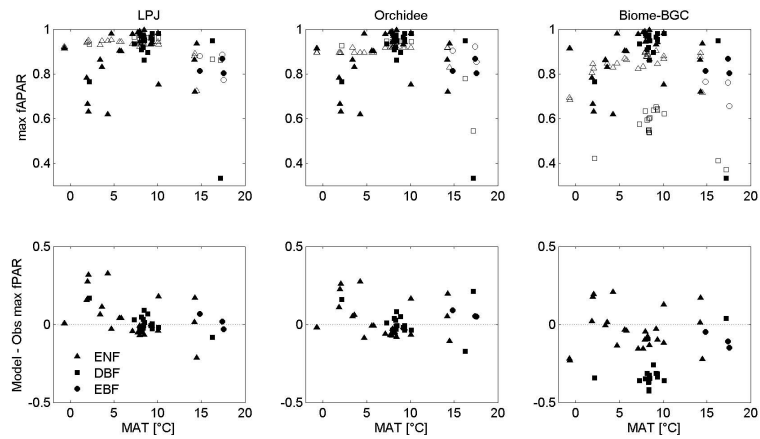
**Fig. 1.** Spatial distribution of GPP and LAI measurements. Sites with GPP measurements have a black filling. Triangles: evergreen needleleaf forests, squares: deciduous broadleaf forests, circles: evergreen broadleaf forests. Colour represents mean annual temperature in °C (1981–2000 mean from REMO).

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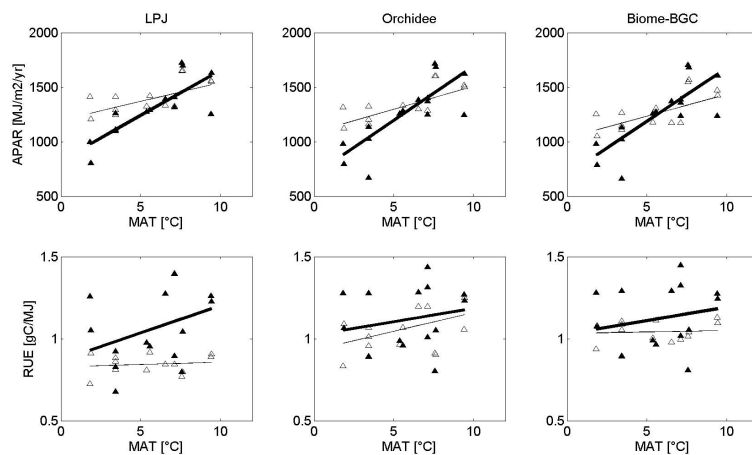
**Fig. 2.** Top panel: eddy covariance flux separated (filled markers) and modelled (open markers) GPP along the mean annual temperature gradient across Europe. Bottom panel: difference between modelled and eddy covariance flux separated GPP along mean annual temperature (MAT, 1981–2000 mean based on the REMO data set). ENF: evergreen needleleaf forests, DBF: deciduous broadleaf forests, EBF: evergreen broadleaf forests.

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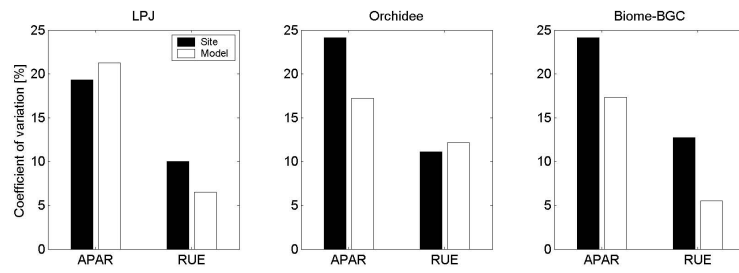
**Fig. 3.** Top panel: observed (filled markers) and modelled (open markers) maximum fAPAR along the mean annual temperature gradient across Europe. Bottom panel: difference between modelled and observed fAPAR along MAT. ENF: evergreen needleleaf forests, DBF: deciduous broadleaf forests, EBF: evergreen broadleaf forests.

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**Fig. 4.** Site (filled markers) and modelled (open markers) trends of APAR and RUE along the mean annual temperature gradient for boreal and temperate coniferous forests. Bold line: trend of site values; thin line: trend of modelled values.

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**Fig. 5.** Coefficient of variation (standard deviation/mean) of APAR and RUE for boreal and temperate coniferous forests based on site and modelled data. The discrepancy of LPJ site data with site data based on Orchidee and Biome-BGC results from the assumption of constant leaf area over the year (see text).