Biogeosciences Discuss., 7, 2227–2265, 2010
www.biogeosciences-discuss.net/7/2227/2010/

Biogeosciences Discussions

Interactions between nitrogen deposition, land cover conversion, and climate change determine the contemporary carbon balance of Europe

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Received: 22 February 2010 – Accepted: 3 March 2010 – Published: 29 March 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

European ecosystems are thought to uptake significant amounts of carbon, but neither the rate nor the contributions of the underlying processes are well known. In the second half of the 20th century, carbon dioxide concentrations have risen by more than 100 ppm, atmospheric nitrogen deposition has more than doubled, and European mean temperatures were increasing by 0.02 °C per year. The extents of forest and grasslands have increase with the respective rates of 5800 km^2 yr-1 and 1100 km^2 yr-1 as agricultural land has been abandoned at a rate of 7000 km^2 yr-1. In this study, we analyze the responses of European land ecosystems to the aforementioned environmental changes using results from four process-based ecosystem models: BIOME-BGC, JULES, ORCHIDEE, and O-CN. All four models suggest that European terrestrial ecosystems sequester carbon at a rate of 100 TgC yr-1 (1980–2007 mean) with strong interannual variability (± 85 TgC yr-1) and a substantial inter-model uncertainty (± 45 TgC yr-1). Decadal budgets suggest that there has been a slight increase in terrestrial net carbon storage from 85 TgC yr-1 in 1980–1989 to 114 TgC yr-1 in 2000–2007. The physiological effect of rising CO_2 in combination with nitrogen deposition and forest re-growth have been identified as the important explanatory factors for this net carbon storage. Changes in the growth of woody vegetation are an important contributor to the European carbon sink. Simulated ecosystem responses were more consistent for the two models accounting for terrestrial carbon-nitrogen dynamics than for the two models which only accounted for carbon cycling and the effects of land cover change. Studies of the interactions of carbon-nitrogen dynamics with land use changes are needed to further improve the quantitative understanding of the driving forces of the European land carbon balance.

1 Introduction

The contemporary terrestrial carbon balance is affected by ecosystem responses to climate variations, land management, changes in atmospheric composition such as the deposition of reactive nitrogen or the increase in CO_2 concentrations, as well as the interactive effects of these factors in the past (Schimel et al., 2001). European ecosystems have been reported to be a sink of carbon in the order of 135–205 Tg yr^{-1} (Janssens et al., 2003) and 185–285 Tg yr^{-1} (Schulze et al., 2009), based on the compilation of various streams of observations ranging from eddy-covariance measurements to inventories and site-level modeling. Schulze at al. (2009) and Janssens et al. (2003) discuss possible contributions of different vegetation types to this sink, however, their methodology prevents them from attributing the net carbon balance to ongoing processes in the vegetation types. The possible driving forces of the net carbon uptake in Europe have been discussed in the literature. These include past trends in climate, atmospheric CO_2 and land cover changes (Zaehle et al., 2007), a growing discrepancy between the increase in timber harvests in comparison to increases in forest biomass (Ciais et al., 2008b), deposition of reactive nitrogen (Magnani et al., 2007) and the combined effects of changing environmental conditions and forest re-growth (Churkina et al., 2007; Vetter et al., 2005).

The land carbon balance, Net Ecosystem Exchange (NEE), is defined as the difference between the carbon assimilated by plants through photosynthesis and the carbon emitted through auto- and heterotrophic respiration, as measured in site-level studies. At the landscape level, non-respiratory processes such as disturbance by fire or harvest, as well as export of organic carbon into rivers and seas further modify the NEE and return CO_2 to the atmosphere or alter rates and place of organic carbon decomposition. The resulting Net Biome Productivity (NBP) is the long-term carbon gain or loss of terrestrial biomass and soil pools, describes the net storage of carbon in terrestrial ecosystems, and indicates whether or not a particular region play a role in reducing or increasing atmospheric CO_2 levels. Process-based models allow integrating the understanding of individual driving forces of the terrestrial carbon balance in different land cover types into a comprehensive framework.

Here we provide a comprehensive assessment of the contemporary terrestrial carbon balance of Europe and its most important driving forces. We analyze the relative roles of rising atmospheric CO_2, increasing deposition of nitrogen, changes in climate, and land cover conversion in increasing land carbon uptake in Europe between 1950 and 2007. We estimate the evolution of European carbon balance over the 20th century with three ecosystem models BIOME-BGC, JULES, and ORCHIDEE driven with a consistent set of model drivers to allow for a meaningful comparison across the models. To corroborate the findings of the only carbon-nitrogen cycle model originally in the study (BIOME-BGC), we present also results from a fourth ecosystem model (O-CN), which extends the ORCHIDEE model inter alia by a representation of nitrogen dynamics. We then assess the degree of agreement between the estimates from process-based models with independent, data-driven estimates obtained from recent bottom-up compilation of field studies and from top-down inverse calculations by atmospheric transport models relying on atmospheric measurements of CO_2 concentrations.

2 Materials and methods

2.1 Models' description

In this study, we use four process-based terrestrial ecosystem models: BIOME-BGC, JULES, ORCHIDEE, as well as its nitrogen cycle version O-CN to simulate carbon fluxes. All models simulate gross primary productivity and respiration independently. The models differe by the number of simulated ecosystem types as well as by implementation of land use conversion algorithm. BIOME-BGC and O-CN simulate nitrogen cycle and carbon-nitrogen interactions explicitly, but do not model effects of land cover conversion. JULES and ORCHIDEE simulate effects of land cover conversion, but not nitrogen cycle. All models estimate NEE as a difference between gross photosynthetic

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uptake and ecosystem respiration. ORCHIDEE and JULES estimate also NBP as a difference between NEE and harvest. Descriptions of photosynthesis, respiration and the terrestrial water cycle in the models are summarized in (Vetter et al., 2008). Below we give only a general overview of the models' concepts.

BIOME-BGC: BIOME-BGC is a process model describing the carbon, nitrogen, and water cycles within terrestrial ecosystems (Running and Gower, 1991; Thornton, 1998). It has been corroborated for a number of hydrological and carbon cycle components (Churkina et al., 2003; Thornton et al., 2002; Vetter et al., 2005). In this study BIOME-BGC was parameterized for seven vegetation types including evergreen needleleaf, evergreen broadleaf, deciduous needleleaf, deciduous broadleaf, shrubs, as well as grass with C3 and C4 type photosynthesis. Ecophysiological parameters were estimated using eddy covariance measurements for evergreen needleaf and broadleaf deciduous forests (Trusilova et al., 2009) and for C3 grasslands, (Tomelleri, 2007). General parameters were used for other vegetation types (White et al., 2000). Croplands were simulated as C3 grasslands which productivity is unlimited by nitrogen availability. Forest management was not included in these simulations.

Joint UK Land Environment Simulator (JULES): JULES is a land-surface model based on the MOSES2 land surface scheme (Essery et al., 2003) used in the Hadley Centre climate model HadGEM (Johns et al., 2006), also incorporating the TRIFFID DGVM (Cox, 2001; Cox et al., 2000). The model simulates carbon, water and energy fluxes of five plant functional types: broadleaf and needleleaf forests, C3 and C4 grasses, and shrubs. In this study conversion of vegetation types within each grid cell was modeled internally based on Lotka-Volterra competition equations driven by predicted rates of photosynthesis. A basic dominance hierarchy is assumed: trees replace shrubs and grasses, shrubs replace grasses, croplands displace all natural vegetation.

