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A comparison of alternative modelling approaches to evaluate the European forest carbon fluxes

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ABSTRACT

The European forest carbon balance studied by various methods shows different results. We compared the regional and national net primary production (NPP) estimated by the forest inventory-based model EFISCEN and the climate-based terrestrial ecosystem models (TEMs: BIOME-BGC, ORCHIDEE, and JULES), and single forests NPP derived from the international network of eddy-covariance towers (FLUXNET). In addition, the paper presents the net ecosystem production (NEP) and the net biome production (NBP) calculated with EFISCEN and discusses the influence of forest management onto carbon fluxes. We aimed to better understand the variance between EFISCEN and TEMs NPP estimates, and to improve the assessment of European forest mitigation potential for the year 2005.

The NPP comparison between the EFISCEN inventory method and the TEMs process-based method showed similar average values for Europe and its countries. The European NPP average 508 ± 183 ($\pm$standard deviation) gC/m^2/year of EFISCEN was close to 487 ± 126 gC/m^2/year of TEMs. The country level average EFISCEN–TEMs difference was just 57 ± 153 gC/m^2/year. Larger differences were apparent at the regional level for the species groups. Especially for coniferous forests, EFISCEN projected higher values (NPP maximum 1480 gC/m^2/year) than TEMs (NPP reaching saturation below 700 gC/m^2/year). Compared to regional TEMs NPP across Europe, the range of regional EFISCEN NPP was consistently larger and with larger variance. Regionally EFISCEN and TEMs NPP averages were close to the individual FLUXNET data. Similar to broadleaves of TEMs, the FLUXNET broadleaves NPP were more productive compared to coniferous forests.

We conclude that the two methods produce similar results, except for higher regional EFISCEN NPP of coniferous forests. The NPP difference between modelling methods was presumably result of TEMs assuming mature steady state forests, and lacking the distribution of highly productive and abundant intermediate age classes (integrated into EFISCEN). Both approaches have their advantages; TEMs include climate and environmental change, whereas EFISCEN includes past and current management. Combining the two approaches will allow more accurate assessment of the forest carbon balance, including direct and indirect human effects.

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1. Introduction

The atmosphere–biosphere carbon cycle has been intensively studied to quantify the different processes affecting atmospheric CO_2 concentrations, with a view to mitigate climate change. Within the carbon cycle, vegetation plays an important role by absorbing CO_2 from the atmosphere through photosynthesis and storing the carbon in organic material. In Europe, forests act as an important carbon sink due to the beneficial age structure and increasing growth rates resulting from environmental changes (Nabuurs et al., 2003; Kahle et al., 2008). Due to the current sink effect, forests help European countries to reduce atmospheric CO_2 content by offsetting fossil fuel emissions.

The European forest carbon balance has been studied by applying various methods in order to better understand the main driving factors and to quantify the European forests mitigation potential. In general there are two different approaches to assess forest carbon dynamics: (1) assessing stock changes in forest

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carbon pools (Karjalainen et al., 2003; Janssens et al., 2003; Eggers et al., 2008); and (2) assessing incoming and outgoing carbon fluxes (Churkina et al., 2003; Jung et al., 2007a,b; Ciais et al., 2005).

Models adopting the first approach mainly use forest inventory data to simulate the biomass growth (Karjalainen et al., 2003; Nabuurs et al., 2007; Eggers et al., 2008). The inventory-based methods usually produce results on forest growth at the regional to country level in annual- or multiple year-time steps. When modelling the forest carbon balance, they can take into account management and natural disturbances. These methods are strongly dependent on the quality of national inventories, of the functions used to simulate forest growth and of the factors to convert growing stock to total tree biomass (Lindner and Karjalainen, 2006).

Methods implementing the second approach include process-based land surface models driven by measurements of meteorological conditions to simulate measurable CO_2 fluxes (Thornton et al., 2002; Churkina et al., 2003; Zhuang et al., 2003; Jung et al., 2007a,b). Process-based terrestrial ecosystem models (TEMs) use mathematical models that calculate gross primary productivity and respiration and predict carbon fluxes in response to meteorological conditions. They generally use a relatively small time step (days to hours), they are run for long time periods and they cover large geographical areas (continental to global scale). At present many TEMs do not include forest management and forest age class distribution (Zaehle et al., 2006), but attempts are currently made to address this gap (Bellassen et al., 2008; Petritsch et al., 2007).

The aid in validation of the algorithms of carbon fluxes simulations of terrestrial ecosystem modellers as well as in the interannual interpretation of carbon fluxes derived from biomass inventories of forest ecologists could provide an international field network of high-precision eddy-covariance system CO_2 and surface carbon flux measurements, FLUXNET (Baldocchi et al., 2001). FLUXNET is a wide network of eddy-covariance system towers established for direct and continuous measurements of carbon, water and energy interactions between various ecosystems and atmosphere. FLUXNET studies measure the carbon budgets, and the carbon flux components e.g. tree stand net primary production (NPP) (Luyssaert et al., 2007, 2009). The FLUXNET data are publicly avalilable at http://wwweosdis.ornl.gov/FLUXNET/.

In this study we assessed the forest ecosystem growth in Europe in terms of NPP at the regional and national level, by comparing the results of forest inventory-based and process-based modelling approaches. We also compared our NPP with NPP of European FLUXNET sites to provide the evaluation of both model types. By comparing NPP simulations of two methods and four 'state of art' models, we aimed to better understand the factors that influence the carbon budgets and thereby contribute to the increasing NPP accuracy. The NPP results between the forest inventory-based model EFISCEN (Sallnäs, 1990; Schelhaas et al., 2007), and the terrestrial biosphere models BIOME-BGC (Thornton, 1998; Running and Gower, 1991), ORCHIDEE (Krinner et al., 2005), and JULES (http://www.jchmr.org/jules/) were compared for the Member States of the European Union (excluding Cyprus, Greece and Malta), Switzerland and Norway at the national, regional and species-group level. By analyzing the level of NPP agreement between two model types, the paper discusses the strengths and weaknesses of the two approaches. In addition, we assessed the influence of forest management on the NPP in EFISCEN to understand how the intensity of forest management affects the sequestration potential of European forests.

