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Discussions**

Environmental change impacts on the C- and N-cycle of European forests: a model comparison study

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Abstract

Forests are important components of the greenhouse gas balance of Europe. There is considerable uncertainty about how predicted changes to climate and nitrogen deposition will perturb the carbon and nitrogen cycles of European forests and thereby alter forest growth, carbon sequestration and N_2O emission. The present study aimed to quantify the carbon and nitrogen balance, including the exchange of greenhouse gases, of European forests over the period 2010–2030, with a particular emphasis on the spatial variability of change. The analysis was carried out for two tree species: European beech and Scots pine. For this purpose, four different dynamic models were used: BASFOR, DailyDayCent, INTEGRATOR and Landscape-DNDC. These models span a range from semi-empirical to complex mechanistic. Comparison of these models allowed assessment of the extent to which model predictions depended on differences in model inputs and structure. We found a European average carbon sink of 0.160 ± 0.020 kgC m^{-2} yr^{-1} (pine) and 0.138 ± 0.062 kgC m^{-2} yr^{-1} (beech) and N_2O source of 0.285 ± 0.125 kgN ha^{-1} yr^{-1} (pine) and 0.575 ± 0.105 kgN ha^{-1} yr^{-1} (beech). The European average greenhouse gas potential of the carbon source was 18 (pine) and 8 (beech) times that of the N_2O source. Carbon sequestration was larger in the trees than in the soil. Carbon sequestration and forest growth were largest in central Europe and lowest in northern Sweden and Finland, N. Poland and S. Spain. No single driver was found to dominate change across Europe. Forests were found to be most sensitive to change in environmental drivers where the drivers were limiting growth, where changes were particularly large or where changes acted in concert. The models disagreed as to which environmental changes were most significant for the geographical variation in forest growth and as to which tree species showed the largest rate of carbon sequestration. Pine and beech forests were found to have differing sensitivities to environmental change, in particular the response to changes in nitrogen and precipitation, with beech forest more vulnerable to drought. There was considerable uncertainty about the geographical location of N_2O emissions. Two of the models BASFOR

and LandscapeDNDC had largest emissions in central Europe where nitrogen deposition and soil nitrogen were largest whereas the two other models identified different regions with large N_2O emission. N_2O emissions were found to be larger from beech than pine forests and were found to be particularly sensitive to forest growth.

1 Introduction

1.1 Biogeochemistry of European forests

According to the Millennium Ecosystem Assessment (2005), forests provide four important services: wood production, regulation of the greenhouse gas (GHG) balance, support of water and soil quality and cultural benefits. The recognition of the regulatory role of forests in carbon sequestration and more generally the overall GHG balance has started to shift the focus of forest research from tree growth to the overall biogeochemistry of forest ecosystems, including both biomass and soils (van Oijen et al., 2004).

Forests are thought to currently mitigate about 10 % of European CO_2 emissions (0.11 Pg C yr^{-1}) (Kauppi et al., 1992; Nabuurs et al., 2003). In a recent study of the European (EU-25) carbon balance, Luyssaert et al. (2010) investigated the carbon gained by forests in 1980–2005 through net primary production (NPP) using three approaches, ecosystem modelling, forest inventories and upscaling of ecological data. They found that European forests constitute a net carbon sink of 75 ± 20 g C m^{-2} yr^{-1}. However, the modelling lacked the important influence of management (thinning and harvesting) and only one of the models considered the influence of nitrogen on the carbon sink.

Forests are dynamic systems and their biogeochemistry undergoes continual change. During the second half of the 20th century, forests were observed to grow faster than before in many parts of Europe (Spiecker, 1999), North America (Turner et al., 1995) and Amazonia (Baker et al., 2004). Ciais et al. (2008) investigated forest

inventory data from the EU-15 countries for 1950–2000. They found that in that period carbon biomass stocks had multiplied by 1.75 and that the standing biomass increased linearly with growth (NPP) in both conifers and broadleaved trees so that NPP had also increased by 1.67. Indeed Luyssaert et al. (2010) suggested that forests continue to sequester carbon in spite of intensive harvesting of wood since growth has outpaced losses from harvesting and heterotrophic respiration. This increase in growth has been attributed to a large fraction of young productive trees (Nabuurs et al., 2003), changes in management and increase in forest area (Ciais et al., 2008), increased CO_2 (Friedlingstein et al., 1995) and temperature (Myneni et al., 1997).