When shrubs and trees are displaced by land use expansion, the removed carbon is either passed to the wood product pool or added to the soil carbon pool following the rules from Table 1. Forest was considered harvested only if its fractional coverage within grid cell decreased due to the expansion of land use. To represent crops, the carbon fluxes of grasses were modified in regions dominated by croplands. A fraction of NPP from grass-crops was diverted from the natural vegetation carbon pools into an external crop harvest pool, which was considered separate to the wood products pool from forest clearance. The default methodology in JULES is to assume no lateral transport of carbon between grid cells, that carbon from crop harvest is respired back to the atmosphere in one year, and that carbon from wood product pool is respired back to the atmosphere on timescales of one, ten, and 50 years.

ORCHIDEE: The ORCHIDEE biosphere model describes the carbon, energy and water fluxes (Krinner et al., 2005; Viovy) at a half hourly time-step. Input daily climate data are converted to half hourly data using a weather generator. ORCHIDEE differentiates between 12 different plant functional types, including temperate broadleaved evergreen, temperate and boreal needleleaved evergreen as well as broad leaved deciduous and boreal needleleaved deciduous trees. Herbaceous PFTs are represented either as natural C3 and C4 grasslands, or as managed C3 and C4 croplands. An improved cropland phenology was applied that mimics the phenology of winter wheat for C3-crops with an early leaf onset day and a short growing season, and of maize for C4 crops with a late onset day of leaves, based on meteorological parameters. ORCHIDEE does not take into account management parameters.

After land cover conversion or harvest, carbon was distributed between different pools following the rules from Table 1. Forest was harvested only if its fraction within grid cell decreased. Harvested biomass of forests decomposed with one year, ten, or 100 years. Different decomposition times of harvested biomass reflect life time of forest products. A fraction of crop biomass was removed to simulate harvest. Thereafter it was decomposed within one year, which was the year of harvest. Biomass removed with harvest of forest or crops stayed in the same grid cell where it was harvested.

O-CN: ORCHIDEE has been advanced by adding a comprehensive nitrogen cycle representation as well as revising the representation of vegetation structure and growth (Zaehle and Friend, 2010; Zaehle et al., 2010). Simulations of this new model only became available after the main study had been conducted, and were performed with a slightly different set of drivers and at a much coarser spatial resolution (see below). To corroborate the findings of the only carbon-nitrogen cycle model used in the study (BIOME-BGC) we present also results from O-CN model runs.

2.2 Models' environmental drivers

As input drivers ecosystem models required climate variables, elevation above the sea level, soil texture, soil depth, fractional land use maps, and nitrogen deposition (models including nitrogen deposition only). All models except O-CN used the same maps of elevation above the sea level, soil texture, soil-depth, atmospheric CO_2 concentrations, and climate drivers. The elevation above sea level, soil texture, and soil-depth data are described in (Vetter et al., 2008). The atmospheric CO_2 concentrations were based on the ice core data from (Etheridge et al., 1996) and atmospheric measurements from Mauna Loa (Keeling and Whorf, 2005). The CO_2 concentrations data covered the time from 1700 until the end of 2007. Climate variables were from the modified Climate Research Unit (MCRU) dataset, which is based on combination of data from Climate Research Unit (CRU), Norwich, UK database and results from ECHAM5 and REMO climate model simulations, (Chen et al., 2009). MCRU data set provides daily climate variables. It covers time period from 1861 until 2007.

Fractional land use maps for 1700–2000 at 0.25° for Europe were available for this study. These maps are a combination of historical croplands/pastures maps with a vegetation classification map adjusted for carbon cycle modeling (SYNMAP, Jung et al., 2006). Historical cropland/pasture maps were derived using hindcasting techniques similar to those of Ramankutty and Foley (1999), by combining historical agricultural census data at the national and subnational levels with remote-sensing cropland/pasture maps for year 2000 from Ramankutty et al. (2008). In this version, a much richer historical census database was used for most of Europe. National-level data from 1961–2000 were obtained for all 36 nations from Food and Agriculture Organization (http://faostat.fao.org). Further, we compiled subnational statistics for 248 administrative units from various sources. Data for 19 countries, with the earliest data available for 1974 in the best case, were obtained from EUROSTAT database (http://epp.eurostat.ec.europa.eu) at the second administrative level of Nomenclature of Territorial Units for Statistics (NUTS2). Data from various other individual national reports (Economic Research Service, 1975; Committee for the World Atlas of Agriculture, 1969; EUROSTAT, 1993; Norwegian Census of Agriculture, 1991; Bouzaher et al., 1994; Organization for Economic Cooperation and Development, 1996) were used to fill some of the gaps in this database. Extrapolation from the earliest available data was used to fill other gaps, which occurred mainly during the 1950–1961 period. Annual maps of land cover were produced by superimposing the fractions of croplands/pastures with a map of potential vegetation derived from SYNMAP (potential SYNMAP, see the online materials in (Churkina et al., 2009)).

Because of grid cell-wise inconsistencies between the crop and pasture area of historical maps and the crop area of SYNMAP, adjustments of the fractions of the natural vegetation types from SYNMAP are necessary. By using a map of reconstructed natural vegetation compatible with SYNMAP or potential SYNMAP, it is possible to account for preferential conversion of natural vegetation types into crops or pastures within each grid cell. The fraction of a natural vegetation type (F) is calculated as:

$$F = F_{pot} - x * (F_{pot} - F_{act}) \tag{1}$$

The subscripts "pot" and "act" refer to the fractions of the vegetation type for potential and actual SYNMAPs respectively. The factor x scales the difference between the fractions of potential and actual vegetation types. It is calculated as the ratio between the crop ($CROP_{rec}$) and pasture ($PASTURE_{rec}$) fractions of historical maps and the crop fraction of SYNMAP ($CROP_{SYNMAP}$):

$$x = (CROP_{rec} + PASTURE_{rec})/CROP_{SYNMAP}. \tag{2}$$

Annual estimates of atmospheric nitrogen deposition for 1860–2007 were used to drive simulations of models with nitrogen cycle. These estimates for Europe were extracted from a global dataset at $1^{\circ} \times 1^{\circ}$ spatial resolution for 1860–2030. The global dataset was created using estimates from the three dimensional atmospheric chemical transport model TM3 (Rodhe et al., 2002) for 1860–1980 and the mean of an ensemble of model results (Dentener et al., 2006) for 2000 and 2030. For each grid cell nitrogen deposition was linearly interpolated for 1980–2000 and 2000–2030. The estimates included wet and dry depositions of both NO_y and NH_x. The depositions of reactive nitrogen between 2000 and 2007 were estimated with a "high emission" scenario which corresponds to the IPCC SRES A2 scenario. The original decadal model outputs for 1860–1980 as well as for 2000 and 2030 were transformed into time series of annual atmospheric nitrogen depositions using linear interpolation for each grid cell.