2. Methods

This study investigates the components of the forest carbon cycle of 26 European countries and 134 European regions (Nomenclature of Territorial Units for Statistics (NUTS) ranging from NUTS2 to a national level) (Fig. 1) for period 2000 to 2005. In EFISCEN Portugal and Ireland broadleaved forests were not included. The results of the study are aggregated at the regional level and at the national level. To better understand regional patterns of the NPP flux, the data were also analysed according to the stratification in European environmental zones identified by Metzger et al. (2005). Some of the original zones were aggregated together to simplify the classification and make it easier to identify possible regional patterns of NPP in Europe (Fig. 1). The zones were merged accordingly: Boreal with North Alpine zone; Atlantic North with Atlantic South and Lusitanian; Mediterranean North with Mediterranean Mountains, Mediterranean South and Anatolian; other zones remained original. In some countries (Portugal, Spain, Italy, and Balkan area) the aggregation was necessary because the forest inventory data for these countries were available only at the national level and disaggregation of results for different environmental zones would not have been possible. In those cases the main environmental zone in the country was chosen. For example, Romania was chosen to represent a Continental zone, though in Metzger et al. (2005) Romania partly includes Continental, Alpine South and Pannonian zones.

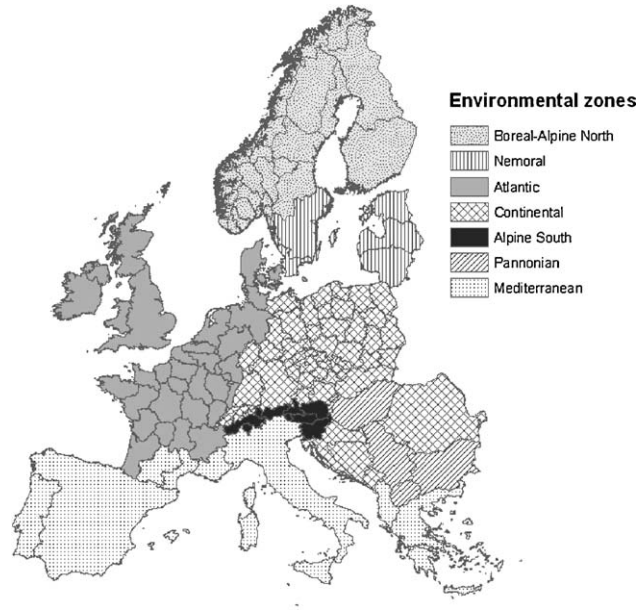

Fig. 1. EFISCEN regions classified according to European environmental zones. Environmental zones are modified according to Metzger et al. (2005) to match EFISCEN regions.

2.1. Fluxes of the carbon cycle

Among the components of the forest carbon balance (e.g. Schulze, 2006), the net primary production (NPP) is the most comprehensive flux assessed by both types of model included in the study. NPP is the difference of the total amount of CO_2 absorbed by plants with photosynthesis, the gross primary production (GPP), and the plant respiration (autotrophic respiration, AR). AR is a sum of maintenance (MR) and growth (GR) respiration. Therefore NPP represents the total CO_2 fixed by plants in organic matter. Part of the organic matter produced is accumulated in the forest ecosystem as plant biomass, litter and soil organic matter (net ecosystem production, NEP) and part is lost as respiration in the decomposition process (heterotrophic respiration, HR). Net biome production (NBP) is the amount of carbon that remains in the forest after harvest removals (R) and losses by disturbances (D).

2.2. Description of models

2.2.1. EFISCEN

The EFISCEN (European Forest Information SCENario) model is a large-scale model that projects forest resource development on regional to European scale (Eggers et al., 2008; Nabuurs et al., 2007; Karjalainen et al., 2003). The model is described in detail by Schelhaas et al. (2007).

EFISCEN describes the state of the forest as an area distribution over age- and volume-classes in matrices, based on data on the forest area available for wood supply (FAWS), average tree growing stock and net annual increment collected from national forest inventories conducted between the 1980s and the year 2001 (Schelhaas et al., 2006; Nabuurs et al., 2007). EFISCEN inventory data for Ireland and Portugal were limited to coniferous tree species only. Transitions of area between matrix cells during simulation represent different natural processes and are influenced by management. First, a basic forest management regime defines the period during which thinning can take place and a minimum tree age for final felling. Secondly, the demand for wood is specified for separately thinning and for final felling. This determines the intensity with which forests are managed.

EFISCEN projects stemwood volume, increment, age classes and wood removals for 5-year time steps. To assess biomass carbon stocks, stemwood volume is converted into carbon in stems, branches, foliage, coarse and fine roots, using basic wood densities (IPCC, 2003), a generic carbon content of 0.5, and age-dependent biomass distributions factors (Vilén et al., 2005; Mokany et al., 2006; Gasparini et al., 2006). Information on litterfall rates (Vilén et al., 2005) and unused harvest residues are input to the soil module YASSO (Liski et al., 2005), which simulates litter fractionation and decomposition based on 30 years (1961–1990) average climate data (Mitchell et al., 2004) for every EFISCEN region.

2.2.2. BIOME-BGC

BIOME-BGC is a terrestrial ecosystem model describing the carbon, nitrogen and water cycles (Thornton, 1998; Running and Gower, 1991). It has been corroborated for a number of hydrological and carbon cycle components as well as for forest management (Churkina et al., 2003; Hasenauer et al., 1999; Vetter et al., 2005). The model can be parameterized for seven biomes including evergreen needleleaf, evergreen broadleaf, deciduous needleleaf, deciduous broadleaf, shrubs, and grass (C_3- and C_4-type photosynthesis) as well as fertilized grasses. For this study we used the model version 4.1.1 with the carbon and nitrogen allocation routine from version 4.1. Parameters for evergreen needleleaf and deciduous broadleaf forests were optimized from field measurements of net carbon fluxes (Trusilova et al., 2009). In this large scale simulation the forest management was not included due to lack of the spatial explicit information of regional inventories describing forest management types and age structure.

2.2.3. ORCHIDEE

ORCHIDEE (Krinner et al., 2005) is a process-oriented integrated global land surface model consisting of a global land surface scheme (Ducoudre et al., 1993), and a global continental carbon cycle model. The model considers 13 plant functional types (PFTs) including for temperate forests deciduous and evergreen broadleaf forest and needleleaf evergreen forest. ORCHIDEE does not include the forest management.

2.2.4. JULES

JULES (Joint UK Land Environment Simulator; http://www.jchmr.org/jules/) is a process-based surface exchange scheme, including a dynamic representation of vegetation and the terrestrial carbon cycle. Its predecessor, MOSES 2.1 (Cox et al., 1999) was the land surface exchange scheme in the Met Office climate model but JULES has been released as a separate community model. JULES includes an improved representation of radiative transfer through the vegetation canopy (Mercado et al., 2007). The PFT classifications are: broadleaf tree, needleleaf tree, C_3-type grass, C_4-type grass and shrub. At any location all of these PFTs can exist with different relative dominances (fractional coverage). Fractional coverage and canopy height (i.e. horizontal and vertical dimensions of a PFT) are continuous variables and are allowed to change. These changes are driven by estimates of the net primary production (Cox, 2001; Hughes et al., 2006).