The role of N in the carbon cycle whilst sometimes overlooked is also thought to be crucial since it been found to be a limiting factor for growth in many terrestrial ecosystems (LeBauer and Treseder, 2008; Vitousek and Howarth, 1991). Increased available N increases leaf N and photosynthesis with allocation changes so that more investment is made aboveground at the expense of the roots (Magill et al., 2004; Poorter and Nagel, 2000). However if other important nutrients, water and climatic drivers are limiting then the importance of N becomes less significant (Poorter and Nagel, 2000; Wamelink et al., 2009; Luyssaert et al., 2010). Whilst the prominent role of increased N deposition for the increased growth is undisputed (Kahle et al., 2008; De Vries and Posch, 2011; Magnani et al., 2007; Solberg et al., 2009) there is controversy about the strength of the relationship between the C sink and N. Magnani et al. (2007) conducted an analysis of CO_2 fluxes using forest chronosequences. They found the influence of temperature on photosynthesis and respiration cancelled so that the overwhelming driver of C sequestration was N deposition (400–700 kg C kg N^{-1}). Luyssaert et al. (2010) found that not accounting for N deposition in BIOME-BGC led to a more modest $11 \pm 30\%$ lower NPP for EU-25. They also found large regional variation with negligible reductions in northern Europe and the Iberian Peninsula but in central Europe it could be as much as 20 %. Sutton et al. (2008) and others disputed the Magnani et al. (2007) quantification of the relationship between N deposition and the C sink. They suggested that if dry deposition and correlations between N deposition and other

environmental drivers such as temperature were included the influence of N deposition on C sequestration reduced dramatically from those predicted by Magnani et al. (2007). In a review of evidence from inventories, observations and models de Vries et al. (2009) supported an aboveground accumulation of C in forests from N deposition in the range 15–40 kg C kg N^{-1}.

1.2 Predicting future change

Because of the importance of carbon sequestration in forests, and the accumulating evidence for changes in its magnitude, recent work has considered the impact of predicted lower N deposition (Dentener et al., 2006) and climate change on future European forest C sequestration. Accurate prediction of biogeochemical cycles in European forests is a complex challenge because of the many interacting environmental factors, large spatial heterogeneity and the fact that there is still uncertainty about how best to represent the processes and their inter-linkage in models. For example, Luyssaert et al. (2010) found over- and underestimated NPP in northern and southern latitudes which they attributed to errors in the modelled LAI and problems with underestimating photosynthesis in very dry regions. Considering first climatic changes, modest increases in temperature would be expected to increase enzymatic activity increasing photosynthesis although as temperature increases still further activity is suppressed. In the soil, large increases in temperature will increase microorganism activity increasing respiration but this would be counterbalanced by any temperature induced decreases in growth and litter production. Temperature increases could lengthen the growing season in northern latitudes. Increasing temperature will also increase evaporation and water stress on trees (Rebetez and Dobbertin, 2004) and stomatal closing (Zweifel et al., 2007) especially in Mediterranean regions leading to reductions in photosynthesis (Körner, 2003). Increasing atmospheric CO_2 concentration stimulates growth and increases water-use efficiency but trees may acclimate. Whilst N is limiting, N deposition would be expected to increase growth however any consequential N saturation in the soil would diminish its influence (Aber et al., 1998; Brumme and Khanna, 2008).

De Vries and Posch (2011) modelled the combined past and future effects of climate and N deposition on tree sequestration by European forests for 1900–2050. They considered two scenarios: no change and change following the SRES A1 scenario and also included limitation by macronutrients other than N. They took a simple modelling approach calculating a reference growth rate from inventory data and made functional changes to this growth rate to simulate the environmental impact using highly smoothed decadal changes in climate and N deposition. Changes in forest area were not considered and forest management was not included. Their results suggested that past changes were dominated by changes to N deposition whereas future changes were dominated by climate change. If management and changes in daily weather are considered then this introduces other factors which are likely to be important. Luyssaert et al. (2010) have suggested that factors such as the age class of trees, limitation in nutrients, less precipitation in the spring/summer, increased storm damage due to more intense storms and more extreme events in general such as more frequent and intense summer droughts (Luterbacher et al., 2004) are likely to influence future growth. There is therefore still considerable uncertainty about the possible changes in NPP in the next decades as driven by changes in environmental variables. There is also considerable uncertainty in other factors that will influence C sequestration. For example, there is substantial uncertainty about the influence of N deposition on heterotrophic respiration (e.g., Grace, 2004). Also, future harvesting intensity is unlikely to remain static as wood demand is expected to double due to the need for bioenergy (COM, 2008).