O-CN was driven at a $2^\circ \times 2^\circ$ spatial resolution with the same atmospheric CO_2 and nitrogen deposition data, however, using observations of the monthly meteorology from Climate Research Unit (CRU) directly as input for 1901–2002 (Mitchell et al., 2004). Land cover was assumed to be constant at 1995 levels (Loveland et al., 2000).

2.3 Models' simulations

All models were initialized with the assumptions that the ecosystem carbon stocks and fluxes were in equilibrium in 1700. To achieve this equilibrium, spinup simulations were performed with repeated MCRU climate for 1901–1930 and constant CO_2 concentrations at year 1700 level. In JULES and ORCHIDEE land use maps for 1700 were used in spinup run. In BIOME-BGC and O-CN pre-industrial nitrogen deposition and land-use maps for 2000 and 1995 respectively were employed. Thereafter three transient simulations were performed with different combinations of environmental drivers for 1700–2007 (Table 2). Because MCRU data set covered only time period from 1861 until 2007, repeated climate for 1901–1930 was used for model simulations from 1700 until 1860. After 2000 fractions of cropland/pasture were assumed to be constant at 2000 values. Transient simulations of ORCHIDEE and JULES without land use change were performed with land cover for 1700.

The models with land use change used different algorithms for conversion of land use types. ORCHIDEE prescribed annual conversion of vegetation types from the supplied

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dataset. In JULES, annual conversion of vegetation types within each grid cell was modeled internally as described above and was constrained by prescribed land use distributions.

2.4 Evaluation of changes in environmental drivers and carbon balance estimates

Rates of change for all environmental drivers were calculated for Europe over the first and second half of the 20th century. We divided the 20th century into two periods (before and after 1950) to reflect different trends in the environmental drivers. Fast industrial growth in Europe and also in some other parts of the world was observed after the Second World War which ended in 1945. Countries were rebuilding their industries and population was growing. Emissions of CO_2 and NO_x from energy production were rising fast. To meet the dietary needs of growing population, production of synthetic nitrogen fertilizers started in 1950's after the discovery of Haber-Bosch process in 1930's. Production and application of fertilizers increased amount of available organic nitrogen.

We evaluated responses of land ecosystems to environmental drivers for the second half of 20th century only because we aimed at understanding the roles of different drivers in the European carbon sink. Furthermore, more confidence can be placed into recent trends of land-cover changes because of the much increased level of documentation in land-use statistics.

The marginal effects of individual forcing factors on the terrestrial carbon balance were attributed by comparing the different factorial experiments. For example, the effect of land-cover conversion was inferred by comparing simulations with climate and CO_2 changes to that accounting for these changes in addition to land-cover changes.

3 Results

3.1 Rates of change in major environmental drivers

In the 20th century one can distinguish two periods with different rates of change in major environmental drivers of Europe: the period of slow changes from 1900 to 1950 and the period of fast changes after 1950 (Fig. 1). Between 1900 and 1950, atmospheric CO_2 concentrations, nitrogen deposition, and temperatures increased only moderately. Their rates of change were 0.29 ppm yr-1, 0.03 Tg N yr-1, and 0.01 °C yr-1 respectively. Forest (4.9 million km^2 in 1900) and grassland (0.75 million km^2 in 1900) extents declined with the rates of 6900 km^2 yr-1 (0.14% yr-1) and 3200 km^2 yr-1 (0.67% yr-1) respectively. The area of land in agricultural use such as cropland and pasture (3.8 million km^2 in 1900) increased with the rate of 10 100 km^2 yr-1 (0.27% yr-1). After 1950, atmospheric CO_2 concentrations, nitrogen deposition, and air temperatures increased at rates 2–3 times higher than in the first half of 20th century. Their respective rates were 1.11 ppm yr-1, 0.1 Tg N yr-1, and 0.02°C yr-1 for the period 1950–2000. To the contrary, the rate of land cover conversion slowed down, with the agriculture coverage declining at a rate of 7000 km^2 yr-1 (0.18% yr-1). Forest and grassland areas expanded with the rates of 5800 km^2 yr-1 (0.12% yr-1) and 1100 km^2 yr-1 (0.24% yr-1) respectively.

Overall changes in land cover of Europe (9.32 million km^2) were relatively small over the 20th century. The fraction of European forests shrank by approximately 3% before 1950 and expanded thereafter by the same amount. Proportion of agricultural land increased by 5% in the first half of 20th century and dropped by 4% after 1950. Changes in the fractions of grasslands were in the order of 1–2% over the first and the second halves of the 20th century.

3.2 Carbon balance and its attribution

Until approximately 1960, the average carbon balance of European terrestrial ecosystems estimated by all models was close to zero (Fig. 2). From the 1960–70's onwards,

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European terrestrial ecosystems were dominantly sequestering atmospheric CO_2 at an average rate of 85 TgC yr-1 in 1980's, 108 TgC yr-1in 1990's, and 114 TgC yr-1 in 2000–2007. An average net carbon uptake was 100 TgC yr-1 between 1980 and 2007 (Table 3). These estimates are subject to considerable interannual variability (85 Tg C yr-1; Table 3, Fig. 2), as was also shown earlier (Zaehle et al., 2007; Vetter et al., 2008). The respective rates of changes in atmospheric CO_2 concentrations were 1.38 ppm yr-1 in 1980's, 1.39 ppm yr-1 in 1990's, and 1.71 ppm yr-1 in 2000–2007. The respective rates of changes in nitrogen deposition were 0.06 Tg N yr-1, 0.09 Tg N yr-1, 0.09 Tg N yr-1. Below we analyze the drivers behind land net carbon uptake after 1950 and the pools in which carbon was accumulating.

3.2.1 Effects of environmental drivers

The overall effect of rising carbon dioxide, changing climate, as well as land cover conversion or rising nitrogen on the average net carbon uptake for 1950–2000 was positive in all models, implying a net storage of 25–94 Tg C yr-1. All models indicated that European terrestrial ecosystem sequestered carbon as a result of the interactions between different environmental factors (Fig. 3). In BIOME-BGC and O-CN, which account for carbon-nitrogen dynamics, the European carbon sink was the result of CO_2 fertilization and nitrogen deposition, as well as interactions between them. The CO_2 fertilization effect on ecosystems was the most important factor responsible for the net carbon uptake simulated in models only accounting for the carbon cycle. This CO_2 fertilization effect on plants more than offsets the negative effects of land cover conversion on terrestrial carbon storage as simulated by ORCHIDEE and strengthened the positive effect of land cover conversion in JULES.

Changes in climate (mostly due to rising temperatures) caused a net carbon source in models only accounting for carbon cycling, due to soil carbon losses (see Fig. 4). Climate had hardly any effect on the carbon balance in models accounting for carbon-nitrogen dynamics (Fig. 3), in which soil carbon losses were roughly compensated for by increases in vegetation growth and carbon storage. Models with nitrogen cycle simulated very small average net carbon uptake (3–6 Tg C yr-1), while models without nitrogen cycle dynamics suggest a net carbon source (30–80 TgC yr-1). Increasing CO_2 enhanced net land carbon uptake in all models. The response of land ecosystems to rising CO_2 was considerably larger in models without nitrogen dynamics (110–230 TgC yr-1) than in models with nitrogen dynamics (30–65 TgC yr-1). Land cover conversion had opposite net effects on the carbon balance in ORCHIDEE and JULES. Land cover changes in JULES led to a small net carbon uptake in land ecosystems (15 TgC yr-1). In ORCHIDEE land ecosystems responded with the substantial net release of carbon (115 TgC yr-1). Nitrogen deposition enhanced ecosystem net carbon uptake between 30 and 37 TgC yr-1.