The current version was improved to correctly account for carbon emissions from deforestation. The representation of forest management, age structure and nitrogen cycling is expected to be included in future versions.

2.3. Description of simulations

The two types of model simulations were compared based on the NPP results for the year 2005 at the scales of Europe, individual countries and EFISCEN regions. In EFISCEN simulations led to NPP results directly at different scales. In TEMs, to obtain the carbon fluxes at different scales the NPP simulations were driven with Europe-wide gridded data, and gridded NPP results were aggregated by averaging of the pixels that belonged to the same region/country.

Using the inventory approach, EFISCEN simulated the forest biomass and soil carbon stocks for the years 2000 and 2005 and subsequently calculating the difference in carbon pools. Firstly, EFISCEN simulated forest resource development until 2005 based on (i) conventional forest management regimes (Nabuurs et al., 2007), (ii) historical roundwood production (FAOSTAT, 2008) converted to overbark volumes (UNECE-FAO, 2000) from coniferous and broadleaved species separately, and (iii) extracted harvest residues (Mantau et al., 2008). To capture regional differences in management intensity, the harvest volumes were regionalised for Austria, Finland, France, Germany, Norway, Sweden and Switzerland based on national reports. Forest area available for wood supply (FAWS) was scaled in EFISCEN database to match the FAWS reported by MCPFE (2007) to correct for small deviations in the area. After the first simulation, EFISCEN conducted additional second and third runs to assess the sensitivity of EFISCEN carbon flux estimates to management intensity in which the harvest volumes were increased and decreased for the period 2001–2005 by ±25%. In a fourth simulation we scaled the forest area and increment in EFISCEN database to the area and increment of the total forest area (MCPFE, 2007; UNECE-FAO, 2000), and the results of this simulation we used for the comparison with other models.

The NPP values in EFISCEN were calculated as a sum of carbon changes of the biomass, litter input and removals. NEP was calculated as a sum of carbon changes of the biomass, soil and removals. NBP is the sum of carbon changes of the biomass and soil (between simulation years 2000 and 2005).

Using the process-based approach in TEMs the productivity (NPP) of a forest was calculated at a daily (BIOME-BGC, ORCHIDEE) to hourly (JULES) basis as a difference between gross photosynthesis (GPP) and autotrophic respiration (AR). Simulated NPP includes both above and belowground production of forest. The TEM simulations were performed with standardized Meteorology input data. Detailed description of GPP and AR equations, the initialization, standardized input drivers, land surface parameterization (e.g. elevation above the sea level, soil texture, soil-depth and land cover classification), and simulations of BIOME-BGC and ORCHIDEE ecosystem models were exactly the same as in Vetter et al. (2008). JULES adopted the modelling protocol of Churkina

et al. (2008), though the model was the same as in Vetter et al. (2008) and both protocols were from the same CarboEurope-IP project. Ecosystem model simulations have been performed with standardized input data. Since measured values for model's state variables were not available for Europe, spinup model simulations were performed for their initialization in this study. In the spinup run, the model was run to a steady state to obtain the size of the ecosystem's carbon and nitrogen pools under the assumption of ecosystem being in equilibrium with the long-term climate. The initial state of model considered no soil carbon and no biomass except for carbohydrate reserves that were used to begin the season (reserve are transferred to leaf biomass) for deciduous vegetation. For evergreen, an initial leaf biomass was set. Model was then run until equilibrium for biomass and soil carbon pools with the long-term climate. Spinup simulation was followed by a transient simulation, where effects of rising atmospheric CO_2 (all TEMs) and nitrogen deposition (BIOME-BGC only) on the carbon cycle of Europe were simulated.

2.4. FLUXNET NPP

The evaluation of simulated NPP values was conducted by comparison with forest ecosystem NPP data (a total NPP of stems, foliage, branches, coarse roots and fine roots) derived from FLUXNET Web page for communication and data exchange (http://wwweosdis.ornl.gov/FLUXNET/) (Luyssaert et al., 2007, 2009) (Table 1). Only forest sites geographically belonging to 26 European countries and with available ecosystem NPP were selected from FLUXNET. FLUXNET NPP in this study represent a random sample of European forests (and not spatially integrated averages of the regions as models NPP) allowing only for rough comparison with our results. Except for three highly productive Poplar plantations (optimally watered and enriched in CO_2) (Gielen et al., 2005), FLUXNET forest sites were managed with common forestry practices; four were unmanaged.

3. Results

3.1. Model comparison at the European, national, regional, and species-group level

Table 2 compares average European NPP from the four models, comparing inventory and process-based approaches. EFISCEN European average NPP lies within the range of values modelled by BIOME-BGC, ORCHIDEE, and JULES. The national values show good agreement between EFISCEN and BIOME-BGC, and even better between EFISCEN and ORCHIDEE. EFISCEN showed the least agreement with JULES in terms of absolute NPP values, which predicted the lowest values. On average at a country level, the forest NPP difference between the two modelling approaches was 57 ± 153 gC/m^2/year. The best agreement for total forests between TEMs and EFISCEN was a difference of 42 ± 18 gC/m^2/year for France dominated by broadleaved forest with a stable level of wood removals during last 15 years. The NPP difference between EFISCEN and TEMs increases with increasing NPP at the country level.

The comparison of NPP at the regional and at the species-group level highlighted some relevant differences between the two approaches (Fig. 2). For data aggregated in regions of broadleaved and coniferous species groups, the EFISCEN estimates were generally larger to TEMs. Although not statistically significant, the European average NPP from the TEMs showed higher NPP average for broadleaved (467 ± 260, 621 ± 291, and 431 ± 97 gC/m^2/year, respectively) (±standard deviation) than for coniferous forests (416 ± 135; 399 ± 168, and 407 ± 78 gC/m^2/year). EFISCEN average NPP was approximately equal for both broadleaved and coniferous forests (525 ± 196 and 533 ± 262 gC/m^2/year, respectively).

Table 1
Number of FLUXNET forest sites with available NPP in 26 European countries selected from Luyssaert et al. (2009) dataset.