1.3 Aims and methods of the present study

It is apparent that there is considerable remaining uncertainty about how carbon sequestration from European forests will change in response to predicted environmental changes. While much uncertainty and controversy remains, previous work has highlighted the crucial interaction of the N and C cycles for European forests. This will be a particular emphasis of this study and where possible changes to the full C- and N-cycles and their interaction will be quantified and considered. We shall include the

impact of management (harvesting and thinning) on forests. This has largely been missing from previous modelling studies of both present (Luyssaert et al., 2010) and future (De Vries and Posch, 2011) studies of carbon sequestration from European forests. Yet Magnani et al. (2007) have suggested that the time since disturbance (harvesting thinning etc.) explains 92 % of the total variability in net ecosystem production (NEP). Thus management will be explicitly included and quantified in this study. Whilst there is much remaining uncertainty in the average European value of the carbon sink, even less is known about the spatial variability of environmental change impacts on European forests. Elucidating regional differences will be an additional emphasis of this study.

The influence of forests in the GHG balance is not restricted to C sequestration. For example, changes in the N cycle due to nitrogen deposition do not only stimulate plant productivity but can also lead to increased losses of nitrogen via leaching (Gundersen et al., 2006; Kiese et al., 2011) or enhanced emissions of N_2O and NO trace gases from soils (Pilegaard et al., 2006; Kesik et al., 2005) with N_2O being a harmful atmospheric gas contributing to climate change. Since N_2O is approximately 310 times as effective as CO_2 as a GHG (Solomon et al., 2007) even small quantities emitted from European forests could have a significant influence. Indeed Pilegaard et al. (2006) have suggested that NO and N_2O emissions from European forests are higher than from other temperate forests in the world. While it is often assumed that the contribution of forests to the European GHG balance is dominated by the carbon sink we know of no conclusive evidence which has established this. Thus the relative contribution of the carbon sink and the N_2O source from European forests will be explicitly quantified in this study.

The key questions we aim to answer here are threefold. First, across Europe, what are the geographical variations in forest productivity, carbon sequestration and greenhouse gas balance and where do we expect environmental change to cause the greatest changes. Secondly, which environmental drivers would be the main causes of those changes? Finally, what underlying mechanisms account for the changes, i.e. which

components of the carbon and nitrogen balance of forests will be predominantly perturbed?

To answer these questions, we employed four different dynamic models (BASFOR, DailyDayCent, INTEGRATOR and LandscapeDNDC) of sufficient complexity to represent the carbon and nitrogen fluxes through forest ecosystems. The models differed strongly in structure and parameterisation, thus accounting to some extent for our current uncertainty about biogeochemical mechanisms and their inclusion into process based models. In a novel approach, we chose not to run our models on a regular latitude-longitude grid but rather to subdivide Europe based on the values of environmental factors that affect forests. This stratification included administrative areas so that subdivisions represented homogeneous forest policy and management strategies, homogeneous soils and slope. We focused on near-future (2011–2030) predictions of one coniferous and one deciduous species grown widely across Europe: Scots pine (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.). We chose to look at one possible climate scenario SRES A1b reflecting the fact that the main climate scenarios do not differ greatly in the near term. To consider sensitivity to environmental change we compared results for two decades 2011–2020 and 2021–2030 considering changes to both average weather and N deposition.

2 Methods

2.1 Model descriptions

2.1.1 BASFOR

The BASic FORest simulator, BASFOR, (van Oijen et al., 2005) is a deterministic daily time step forest model used for simulating coniferous or deciduous forests. The model simulates carbon and nitrogen cycling in trees, soil organic matter and litter. It simulates the response of trees and soil to radiation, temperature, precipitation, humidity,