3.2.2 Changes in carbon pools

In land ecosystems, carbon can accumulate in soil or in vegetation or in both. Our study points to changes in the growth of woody vegetation as a possible important contributor to the European carbon sink (Fig. 4). Three out of four models reported that vegetation accumulated most of the additional carbon. Model simulations of BIOME-BGC, ORCHIDEE, and O-CN indicated that carbon was accumulated in both vegetation and soil. Vegetation was a stronger sink (20, 60, 60 TgC yr-1 in ORCHIDEE, BIOME-BGC, O-CN respectively) than soil (10, 5, 25 TgC yr-1 in ORCHIDEE, BIOME-BGC, O-CN respectively) in all three models. JULES simulations indicated that soil stored all additional carbon (100 TgC yr-1), while vegetation was a small carbon source (4 TgC yr-1).

The differences in ecosystem pools accumulating carbon stem from differences in ecosystem responses to individual environmental drivers. In the model simulations with changing climate only, soil carbon pool was substantially affected in all models (Fig. 4). In JULES and ORCHIDEE rising temperatures led to soil carbon releases that averaged at 37 and 65 TgC yr-1 respectively over the period 1951–2000. Soil carbon loss was not compensated for by small vegetation carbon gain in JULES (7 TgC yr-1), and enhanced by vegetation carbon losses in ORCHIDEE. BIOME-BGC and O-CN accounted for the feedback of increasing temperatures on increased nitrogen mineralization and therefore improved plant nutrition. Therefore these models simulated a stronger vegetation carbon gain (13 and 3 Tg C yr-1 respectively) and weaker soil carbon loss (10 and 5 TgC yr-1 respectively), resulting in approximately zero carbon balance.

All models agreed that rising atmospheric CO_2 concentrations lead to carbon accumulation in both soil and vegetation. In JULES and ORHIDEE more carbon was accumulated in vegetation (44 and 107 TgC yr-1 respectively) than in soil (65 and 120 TgC yr-1 respectively). Conversely, BIOME-BGC and O-CN simulated higher increase in carbon storage in vegetation (21 and 40 TgC yr-1 respectively) than in the soil (8 TgC yr-1). These differences are related to various simulations of tree mortality and soil carbon turnover rates in the models.

In the simulations with land cover conversion, both JULES and ORCHIDEE simulated a comparable rate of carbon loss due to the removal of vegetation (55 and 70 TgC yr-1, respectively). The models disagreed strongly on the fate of carbon in the soil pool. While JULES simulated substantial soil carbon gains (70 TgC yr-1), which more than offset the rate of carbon lost by vegetation removal, ORCHIDEE simulated net soil carbon losses (45 Tg C yr-1).

4 Spatial patterns of NEE and NBP (1951–2000)

The models generate substantially different patterns of net carbon sources and sinks when averaged over 50 years (Fig. 5). BIOME-BGC shows rather homogeneous carbon sink over Europe with several patches of carbon sink where high nitrogen deposition rates overlap with forests. JULES and ORCHIDEE have very heterogeneous distribution of carbon sources and sinks as a consequence of the land cover conversions assessed and harvest decomposition in these model simulations. If we do not account for the effect of land-cover conversions in these models, the NEE patterns are rather homogeneous in both models and similar to the estimates of BIOME-BGC (supplement, Fig. 1, http://www.biogeosciences-discuss.net/7/2227/

2010/bgd-7-2227-2010-supplement.pdf), even though absolute NEE values in these models are substantially higher than in BIOME-BGC.

The aforementioned uncertainties in the simulation of harvest as well as in where and how fast carbon from harvested biomass is released back to the atmosphere, cause different patterns of NBP (Fig. 6). ORCHIDEE simulates a large carbon source in Eastern Europe, which patterns seem to coincide with areas of continuing agricultural areas expansion.

5 Discussion

5.1 Carbon balance of European ecosystems

Previous observation-based (Schulze et al., 2009; Janssens et al., 2003) and modeling studies (Vetter et al., 2008; Zaehle et al., 2007) suggest a substantial net carbon uptake in European terrestrial ecosystems over the last decades. The ensemble average estimate of net carbon uptake from this study (100 Tg C yr-1 for 1980–2007) is slightly lower, but of comparable magnitude to those based on extrapolated field studies and previous model estimates (Table 3). The most recent bottom-up estimate of the European net carbon uptake of 235± 50 Tg C yr-1 (Schulze et al., 2009) This estimate is higher than previous one of 111 ± 280 TgC yr-1 (Janssens et al., 2003) because of higher carbon uptake estimated for forests and grasslands as well as almost negligible carbon source for croplands (33 TgC yr-1). Croplands emitted 300 TgC yr-1 in the previous report (Janssens et al., 2003).

Estimates of the European carbon balance based on the inversion of atmospheric CO_2 measurements by atmospheric transport modeling give a wider range of the terrestrial net carbon storage rate. The most recently published estimate of land-atmosphere flux from atmospheric inversions averages at −313 ± 342 TgC yr-1 (Schulze et al., 2009), with the uncertainty estimate being the quadratic sum of the spread between individual inversions and the uncertainties in each inverse estimate.

The earlier estimates by Janssens et al. (2003) are at a comparable level, suggesting a net carbon uptake of 290 TgC yr-1 (80–560 TgC yr-1). While there is thus a substantial difference of 213 TgC yr-1 between the atmospheric and simulation based mean estimates of net carbon uptake for 2000–2007, the model based estimate easily falls into the range of the atmospheric inversions.

Based on the results of seven vegetation models Vetter et al. (2008) calculated the net carbon balance of European ecosystems between 70 and 230 TgC yr-1. This carbon balance was calculated as a mean of annual NEP for 1980–2005 from model simulations driven by REMO climate data and did not include effects of land cover conversion, but nitrogen deposition in BIOME-BGC model. Zaehle et al. (2007) used one vegetation model LPJ to estimate the effect of land-cover changes, climate, and CO_2 on the Western European terrestrial carbon balance. The resulted net carbon uptake of 30 Tg C yr-1 is compatible with our estimates given the substantially smaller spatial domain.

5.2 Attribution

What are the processes driving the European land net carbon uptake? Previous observation-based studies analyzed contributions of land cover types or forest processes to this sink. Schulze at al. (2009) and Janssens et al. (2003) consistently suggest that there is a net carbon uptake in the European ecosystems mostly because of carbon gains in forests and grassland soils, which are partly offset by losses of carbon from croplands and peat soils. Schulze at al. (2009) also quantify land use change as an additional carbon sink (discussed below).