FLUXNET sites with NPP	Total
Environmental zone	
Atlantic	21
Continental	16
Boreal-Alpine North	13
Mediterranean	5
Nemoral	6
Southern Alds	0
Deciduous broadleaved forest (DBF)	
Fagus sylvatica	20
Quercus sp.	8
Populus sp.	3
Alnus sp.	2
Betula pubescens	1
Evergreen needleleaved forest (ENF)	
Picea abies	18
Picea sitkensis	1
Pinus sylvestris	9
FLUXNET sites with NPP and age	
DBF	32
ENF	24

The regional maximum NPP values for individual models were located in different regions and in different environmental zones of Europe. The maximum NPP estimates of EFISCEN and BIOME-BGC were found for coniferous forest in Atlantic, Continental, and Pannonian zones. The JULES NPP maximum was similar to BIOME-BGC centred into Atlantic environmental zone of Europe. The maximum NPP of ORCHIDEE was shifted northwards to the Continental, Nemoral and Boreal zones. The common zone of regional maximum NPP levels of Europe showed a broad range including west coast (Atlantic zone), South Alps, Continental, Nemoral, and partly Pannonian zone.

Table 2
Average forest NPP at the national and European level as assessed by different models.

		EFISCEN	BIOME-BGC	ORCHIDEE	JULES
		NPP (gC/m^2/year)			
Austria	AT	921.8	578.6	612.6	391.6
Belgium	BE	834.8	672.0	866.6	529.6
Bulgaria	BG	610.4	431.2	579.4	432.2
Czech Republic	CZ	858.3	638.7	734.2	451.8
Denmark	DK	650.6	600.5	677.4	467.3
Estonia	EE	583.6	559.2	667.5	383.5
Finland	FI	373.1	456.9	578.3	198.1
France	FR	567.8	538.6	535.4	504.5
Germany	DE	812.8	621.4	638.1	485.8
Hungary	HU	617.1	556.0	802.7	460.6
Ireland	IE	691.8	563.6	577.3	464.3
Italy	IT	510.0	401.7	333.0	437.3
Latvia	LV	549.5	602.9	708.1	417.7
Lithuania	LT	556.7	609.4	719.2	435.2
Luxembourg	LU	972.7	661.2	928.5	515.7
Netherlands	NL	720.5	622.4	577.6	497.3
Norway	NO	365.5	268.6	329.7	186.4
Poland	PL	540.6	810.1	716.4	467.6
Portugal	PT	344.3	327.0	192.7	438.7
Romania	RO	721.7	616.7	769.4	420.3
Slovakia	SK	592.5	649.1	859.5	433.5
Slovenia	SI	598.7	552.1	297.0	477.4
Spain	ES	210.3	353.7	296.3	203.1
Sweden	SE	422.7	424.0	507.9	214.4
Switzerland	CH	922.4	471.9	516.7	318.6
United Kingdom	UK	642.7	518.3	517.5	447.5
Europe		507.8	492.8	548.5	418.7
Standard deviation		179.5	119.9	155.5	87.1

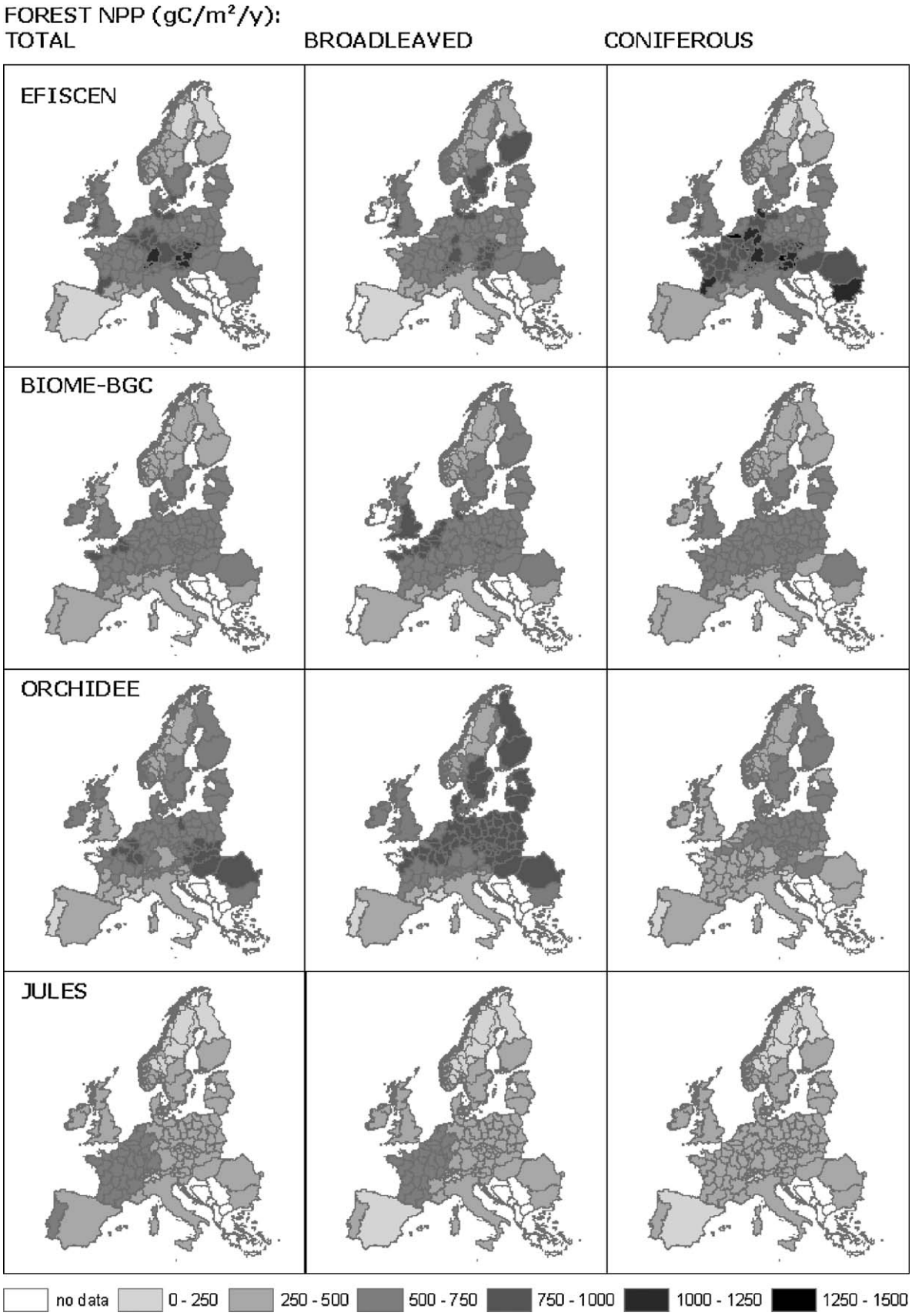

Fig. 2. Comparison of NPP modelled by EFISCEN, BIOME-BGC, ORCHIDEE, and JULES for coniferous, broadleaved and total forest of regions of Europe in year 2005.