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wind speed, atmospheric CO_2 and N-deposition, and thinning regime. The model has 14 state variables, representing carbon and nitrogen pools in trees and soil, and 48 parameters, which include the initial state variables constants. Besides time series for the state variables, output may be produced of NPP, tree height, stem diameter, ground cover, LAI, N-mineralisation and other tree and soil variables. BASFOR is built from well known process representations. Light absorption is calculated by Beer's law. GPP is calculated as light absorption times a light-use efficiency (LUE). NPP is calculated as a fixed ratio of GPP. LUE is temperature-, CO_2- and soil water content-dependent and may be reduced if insufficient nitrogen is taken up by the plants. Potential nitrogen uptake scales with root system surface area. Actual nitrogen uptake is the minimum of demand, determined by tissue N-concentration, and potential uptake. Allocation of assimilates follows allometric rules, but water stress may limit leaf area index (LAI). Turnover of tree and soil components proceeds at temperature-dependent relative rates. The model structure was described by van Oijen et al. (2005), more recent model applications are reported by van Oijen and Thomson (2010) and van Oijen et al. (2011), and the model is now also in use as the tree component of an agroforestry model (van Oijen et al., 2010).

To find the most plausible BASFOR parametrisation for use across Europe we employed Bayesian calibration (BC), computing the Markov Chain Monte Carlo with an adaptive Metropolis algorithm. Observational data of height, LAI and biomass in stems, branches and foliage were taken from 20 *Pinus sylvestris* L. and 20 *Fagus sylvatica* L. sites in Cannell (1982) with an assumed observational error of 10 %. The model was run from planting until the observational year of 1981 for each of the sites. In addition, BASFOR was calibrated against observational data of averaged N_2O and NO from Bloemerts and de Vries (2009) for 17 pine and 18 beech sites with an assumed error of the maximum of 10 % or 0.5 kgN ha^{-1} yr^{-1}. This was combined with the initial carbon and nitrogen values calculated as described in Sect. 2.3 with an error of 10 %. The model was initialised with EFISCEN forest data described in Sect. 2.4 and run for 50 yr taking the average over the last 10 yr to compare against the data. For the beech forest

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parameters influencing the phenology of the model were calibrated against COST Action 725 Pan European Phenology Project (http://www.pep725.eu/index.php) budburst and leaf colour data from 17 European sites. The model was run for 30 yr from 1950–1980 with the average budburst day and leaf fall day compared against the data. The maximum a posteriori (MAP) parameter set was taken as the parametrisation for BASFOR.

BASFOR was initially run for 50 yr with the model reset to initial forest values from EFISCEN each year. This was done to bring the initial trees and soil into closer equilibrium. Thus avoiding perturbations due to out of balance initial conditions leading to spurious model responses.

2.1.2 DailyDayCent

The biogeochemical model DailyDaycent is a daily time step version of the CENTURY model (Parton and Rasmussen, 1994). DailyDaycent simulates the biogeochemical processes of C, N, phosphorus, and sulphur cycling associated with SOM dynamics for grasslands, agricultural lands, forests, and savannas. DailyDaycent simulates decomposition, nutrient flows, soil water, and soil temperature. Key submodels in DayCent model include soil water content and temperature by layer, plant production and allocation of net primary production (NPP), decomposition of litter and soil organic matter, mineralization of nutrients, N gas emissions from nitrification and denitrification, and CH_4 oxidation in non-saturated soils. Plant production is a function of genetic potential, phenology, nutrient availability, water/temperature stress, and solar radiation. NPP is allocated to plant components (e.g., roots vs. shoots) based on vegetation type, phenology, and water/nutrient stress. Nutrient concentrations of plant components vary within specified limits, depending on vegetation type, and nutrient availability relative to plant demand. Decomposition of litter and soil organic matter and nutrient mineralization are functions of substrate availability, substrate quality (lignin %, C / N ratio), and water/temperature stress. N gas fluxes from nitrification and denitrification are driven by soil NH_4 and NO_3 concentrations, water content, temperature, texture, and labile

C availability (Parton et al., 2001). For the different age classes the tree growth is initialised at different years. The growth for age class 0–10 yr starts 2000, for age class 10–20 yr at 1990 and so on. Before the initialisation of growing the areas were assumed as forests start growing from 1901. This previous forest was cut off and removed before the new planting. Trees of the age classes older than 110 yr started earlier (according to their age) without any previous forest. Accordingly there is at minimum a 110 yr spin up for the presented simulations.