As we have discussed the effect of climate and climate variability in a previous paper (Vetter et al., 2008), here we focus our discussion on the effects of the other transient changes in driving forces of the terrestrial carbon balance. Responses of the European carbon balance to changes in single drivers differed between models with and without nitrogen cycle. Simulated ecosystem responses were more consistent for the two models accounting for terrestrial nitrogen dynamics than for the two models accounting for carbon cycling and the effects of land use change. The latter is because the carbon – nitrogen interactions are easier to upscale to a larger scale than the carbon- land-use change interactions.

5.2.1 Atmospheric CO_2 concentrations

Because very few studies (Hamilton et al., 2002) have attempted to quantify the effect of elevated CO_2 on NEE, we focus the discussion on the response of NPP, which is the primary cause for changes of the modeled net carbon uptake in response to increase in atmospheric CO_2. This comparison is challenging because experimental designs of field and model experiments are not the same. In the model experiment terrestrial ecosystems have been exposed to continuously rising CO_2 over 200 years. Field experiments impose a 6–10 years "step" increase of CO_2 to at least 200 ppm above recent ambient levels of atmospheric CO_2. The modeled response of European NPP to 100 ppm increase in atmospheric CO_2 concentrations (from 287 ppm in 1870 to 387 ppm in 2007) was 10% (BIOME-BGC), 20% (O-CN and JULES), and 36% (ORCHIDEE). Above-ground dry matter production increased 20% on average for 29 C3 species grown in six different Free Air CO_2 Enrichment (FACE) experiments (Ainsworth and Long, 2005). The response of the above-ground dry matter production reported in field studies ranges from 10% for C3 grasses to 28% for forests to 190-200 ppm increase of CO_2 (from ambient CO_2 concentration in 1990's of 360 ppm to maximum 550–600 ppm of CO_2). Trees grown under nutrient limitations had an insignificant 14% stimulation in above-ground biomass accumulation (Ainsworth and Long, 2005). Field studies suggest that plant growth response to elevated CO_2 likely slows over time, probably because of reduced nitrogen availability (Hungate et al., 2006). The latter effect explains weaker response to increasing CO_2 in BIOME-BGC or O-CN than in ORCHIDEE or JULES.

5.2.2 Atmospheric nitrogen deposition

Soil nitrogen status, frequency and intensity of nitrogen additions play important roles in the ecosystem's response to increased deposition of atmospheric nitrogen. In field experiments 1–1000 kgN/ha/yr is added one-two times per year. These frequencies and magnitudes of nitrogen addition cannot be directly compared to the gradual increase in nitrogen deposition from atmosphere (2–28 kgN/ha/yr) in "undisturbed" ecosystem such as those represented in our numerical simulations. Between 1860 and 2007 the modeled European NPP increased on average by 7.5% in BIOME-BGC and by 16% in O-CN in response to the rise in average nitrogen deposition rate of 5 kgN/ha yr-1. This response seems plausible given the evidence from field studies. Observational studies suggest that aboveground NPP increased by approximately 28–29% in the cross-biome analyses of terrestrial plants (LeBauer and Treseder, 2008; Elser et al., 2007) in fertilizer experiments. Taking into account uncertainties about the response of belowground NPP which might compensate for the increase in aboveground growth, this estimate gives the upper bound of the likely response of total net primary production as simulated by the models. The average biomass response to low nitrogen additions of approximately 10–50 kgN/ha/yr was considerably weaker for woody than for herbaceous plants or 24.6% and 50% respectively (Xia and Wan, 2008). In opposite, modeled NPP response of herbaceous plants (6%) to nitrogen additions was weaker than for deciduous forests (10%), but stronger than for coniferous forests (3%) in the BIOME-BGC model. Differences in forest responses can be explained by different average rates of nitrogen deposition over coniferous and broadleaf forests (4 and 11 kgN/ha/yr respectively). Modeled NPP response of herbaceous vegetation is underestimated, because average nitrogen depositions over herbaceous vegetation and deciduous forest were comparable (6–10 kgC/ha/yr and 11 kgC/ha/yr). This underestimation is most likely responsible for lower European NPP response to rising nitrogen deposition in BIOME-BGC model as compared to O-CN.

A number of recent studies (Magnani et al., 2007; Sutton et al., 2008; de Vries et al., 2009) analyzed the response of net carbon storage in forest ecosystems to nitrogen deposition using manipulation experiments and other streams of data. The most recent study (de Vries et al., 2009) reports the response of 5–75 kgC/kgN for both forests and heathlands after discounting for potential interaction effects due to concommittant changes in other environmental factors. The mean responses of BIOME-BGC (43 kgC/kg N) and O-CN (38 kgC/kg N) fall well into this range.

5.2.3 Land cover conversion

The estimates of changes in the net land-atmosphere carbon flux associated with land cover conversion and management depend on the accuracy of the estimates of past land-use changes and on the ecosystem response to the change in land use type. Consistent data of historical land use changes are very sparse at a continental scale, so that substantial uncertainty is inherent in any backward projection of land-use patterns (Ramankutty and Foley, 1999; Hurtt et al., 2006). These data typically only record net changes in a land-cover type within a region. They do not specify co-occurring de- and reforestation of this region. Because these two parallel processes determine the net carbon flux due to land-use changes, our model results provide a low bound of the effect of land-use changes on the carbon balance.

In 1950–2000 conversions of croplands into forests and grasslands prevailed in Europe (Fig. 1). Schulze et al. (2009) estimated a net sink of 60 Tg C yr-1 associated with soil carbon gain and loss following land use change in Europe. Based on meta-analysis of experimental studies Guo and Gifford (2002) suggested increase in soil carbon after changes from crop to pasture or to forest plantation (+18–19%) and from crop to forest (+54%). The change in soil carbon stock as a result of land cover conversion depends on the sizes of the soil carbon pools of the land cover types at equilibrium. Cropland soils have lower carbon stocks than grasslands, whereas forest and grassland soils have similar pool sizes (Guo and Gifford, 2002). Although JULES and ORCHIDEE models are able to simulate such differences, models had substantially different responses to land cover conversion (Fig. 3). JULES simulated a small net carbon uptake in land ecosystems (15 TgCyr-1). In ORCHIDEE ecosystems responded with a substantial net release of carbon (115 TgCyr-1). Using data compilation Schulze et al. (2009) estimated a net sink of 60 Tg C yr-1 associated with soil carbon gain and loss following land use change in Europe. This discrepancy results from uncertainty in the fate of residuals remaining in the ecosystem upon conversion and in the representation of the differences between soil carbon stocks of different land-use types in the model. The amount of carbon which enters the soil carbon pools as residuals increases the potential for longer-term accumulation of soil organic matter with time.

ORCHIDEE suggests that vegetation is the major store of extra carbon, while the results of JULES imply that carbon storage in soils dominates. Model simulations give different answers, because of different model algorithms. In ORCHIDEE, forests regrow on abandoned agricultural areas following the land cover conversion prescribed in this study. Regrowing forests first accumulate carbon in wood, which only later propagates into increases in soil carbon due to the reduced carbon export in forests relative to highly managed cropland ecosystems. Therefore the vegetation pool contributes stronger to the carbon storage in the ORCHIDEE model. In JULES, while net conversion rates were used as required from the modeling protocol, the internal land conversion routine (see Methods section) resulted in a different fate of the land from cropland abandonment. In JULES agricultural contraction after 1950 implies grassland replace cropland. The major difference between these two vegetation types in JULES is that crops are regularly harvested, while grasslands are not. Once grassland replaces cropland all aboveground carbon enters soil pool after litter fall and soil carbon increases in this model, whereas the vegetation carbon pool hardly changes.