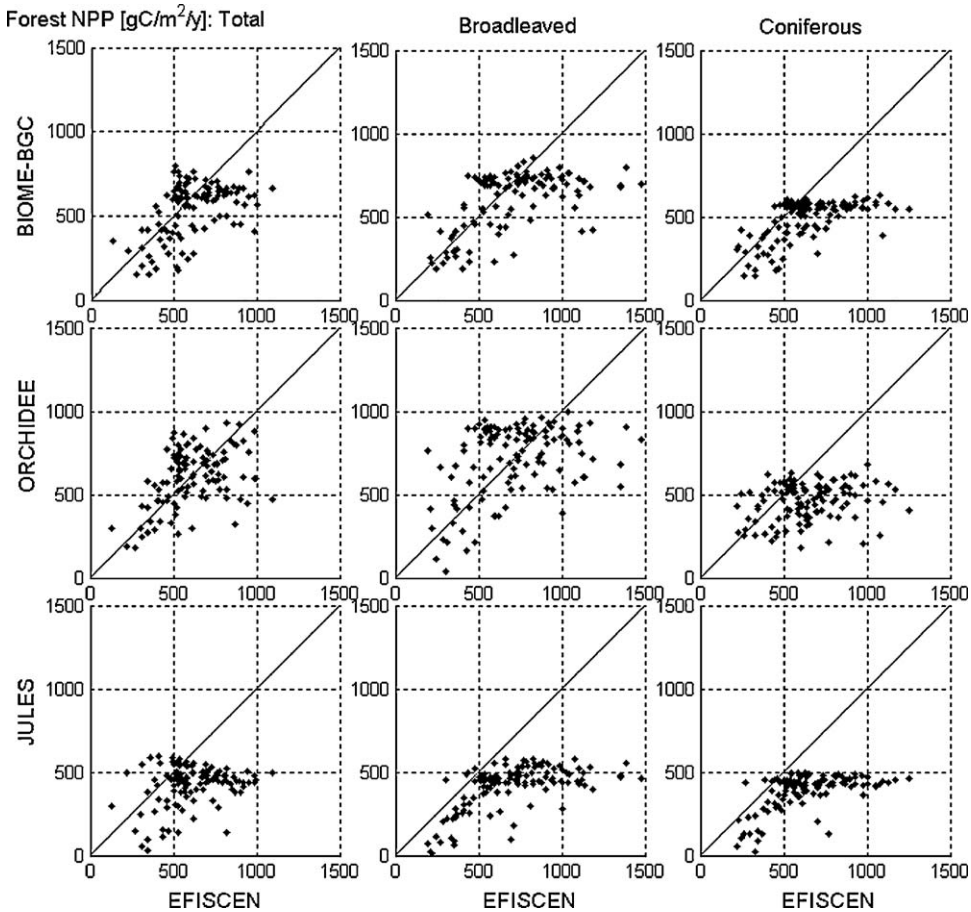

Fig. 3. Scatter plot of modelled NPP between EFISCEN versus BIOME-BGC, ORCHIDEE, and JULES for total, broadleaved, and coniferous forest of regions of Europe in year 2005.

The regional NPP estimates by all TEMs are plotted against the estimates by EFISCEN in Fig. 3.There is a clear saturation effect in TEMs NPP, between 500 and 700 gC/m^2/year. The TEMs limit was particularly evident for coniferous forests. The limit is much higher for broadleaves in ORCHIDEE (1000 gC/m^2/year) and in BIOME-BGC (800 gC/m^2/year), while in JULES the limit is similar for both broadleaves and conifers (600 gC/m^2/year). These thresholds could not be detected in estimates by EFISCEN, where NPP values went up to 1300–1500 gC/m^2/year in some of regions for both species groups. Each point in Fig. 3 represents individual regions with different forest area, and extreme NPP values may be only small regions with small forest area. The agreement between the two approaches increased at the level of total forest, and it was strongest between ORCHIDEE and EFISCEN.

3.2. Modelled NPP evaluation with FLUXNET NPP

EFISCEN represents many thousands of measurement locations of forest inventory dataset, while TEMs and FLUXNET cover only a small fraction of this sampling size. The 62 FLUXNET forest sites, in terms of age class distribution are highly skewed towards the younger classes (Fig. 4a). In Fig. 4a both species groups life span reached the age class 300 years, but 50% of coniferous (ENF) sites were less than 50 years old (83% $<$ 100) while only 22% of broadleaved (DBF) sites were less than 50 (41% $<$ 100). Apparently, the highest variability and highest production were observed in the youngest age class (Fig. 4b). NPP was generally larger in DBFs than in ENFs.

The spatial distribution of the 62 FLUXNET forest sites is biased towards western, northern and middle European countries (Fig. 5).

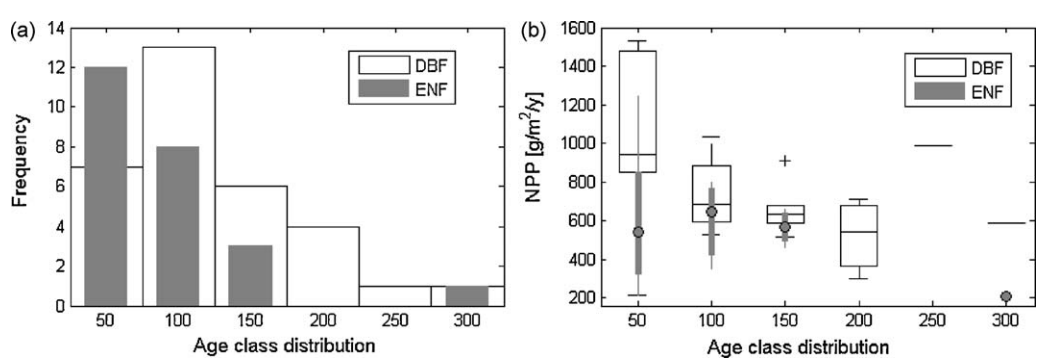

Fig. 4. (a) The difference in the age class occurence and (b) the boxplot differences in NPP values for individual age classes of FLUXNET broadleaved (DBF) and coniferous forests (ENF) across European countries. Dataset from Luyssaert et al. (2009).