2.1.3 INTEGRATOR

INTEGRATOR has specifically been developed to assess N and GHG (N_2O, CH_4 and CO_2) emissions from all major terrestrial ecosystems in response to changes in land use, land management and climate at a high spatial resolution for the EU27 (de Vries et al., 2011b). INTEGRATOR includes sub-models for the prediction of:

– N (NH_3, NO_x, N_2O and N_2) emissions and N leaching from (i) housing and manure storage systems and agricultural soils, i.e. an adapted version of the MITERRA-Europe model (Velthof et al., 2009; Lesschen et al., 2011), and (ii) non-agricultural terrestrial systems, using either either empirical relationships or a meta-model, based on results of the DNDC model (Li et al., 1992, 2000) while including (iii) an emission-deposition matrix for NH_3 and NO_x, based on the EMEP model (Simpson et al., 2006) to assess interactions between agricultural and non-agricultural land.

– CO_2 emissions from agricultural and non-agricultural terrestrial systems on mineral soil systems (the YASSO soil model: Liski et al. (2005)) and peat soils (empirical relationships), in combination with models that allow the estimation of carbon inputs to forests, i.e. EFISCEN (Schelhaas et al., 2007) and agriculture, i.e. MITERRA-Europe.

This study is limited to the calculation of CO_2 and N_2O exchange fluxes from forests in the entire EU27, making use of the models EFISCEN and YASSO. The European

Forest Information Scenario model (EFISCEN V3.1) is a model that simulates the development of forest resources in terms of increment and growing stock changes at scales from provincial to European level (Schelhaas et al., 2007). Data from National Forest Inventories (NFIs) are used to construct the initial age class distribution and growth function for each combination of province, tree species, site class and owner class that can be distinguished in a country. Each of these combinations is assigned a management regime, defined as the probability that a thinning or final harvest can be carried out as a function of age. For each five-year time step, the national amount of wood to be produced from the forest has to be defined. This total amount is then allocated over the different (forest types), according to the felling possibilities as defined by actual age class distributions and the management regime. Principal outputs of EFISCEN are increment, growing stock volumes, harvesting levels and age class distributions. Supplemented with factors to convert growing stock volumes to biomass in different tree compartments (biomass expansion factors, BEFs) and turnover rates, EFISCEN is able to estimate carbon stocks in, and litterfall from, living tree biomass. In INTEGRATOR, these litterfall rates are used in the subsequent soil carbon model YASSO.

YASSO (Liski et al., 2003, 2005) is a dynamic soil carbon model that consists of five decomposition compartments and two woody litter compartments. Non-woody litter (foliage and fine roots) entering soil is divided into the decomposition compartments of extractives, celluloses and lignin-like compounds according to its chemical composition. Woody litter is put into the compartment of fine (branches, coarse roots) or coarse woody litter (stem) depending on its size. Each of these woody litter compartments has a fractionation rate that determines the proportion of its contents to be released to the decomposition compartments in a time step. Each decomposition compartment has a decomposition rate that determines the proportion of its contents to be removed in a time step. The decomposition rates are controlled by temperature and drought. Particular attention has recently also been paid to studying the suitability of the model in other ecosystems including agricultural soils.

2.1.4 LandscapeDNDC

LandscapeDNDC (Haas et al., 2012) is a direct successor of the Modular Biosphere Simulation Environment Grote et al. (2009) and describes microclimate, water cycle, plant physiological processes, soil biogeochemistry, and silvicultural properties (such as height, diameter and number of trees). The soil biogeochemical part has been re-coded from the agricultural DeNitrification-DeComposition (DNDC) model and its forest adaptation PnET-N-DNDC (Li et al., 1992, 2000). The new version is now applicable to any vegetation type and, thus, enables the consistent simulation of land-use changes using different modules for plant physiology with the same soil module. LandscapeD-NDC also allows users to explicitly initialize number and properties of all soil- and canopy layers. An assessment of model parameter uncertainty for forest simulations of a temperate forest is given by Rahn et al. (2012) and a first regional application about biomass production in poplar plantations has been recently presented by Werner et al. (2012). For the present study, LandscapeDNDC was used in a setup with the PnET-N physiology module running in daily time steps. In addition, the silvicultural tracking routine is called once a year (Grote et al., 2011). PnET-N is derived from PnET-II (Aber et al., 1995) which describes forest carbon uptake (without explicit consideration of ground vegetation) based on a light-use efficiency approach that depends on water availability, foliar nitrogen concentration, air temperature and radiation. Respiration is differentiated into a fixed component (growth respiration) and a fraction depending on temperature and biomass (maintenance respiration). Total carbon is separated into the tree compartments foliage, fine roots and wood, and is accumulated throughout the year within storage compartments that are then used for foliage and wood growth in the next year. The latter is used for the calculation of stem dimensional changes following allometric rules. In PnET-N (Li et al., 2000) the nitrogen concentration in all tree compartments is calculated from the difference between optimum and actual nitrogen content and the availability of nitrogen in the soil. Litterfall is described from compartment turnover rates in terms of carbon and nitrogen loss, considering retranslocation