5.3 Uncertainties in the modeled carbon balance

The present study quantifying the decadal budget of European terrestrial ecosystems and their driving forces provides the latest of various model assessments in which we addressed various uncertainties in modeled components of carbon balance. We

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have previously assessed ability of the models to replicate the ecosystem responses to regional gradients in climate (Jung et al., 2007a) and large scale climate anomalies (Vetter et al., 2008), identifying biases of individual models and key uncertainties in regional scale carbon balance from input drivers (Jung et al., 2007b). Among input drivers climate data has been identified as the dominant source of uncertainty (Jung et al., 2007b). The ecosystem models systematically underestimated the decrease in gross photosynthetic uptake from temperate to boreal forest sites, (Jung et al., 2007a). This underestimation was attributed to insufficiently accounting for nitrogen limitation that acts mainly on leaf area and thus light absorption. An experiment combining ecosystem models with atmospheric transport models indicated that modeled CO_2 concentrations were biased at the measurements stations, which are located in large agricultural regions of Hungary (Hegyhatsal station) and the Netherlands (Cabaw station) (Ute Karstens, personal communication, 2009). These biases point to difficulties in capturing the heterogeneity of agricultural landscapes and in modeling cropland carbon dynamics influenced by land management.

Change in land management could be the other reason behind carbon balance change, which we did not account for in this study. Discrepancy between timber harvest and forest productivity has been discussed as a possible reason behind carbon accumulation in European ecosystems. Analysis of forest inventories (Nabuurs et al., 2003; Ciais et al., 2008b) points to forests as a potential sink of carbon. They suggest that the slow increase in timber harvests in comparison to the rapid increase in forest ecosystem productivity is the key driving factor behind this trend, causing forest tree biomass in the EU-15 plus Norway and Switzerland to accumulate 2.3 Pg of carbon between 1950 and 2000. NPP of needleaf forests from three ecosystem models used in this study was lower in than from forest inventory based model (Tupek et al., 2010), which included forest age and management effects on NPP. This comparison indicates that forest carbon uptake may have been underestimated in this study. A modeling study analyzing forest inventories, forest use statistics, climatic changes, and CO_2 increases suggests that the effects of changes in forest management, forest area and

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age-structure explain 50% of the increase in forest biomass for EU 25 (Zaehle et al., 2006). Although past land-management changes further affect soil carbon inputs or soil carbon turnover times, their effect are poorly quantified for large regions (Zaehle et al., 2007). Model simulations show that alternative assumptions about crop management and the fate of residues significantly alter the soil carbon stock and trajectories following conversion (Bondeau et al., 2007; Smith et al., 2005, 2006). These factors more than offset temperature-related soil carbon losses from simulated in this study. Because of a lack of data to parameterize land management changes over time, these effects have not been considered in the present study.

The interactions between individual driving forces of carbon balance complicates accurate attribution of the simulated trends to these forces. For instance, compensating effect of increasing nitrogen availability in soil due to enhanced atmospheric nitrogen deposition versus decreased nitrogen availability in soil due to fertilizing effect of CO_2 on plant growth, as discussed by (Churkina et al., 2009) and (Zaehle et al., 2010). Disentangling these effects requires multi-factorial model simulations to identify the (non-linear) in-between factor interactions. For instance by running a simulation with only the factor of interest varying or by calculating the difference between two simulations, one with all factors and a second, in which all but the factor of interests vary with time. Doing so has not been feasible within the present analyses. Hence, our results allow identifying the relative importance of the driving forces, but the absolute values need to be treated with caution. Interaction effects may shift individual contribution up or down by a few percent, depending on the way the individual contribution has been calculated.

We did not investigate uncertainties is related to the lateral carbon fluxes such as soil erosion, relocation of forest and crop harvests, etc. (Ciais et al., 2008a). None of the models here accounted for soil erosion. JULES and ORCHIDEE simulated forest and crop harvest and their decomposition. None of them however simulated harvest relocation.

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6 Conclusions

The model projections consistently suggest that the European ecosystems acted as net carbon storage during the period 1951–2007, averaging 100 Tg C yr-1 in the period 1980–2007, with an intermodal uncertainty of ± 45 Tg C yr-1. The models suggest a slight increase in the decadal mean uptake from 85 Tg C yr-1 in the 1980s to 114 Tg C yr-1 in the 2000's. Increases in atmospheric CO_2 enhanced the carbon uptake across all models. Models accounting for nitrogen dynamics consistently simulated a weaker response to increases in atmospheric CO_2 than models without nitrogen cycle included. The positive response of net carbon uptake to increased atmospheric input of reactive nitrogen only partly compensated the difference in uptake between two model types. In 1951–2007 land cover conversion increased European carbon stock in vegetation. Large uncertainty exists in its impact on soil carbon because of uncertainties in the fate of carbon upon conversion. It is likely that co-occurring changes in management may have affects these trends, potentially even overriding the effect of land cover conversion. Closing this gap requires advancing the existing modeling approaches and collecting and harmonizing the information describing management regimes at the scale of the European continent. Only then it will be possible to determine whether the consequences of management explain the remaining difference between the model based-estimates of our study and observation estimates based on field (235 ± 50 TgC yr-1) and atmospheric observations (313 ± 342 TgC yr-1).

Acknowledgements. This article benefited from the work done under the CARBOEUROPE project (No. GOCE-CT-2003-505572) funded by the European Commission.

The service charges for this open access publication
have been covered by the Max Planck Society.

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Table 1. Fate of biomass after land cover conversion or harvest in simulations of model including effects of land cover conversion on carbon cycle (after Zaehle et al., 2007)

Land use type	Proportion of biomass left on site		Harvested biomass [%]
	Aboveground	Belowground	
Forest	leaves 100 wood 40	100	60 (wood only)
Grassland	leaves 100	100	0
Cropland	10	100	90 (leaves and grain)
Pasture	50	100	50 leaves

Table 2. Protocol of transient models' simulations.

Model Simulation	Climate Change	Change in Atmospheric CO_2 Concentrations	Change in Atmospheric Depositions of NO_y and NH_x^*	Land cover** Conversion
Reference	No	No	No	No
Clim	Yes	No	No	No
Clim+CO_2	Yes	Yes	No	No
Clim+CO_2+LUC	Yes	Yes	No	Yes
Clim+CO_2+N	Yes	Yes	Yes	No

* Only for models including nitrogen cycle.
** Only for models including effects of land cover change.

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Drivers behind the European carbon balance

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Table 3. Mean carbon balance of Europe from different land-based data compilations and model simulations.