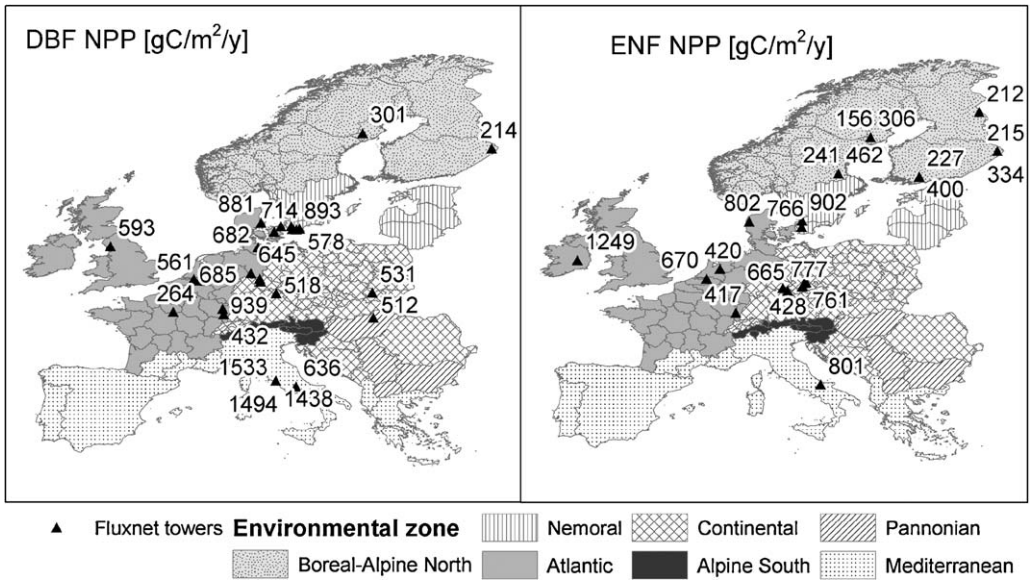

Fig. 5. The FLUXNET NPP values distributed across European countries and environmental zones (modified according to Metzger et al., 2005) for deciduous broadleaved (DBF) and for evergreen needleleaved forests (ENF). Dataset from Luyssaert et al. (2009).

Despite the biased distribution of sites and caution with interpretation when comparing individual forest NPP to regional NPP averages of models, FLUXNET NPP showed similar production patterns of European environmental zones as TEMs and EFISCEN (Figs. 5 and 6). Especially for the European environmental zones with highest number of FLUXNET sites (Atlantic and Continental), the regional TEMs and EFISCEN NPP averages fell close or into the range of individual forests FLUXNET NPP. However, the reducing of the NPP variation by regional averaging was more strongly pronounced in TEMs, than in EFISCEN. EFISCEN generally shows a good agreement with both FLUXNET data and the upper range of TEM NPP. A relatively high number, 13 (21%), of FLUXNET sites in Boreal-Alpine North zone exhibit lower NPP than TEMs or EFISCEN NPP (Fig. 6). In contrast, NPP in the Nemoral zone are higher than simulated. The FLUXNET sites of the Nemoral zone were located in zone's southern most and western edge, in Denmark, with similar environmental conditions to highly productive Atlantic zone.

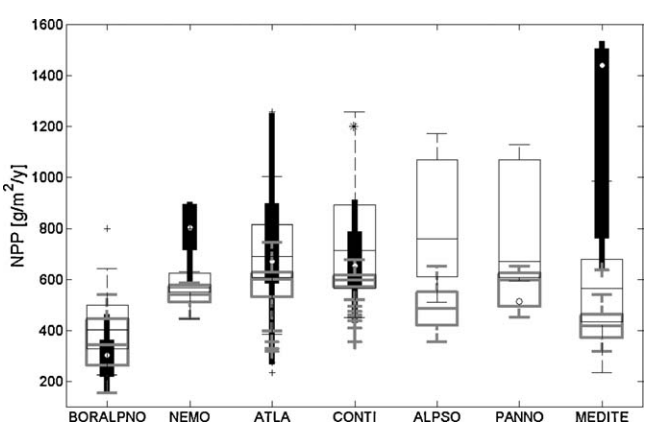

Fig. 6. The boxplot comparison of NPP values between FLUXNET broadleaved and coniferous forest sites (compact black boxes), and the regional total forest NPP values of the terrestrial ecosystem models BIOME-BGC, ORCHIDEE, JULES (open gray boxes) average and forest inventory-based model EFISCEN (open black boxes) across European environmental zones. Environmental zones Boreal-Alpine North (BORALPNO), Nemoral (NEMO), Atlantic (ATLA), Continental (CONTI), South Alp (ALPSO), Pannonian (PANNO), and Mediterranean (MEDITE) are modified after Metzger et al. (2005). Dataset for FLUXNET forest sites from Luyssaert et al. (2009).

3.3. NPP, NEP and NBP in EFISCEN

In addition to the assessment of NPP by all models, in EFISCEN we calculated the net ecosystem production (NEP) and the net biome production (NBP). The comparison of the three fluxes between countries highlights that the different contributions of NEP and NBP to NPP greatly varied (Fig. 7). The levels of NEP (NBP plus wood removals) increased with NPP linearly, and all were highest for Austria, Switzerland, and Czech Republic. The important component which determines the difference between NPP and NEP is the heterotrophic respiration (Rh). In EFISCEN Rh contributes on average to about 72% of the NPP, but with significant variability between countries (60–98%). High (98%) values of heterotrophic respiration in Portugal were a result of negative change in biomass and soil carbon stocks between the years 2000 and 2005. Similarly high Rh was also found for Poland 84% and Latvia 82%, all for countries with negative NBP (Portugal—71 gC/m^2/year, Poland—3 gC/m^2/year, Latvia—19 gC/m^2/year). The NEP shows an increasing trend moving from the edges of Mediterranean (7 and 62 gC/m^2/year in Portugal and Spain) and

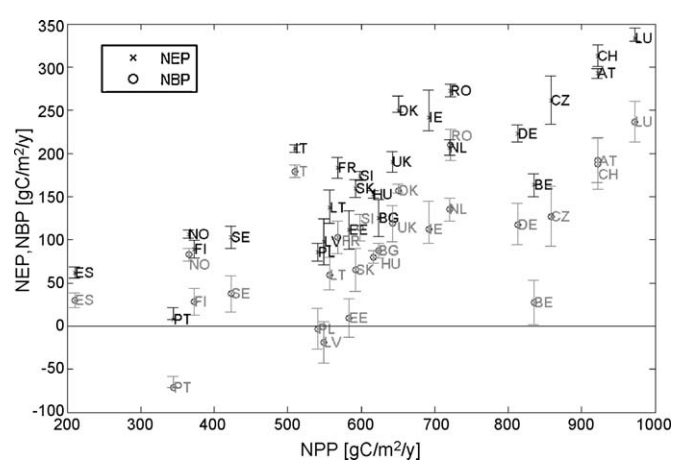

Fig. 7. Scatter plot between country average NPP values versus NEP (black) and NBP values (grey). The difference between NEP and NBP values is the amount of removals. The error bars of NEP and NBP show the effect of ±25% change in removals extraction on NEP and NBP.