back into the plant before foliage shedding. Tree mortality is generally calculated in dependence on stand density and thus depends on dimensional growth, but neglected in this study. Litter mineralization and linked heterotrophic respiration as well as mineral N release is calculated as described earlier (Li et al., 2000). For ecosystem N turnover the model considers all major physico-chemical, plant physiological and microbial processes such as plant N uptake, mineralization, microbial immobilization, nitrification, denitrification or leaching. These processes are calculated in dependence on layer-specific temperature, water and N availability, thereby considering aerobic as well as anaerobic pathways for N turnover (Li et al., 2000). In this study we allowed the model to spin-up for five years (simulation years 2005–2009) before data was evaluated. This aims to minimise system responses that origin from the unknown but estimated carbon and nitrogen distribution in different litter fractions.

2.2 NitroEurope Classification Units (NCUs)

To facilitate model computations across Europe, the EU25+5 region was subdivided into so-called NitroEurope Classification Units (NCUs). These NCUs are composed of multipart polygons, each of the polygons being a cluster of 1 km × 1 km pixels. The composition of the NCUs were chosen to share the same administrative unit (Nomenclature of Territorial Units NUTS2 and NUTS3, EC, 2003; Statistical Office of the European Communities, 2003), the same soil mapping units (Soil Geographic Database SGDB classification, European Commission, 2004), and are homogeneous with regard to slope (Catchment Characterisation and Modelling Digital Elevation Model, CCM 250 DEM), distinguishing five slope classes (i.e. 0–2 %, 2–8 %, 8–15 %, 15–25 %, > 25 %). The NCUs are a further development from 'Homogeneous Spatial Units' (Leip et al., 2008, 2011). However, as a main difference, a criterion on homogeneous altitude was added for the NCU. To this purpose, the average height of the multi-polygon obtained with the procedure above was compared with the average height of each individual polygon. Those polygons for which this difference was larger than 200 m were grouped into a separate spatial unit. All maps were re-sampled to a 1 km raster map (ETRS89

Lambert Azimuthal Equal Area 52N 10E, Annoni, 2005), geographically consistent with the European Reference Grid and Coordinate Reference System proposed under INSPIRE (Infrastructure for Spatial Information in the European Community, Commission of the European Communities, 2004).

2.3 Initial soil data

Model simulations required initialisation of soil conditions across the simulated area. Initial soil data were created from spatial averages of predictions of seven soil properties (pH, organic carbon, clay, sand, bulk density, total nitrogen and horizon thickness) for the A, B and C horizons, for all NCUs within EU25+5. Predictions were obtained using a geostatistical regression cokriging approach (Hengl et al., 2004) in which the value of a soil property at some location is derived from observations nearby and correlated environmental factors such as landuse and soil type. Organic carbon and total nitrogen were log transformed prior to the geostatistical modelling. Observations were derived from the ISRIC WISE/SPADE (http://www.isric.org) and the EFSDB datasets. Spatial averages were obtained by taking the arithmetic mean of all predictions within the NCU.

Each model derived its own soil water profile, except for INTEGRATOR which does not simulate soil hydrology but uses a transfer function to compute N_2O emissions based on N inputs, soil characteristics and meteorology. For BASFOR, pedo-transfer functions from Robertson (1999, p. 45) were used. For NCUs where the field capacity and wilting point were found to be unrealistically high they were truncated to 0.6 and 0.54 respectively. For DailyDayCent the physical parameters are derived from texture, bulk density and organic matter with the pedo-transfer-functions of Gupta and Larson (1979) and Rawls et al. (1982). These parameters give also the upper and lower limits of the soil water content. Simulations using LandscapeDNDC were performed with explicit soil profile stratification and layer-specific initialisation of soil attributes. Therefore, soil organic carbon, pH, texture, bulkdensity, and layer thickness were provided for all three soil horizons and the full profile depth. In addition, field capacity and wilting point

estimates were computed prior to simulations as soil water dynamics are computed explicitly in LandscapeDNDC. The layer specific properties were calculated from texture, carbon and bulk density according to Ad-Hoc-AG Boden (2004) to provide parametrisation for the van Genuchten formula (van Genuchten, 1980), which then gives the desired water holding properties.