	Carbon Sink TgC yr-1	Uncertainty TgC yr-1	Area 10^6 km^2	Time Period
Modeled (this study, Clim+CO2+LUC/N)	100	± 45 inter-model difference ± 85 interannual variability range	9.32	1980–2007
(Schulze et al., 2009)	235	± 50	9.29	2000–2005
(Janssens et al., 2003)	111	± 280	10.4	unspecified
Modeled (Vetter et al., 2008)	157	70–230 (intermodel range)	9.32	1980–2005
Modeled (Zaehle et al. 2007)	30	−45–106 (interannual variability range)	3.7	1990–1999

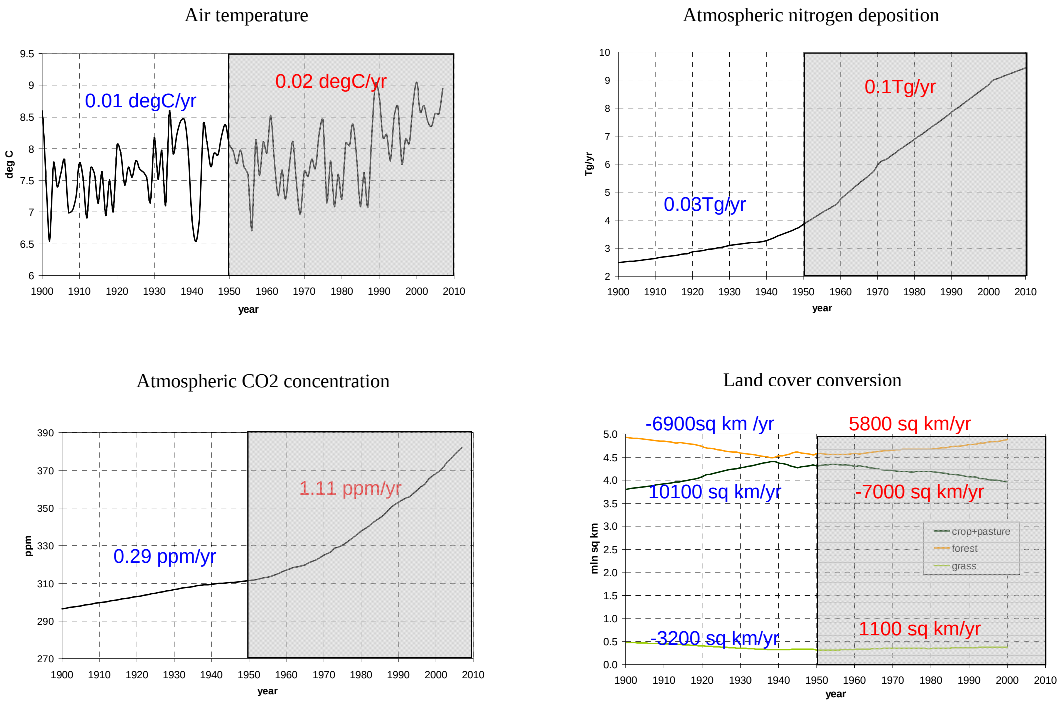

Fig. 1. Changes in major environmental drivers of carbon balance of Europe over 20th century. Annual values of average air temperature, atmospheric nitrogen deposition, and land cover conversion are calculated for the whole study domain. Atmospheric CO_2 concentrations are calculated as global averages.

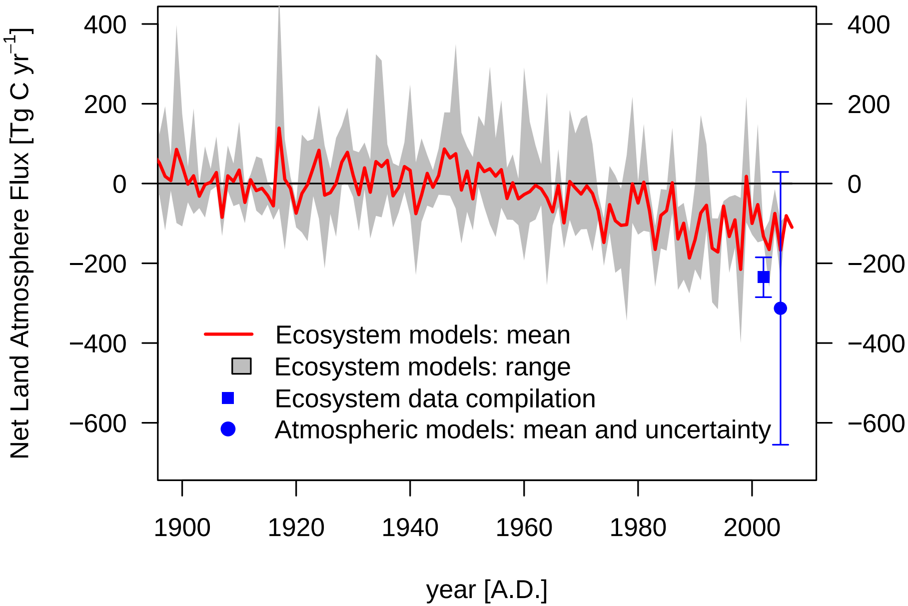

Fig. 2. European carbon balance in 20th century estimated with ecosystem models. Red line is an average value estimated with three ecosystem models (BIOME-BGC, ORCHIDEE, and JULES). The gray shaded area depicts the models' range. Modeled carbon balance at the end of the 20th century is lower than the mean value of carbon balance from the ecosystem model compilation (blue square) or the inverse estimations of atmospheric models (Schulze et al., 2009) reported as an average for 2000–2005.

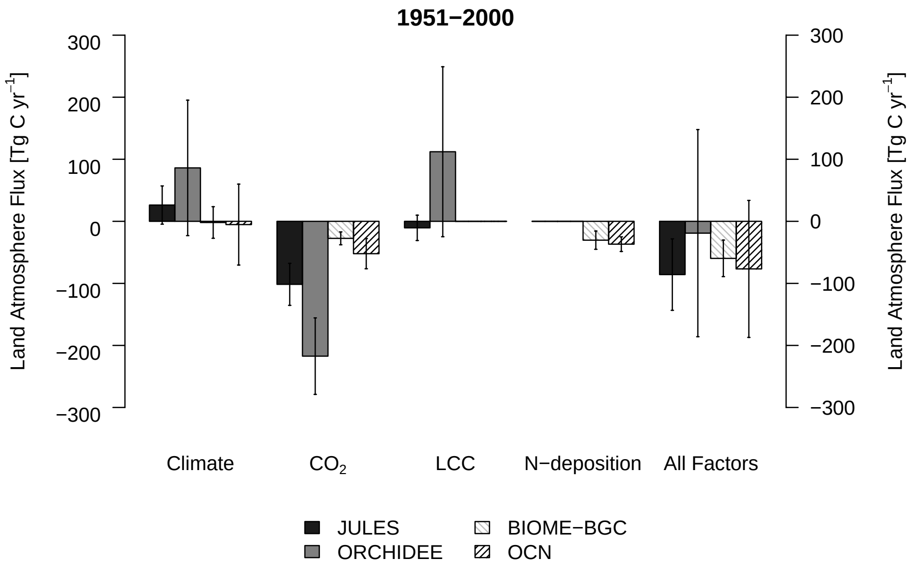

Fig. 3. Changes in European terrestrial carbon stocks over the period 1951–2000 attributed to the major environmental drivers climatic changes, increases in atmospheric CO_2, land-cover changes (LCC), N-deposition, and all factors combined. Land-atmosphere carbon flux was estimated with four ecosystem models such as JULES, ORCHIDEE, BIOME-BGC, and O-CN. Two models including N cycle (solid shaded bars) show better agreement than the models including land cover conversion (bars with diagonal stripes). Each bar depicts the annual change in terrestrial C storage averaged over 1951–2000, with the error bars denoting the standard deviation of the change.