Boreal zones (from 89 to 106 gC/m^2/year in Finland, Sweden, and Norway), towards middle Europe (approximately 150–250 gC/m^2/year) with maximum calculated for the Alpine area (293 and 313 gC/m^2/year in Austria and Switzerland) (Fig. 7).

Wood removals (the difference between NEP and NBP) form another component of NPP values. A sensitivity analysis, imposing ±25% changes in the wood removals rate indicated that the average EFISCEN NPP for 2001 to 2005 was relatively insensitive to wood removal rate changes during the period. The 2005 NPP changed only by 5% on average. However, the change in removals more strongly affected 2005 NEP (11% on average) through the change of litterfall and heterotrophic respiration, and logically even more affected 2005 NBP (by 23% on average) (Fig. 7). In the South Alpine forests (Austria, Switzerland, and Italy) with relatively little removals (relative to NPP), the NEP was largely unaffected by changed removals. In countries with relatively high removals (Czech Republic, Sweden) the NEP was affected to a greater extent. In Estonia and Latvia a 25% increase of removals would force NBP to become zero or negative since these countries are currently removing wood close to the maximum limit of NEP.

4. Discussion

4.1. Carbon flux estimates and the effect of forest management

The net primary production was the primary component of the terrestrial carbon balance compared between the two modelling approaches. NPP values from EFISCEN (depended on forest inventory data, independent of meteorological records, and including forest management) were compared to NPP results of TEMs (independent from the forest inventories, dependent on meteorological records, and not including forest management). We investigated EFISCEN NPP and TEMs NPP at the European, country, regional and species-group level. The average European forest NPP values of TEMs and EFISCEN were similar to NPP values of simulations without management reported by Ciais et al. (2008). While the NPP values were comparable at the European level, we found distinct differences by species groups and regions within 26 European countries. We hypothesised that the EFISCEN and TEMs NPP differences are due to forest management effects, which are currently not well represented in TEMs (Zaehle et al., 2006). This hypothesis would require a good agreement between EFISCEN and TEMs for the countries with low intensity harvesting; however the best agreement was for Baltic countries (Estonia and Latvia) with current high intensity harvesting. The role of historic management affecting the forest age structure of presumed mature forest e.g. Estonia and Latvia may be one explanation of the reason for the EFISCEN–TEMs differences. In managed forest, the harvesting and afforestation history affects NPP by modifying the distribution of tree species and age classes with typical productivity over the forest area. In general in the long term, the wood harvesting determines the age structure, wood increment and NPP (Kauppi et al., 1992). The large post-war afforestation followed after a few decades by expansion of conifer plantations also caused the long term changes of forest age structure (Ciais et al., 2008). Estimations of carbon balance of European forests are influenced by the higher sequestration of intermediate-aged stands than stands reaching the climax state (Kohlmaier et al., 1995; Pregitzer and Euskirchen, 2004). Forest carbon sequestration was higher when estimated by the model including management regime (Ciais et al., 2008), and carbon sequestration increases if the management allows higher tree stocking than usual (Garcia-Gonzalo et al., 2007). The EFISCEN and TEMs NPP differences could result from higher NPP values of intermediate-aged fast growing forests as a consequence of afforestation programmes and management history.

The ±25% change in wood removals of current harvesting did not affect the age structure on the short term on the larger scale. The only one time removals change in year 2000 expands/reduces mostly the less productive forest area of the oldest age classes in 2005 than more productive younger forests. Only 5 years difference is too short to quantify the removals change effect on NPP, because it does not allow enough time to propagate the changed contribution of expanding/reducing area of more productive younger age classes to regional NPP. Therefore, NPP showed little sensitivity to current ±25% change in removals on EFISCEN NPP values. The largest NPP differences between EFISCEN and TEMs corresponded to countries with abundant spruce forests and with currently highest removals: Switzerland, Austria, Czech Republic and Germany, but for the other European countries the relation between NPP differences and current removals was weak. The ±25% change in removals strongly affected the NEP values through the change of litterfall and heterotrophic respiration, and also strongly affected NBP. Regarding the uncertainties in wood statistics, the sensitivity by ±25% change in removals implies that the true levels of NEP and NBP may fall within simulated range. Changing the wood demand drives the forest management, tree harvesting, development of carbon fluxes and may increase European tree carbon stock by 33–114% between 2000 and 2100 (Eggers et al., 2008). EFISCEN results suggest that a 25% increase of removals would force NBP to become zero or negative in Estonia and Latvia (currently removing wood close to the maximum limit of NEP). On the other hand, present removals could increase in the alpine forests (Austria, Switzerland, and Italy) and in the Atlantic zone without compromising the mitigation potential of forest carbon sinks.

In EFISCEN, the historic management is represented in the initial distribution of wood volume over forest survey based age structure with specific growth functions. Wood volumes in each age class are also affected by the current management represented by wood removals during thinnings and final fellings (Schelhaas et al., 2007). In BIOME-BGC, the forest management was not included in our study, but it was included and tested for single forest stands on the smaller scale (Cienciala and Tatarinov, 2006; Petritsch et al., 2007) and larger scale Churkina et al. (2007). There was no forest management module in the current version of ORCHIDEE and JULES (the Ecosystem Demography model, Moorcroft et al., 2001, version of JULES was not available). Although we are aware that the historic and current management effects the soil carbon storage and aboveground biomass (Pietsch et al., 2003; Petritsch et al., 2007; Ciais et al., 2008) our objective was showing precisely a comparison between "state of art models" on the continental and regional scales. In particular, to investigate how models that simulate a steady state, natural forest differ from EFISCEN values based on observation that implicitly include land use. If spatially explicit information describing forest management types and age structure becomes available, the methodology developed in ongoing studies with forest management could be incorporated into large-scale model simulations.

4.2. Reliability of NPP estimates

NPP estimates of JULES adopting modelling protocol of Churkina et al. (2008) were lower compared to BIOME-BGC and ORCHIDEE adopting modelling protocol of Vetter et al. (2008) and were rather the results of the model than the results of using two modelling protocols. The statement is supported by a lower European gross primary production of JULES evergreen neadleleaf forest compared to BIOME-BGC and ORCHIDEE also found in Vetter et al. (2008), where all models used the same modelling protocol.

While TEMs NPP were generally lower than EFISCEN NPP, TEMs lower values in Europe seem to be reasonable when considering the range of presumably more productive tropical forests. For example, the net primary production for Maui tropical forest

moisture gradient sites in Hawaii ranged from 388 gC/m^2/year for wettest (5050 mm) to 956 gC/m^2/year for the driest (2200 mm) site (Schuur, 2005). However, EFISCEN NPP values were comparable with an estimated average NPP for German Thuringian coniferous forest 730 gC/m^2/year (Vetter et al., 2005), and high average NPP value 910 gC/m^2/year for German Bavaria spruce forests (with maximum 1340 gC/m^2/year for age class 40) reported by Mund et al. (2002). The realistic magnitude of both TEMs NPP and EFISCEN NPP values was also supported by the set of European forests NPP derived from FLUXNET Web page for data exchange (Luyssaert et al., 2007, 2009). A strong disagreement between the models NPP and FLUXNET NPP was for just five FLUXNET sites in Mediterranean zone, caused by exceptional management of three highly productive Poplar plantations (well watered and enriched in CO_2) (Gielen et al., 2005).

The agreement between modelling NPP estimates was good for total forests, however the estimates deviated more strongly for coniferous and for broadleaved forests. Although not statistically significant and unlike EFISCEN, TEMs NPP were higher for broadleaved forests versus conifers. The differences were caused by the set of ecophysiological parameters in TEMs deriving the growth, the balance between photosynthesis, allocation and turnover of wood. Higher NPP of broadleaves was a result of the choice of model parameters being more suited to the European climate data used here.

4.3. Strengths and limitations of the models

BIOME-BGC, ORCHIDEE and JULES all capture the effects of changes in climate and rising atmospheric CO_2 concentrations on forest productivity. The uncertainties in simulated European/country NPP are related to input data quality (e.g. climate variables, land cover classification) and resolution (e.g. small countries and countries with fragmented forest cover have larger uncertainty) and uncertainty in the processes and parameter values used to simulate carbon fluxes (Jung et al., 2007a,b). BIOME-BGC NPP values are also sensitive to the nitrogen cycle.

JULES forest NPP is strongly coupled to the surface energy balance. This is strength of JULES since it allows land surface processes to be studied more completely, and facilitates comparison with FLUXNET sites; however it increases the complexity of environmental forcing data required to 30 min resolution and 9 different fields of environmental data, which is more than the other TEMs require. JULES is particularly sensitive to the quality of forcing data and it is thought that this led to the relatively lower NPP values. None of the TEMs accounted for effects of forest management on NPP.

In EFISCEN, forest management regimes were based on a country level compilation of management guidelines (Yrjölä, 2002). The model strengths are that it explicitly accounts for the structure of the forests and also management effects. The model limitations are that environmental and climate changes (e.g. increasing occurrences of droughts, heat waves, large-scale disturbances) are not included in the model directly. Disturbances can have a strong effect on NPP, e.g. wind in Sweden in 2005 (Lindroth et al., 2009), drought in 2003 (Ciais et al., 2005). Disturbances like storms and fires are not included directly in EFISCEN except if appearing in removals.

EFISCEN depends strongly on the quality of wood statistics. Wood removals from FAOSTAT are available only at the national level; therefore regional estimates by EFISCEN can be less accurate (Thürig and Schelhaas, 2006) although we tried to capture regional differences in management intensity by regionalising harvest volumes based on national reports. The reported wood removals may be largely different from total removals, due to unregistered harvesting activities (Mantau et al., 2008). In European countries it is a common practice to remove stem tops and large branches as fuelwood, and the trend in utilising wood chips from harvest residues is increasing (Hetsch, 2008).

The biomass expansion factors (BEFs) used to convert stem wood volume into whole-tree biomass strongly affects the EFISCEN estimations of NPP, NEP and NBP. BEFs show large variation depending on the site conditions, regeneration history and silvicultural practices, tree age and growing stock. Though, the average BEFs values are used for the countries where the measurements of the all biomass compartments are not available. For example, there are no country-specific BEFs for the Baltic countries and therefore we had to use BEFs either from Finland or Germany. However, the BEFs for Finland have lower stem shares than for same species in Germany (Lehtonen et al., 2004; Vilén et al., 2005), and transferring BEFs can have strong implications (Teobaldelli et al., 2009) adding to the uncertainty in the EFISCEN results (Eggers et al., 2008).

5. Conclusions

In this study we compared 2000 and 2005 NPP estimates at European, country and regional levels of two modelling approaches, terrestrial ecosystem models (TEMs—BIOME-BGC, ORCHIDEE, and JULES) and forest inventory-based model (EFISCEN). The approaches produce similar results at European level and at the national level for total forests. Differences between two modelling approaches increased for European regions and species groups NPP. We found TEMs NPP to be generally lower than EFISCEN NPP. In contrast to EFISCEN, in TEMs European regions showed higher production for broadleaved than for coniferous forests. Regional TEM values of NPP for coniferous forests demonstrated saturation levels between 500 and 700 gC/m^2/year while the maximum EFISCEN NPP reached up to 1500 gC/m^2/year. The regional NPP comparison to NPP of a wide international network of eddy-covariance FLUXNET forest sites showed both TEMs and EFISCEN NPP to be reasonable. The main difference between two methods, EFISCEN and TEMs, was accounting for the effect of forest management on NPP. Forest management was included in EFISCEN and was lacking in TEMs. Based on the literature and the effects of forest managements on NPP we conclude that generally higher EFISCEN NPP estimates resulted from the forest management being included in EFISCEN and not included in TEMs. Particularly, the reason behind the lower TEMs NPP was due to the estimation of NPP for mature steady state forests with lower NPP rather than highly productive intermediate age class forests being more widespread across Europe. The main strength of EFISCEN was the ability to include the effects of current and past management on NPP and to be able to assess the sensitivity of carbon fluxes (NPP, NEP, and NBP) to changes in current wood removals. However, EFISCEN heavily relied on the quality of the forest inventory data updated in one decade steps, with infrequent detection of extreme environmental events and adding uncertainties of applied averages if measurements were not available. The strengths of TEMs were in utilising climate data to directly simulate carbon fluxes on the daily or half hourly time steps, being able to detect extreme environmental events, and accounting for the effects of increased temperature, atmospheric nitrogen deposition and CO_2 fertilization on NPP. However, TEMs did not include the effects of forest management on NPP. The effect of forest management has been previously included in TEMs on the smaller scales and the ongoing studies have including forest management on the larger scales allowing for the further model evaluations in the future. Our study demonstrates how the different modelling methods can be combined to more accurately assess the forest carbon balance, taking into account direct and indirect human effects on the forest carbon balance.

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