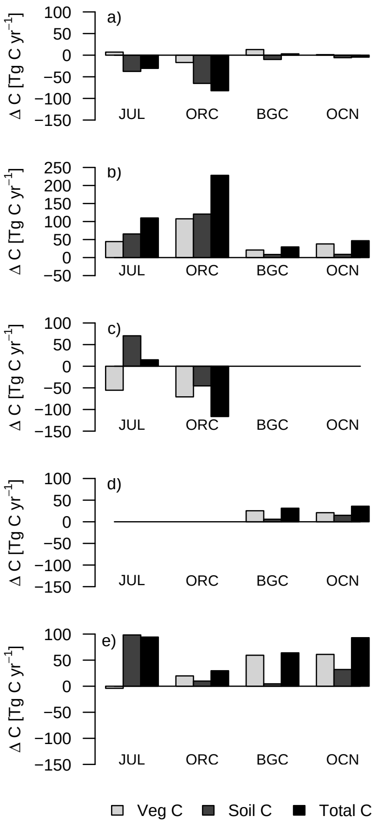

Fig. 4. Changes in soil and vegetation carbon pools in response to climate **(a)**, atmospheric carbon dioxide concentration **(b)**, land cover change **(c)**, atmospheric nitrogen deposition **(d)**, and all factors together **(e)**. Each bar represents annual change in carbon stock averaged over 1951–2000. Carbon stocks are estimated with JULES, ORCHIDEE, BIOME-BGC, and O-CN.

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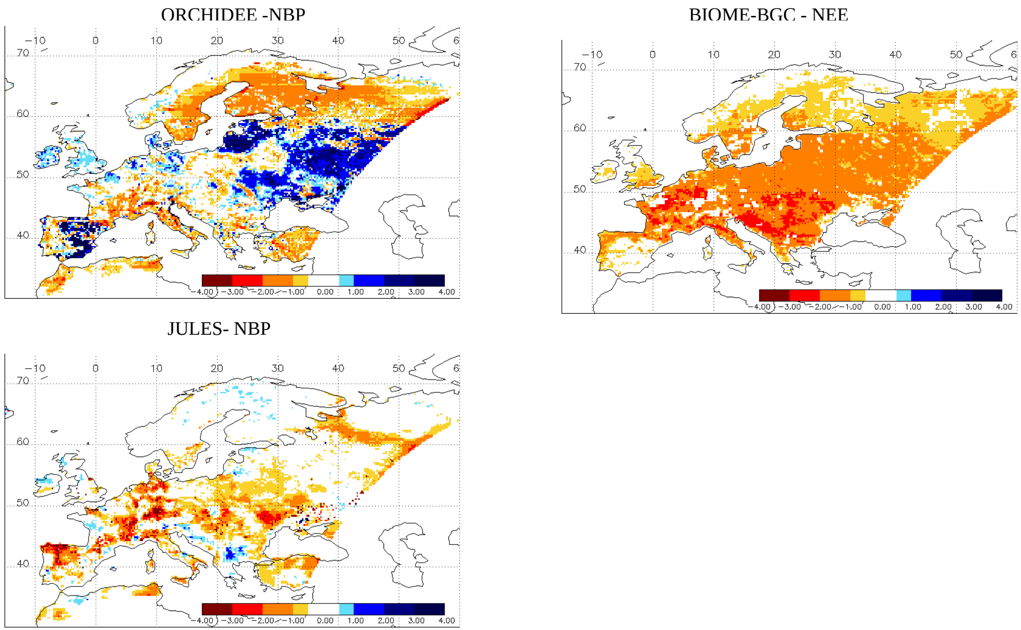

Fig. 5. Cumulative net land-atmosphere fluxes (kgC per 50 years, sum over 1951–2000) estimated with three ecosystem models. NBP for JULES and ORCHIDEE refer to a simulation accounting for climatic changes, increases in atmospheric CO_2 concentrations, and land use changes (Clim+CO_2+LUC). The NEE simulated by BIOME-BGC is driven by climatic changes, increases in CO_2 and atmospheric nitrogen deposition (Clim+CO_2+N). Areas colored in different shades of red and yellow are carbon sink. Areas colored in different shades of blue are carbon source.

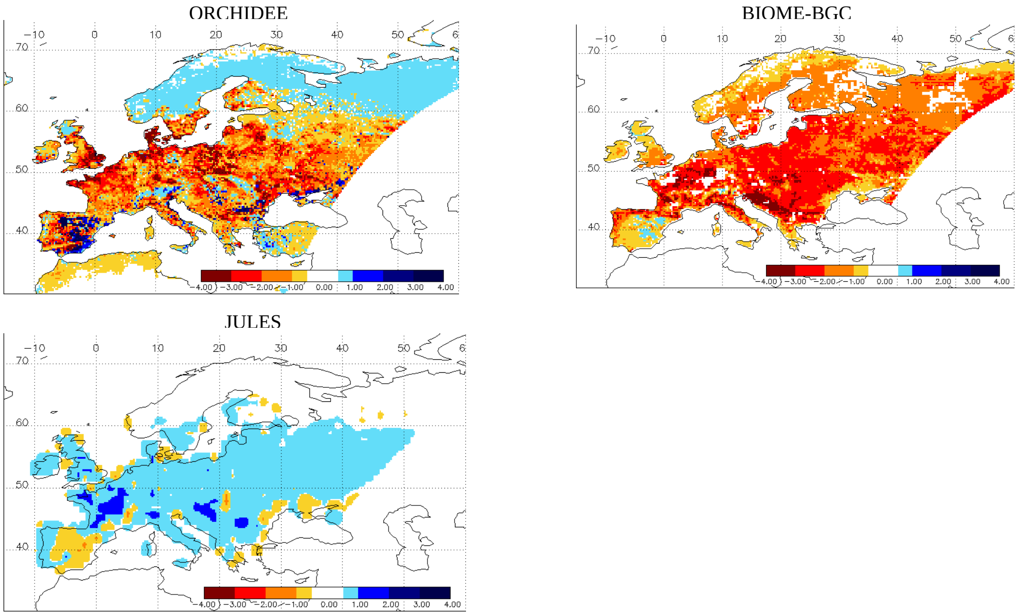

Fig. 6. Cumulative land-atmosphere fluxes (kgC per 50 years, sum over 1951–2000) resulted from land use conversion and rising nitrogen deposition. These fluxes are calculated as difference between NEE from two model experiments Clim+CO_2+LUC and Clim+CO_2 for ORCHIDEE and JULES and as difference between Clim+CO_2+N and Clim+CO_2 for BIOME-BGC. Areas colored in different shades of red are carbon sink; areas colored in different shades of blue are carbon source.

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