2.4 Initial forest data

Initial forest data were derived from the European Forest Information Scenario Model (EFISCEN V3.1). EFISCEN simulates the development of forest resources at scales from provincial to European level (Schelhaas et al., 2012). Data from National Forest Inventories (NFIs) are used to construct the initial age class distribution and growth functions. Initialisation data were taken from the forest resources part of the European Forest Sector Outlook Studies of the UN-ECE (Schelhaas et al., 2006a,b). Since initial data refer to different years for the different countries, all countries were projected until a common year (2005), using historical harvest levels (FAOSTAT, 2009). Results for 2005 were extracted for pine and beech, at the regional level available in EFISCEN (mostly NUTS2 or national). Data included area, timber volume and biomass per compartment per age class. The procedure used was to create an overlay between the NCU map and the EFISCEN regions. Where an NCU straddled more than one EFISCEN region, the region with the largest share in the NCU was assigned. The EFISCEN data were then assigned to the NCUs using the mapping of NCU to EFISCEN regions so that all NCUs within the same region were assumed to have the same forest data.

2.5 Rotation length and thinning regime

BASFOR and LandscapeDNDC employed a rotation length of 80 yr for Scots pine and 100 yr for beech. Trees which were initially aged above the rotation length were considered to be natural unmanaged forests and therefore not harvested. We started thinning in stands after 20 yr of age employing a thinning of 20 % at each subsequent

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decade. The thinning was skipped whenever the forest stand was not closed. This was defined as an LAI of less than 3, a crown-covered area of less than 95 % or an aboveground biomass of less than 4000 kg DM ha^{-1}. These restrictions were relaxed for LandscapeDNDC because LAI and ground coverage is calculated from initialized stand properties including stemwood volume so that for stand density all three criteria are intrinsically connected.

2.6 Climate and N deposition scenario

The IPCC SRES A1b scenario (Nakícenović et al., 2001) was used in this study.

2.6.1 Weather driving data

The weather driving data for A1b were taken from the climate model REMO. Data from REMO model runs provided by MPI Hamburg were converted into netcdf data format, merged into 10 yr slices and remapped to a 0.22 degree resolution longitude latitude grid using CDO V1.4.0.1 available from http://www.mpimet.mpg.de/cdo. Downscaling was performed using a python algorithm based on the libraries numpy, scipy and gdal, sorted according to the respective NCU-order, and converted into a binary file to be used as input model data.

2.6.2 Nitrogen deposition

The annual atmospheric N deposition was calculated on the basis of NH_3 and NO_x emissions from agro-ecosystems calculated by the INTEGRATOR model (de Vries et al., 2011b), combined with historic EMEP data on NO_x emissions and an emission-deposition matrix for NH_3 and NO_x, derived from the EMEP model (Simpson et al., 2003; Tarrasón et al., 2007). For 2020 the non-agricultural N emission scenarios was used that was developed for the Thematic Strategy on Air Pollution of the EU and reflects the current legislation (Amann et al., 2007). From 2020 onwards, the anthropogenic N emissions were assumed constant.

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2.6.3 CO$_2$ timeseries

Future CO$_2$ air concentrations consistent with the IPCC SRES A1b scenario (Nakícenovíc et al., 2001) were obtained from Carter (2007).

3 European average results

3.1 Greenhouse gas balance

The models agree on a number of aspects of GHG balance. Firstly that the CO$_2$ sink is larger than the N$_2$O emission source (Fig. 1) although, the CO$_2$ sink for DailyDayCent pine is substantially larger than the others. Comparing the GHG balance for the two decades, there is generally a greater CO$_2$ sink in the first decade than in the second, although DailyDayCent pine has the opposite. All the models have larger N$_2$O emissions for beech than pine forests.

There is, however, disagreement on whether pine or beech forests have a greater CO$_2$ sink, with LandscapeDNDC and DailyDayCent having a larger sink for pine forests than beech and BASFOR and INTEGRATOR visa versa. In addition, there are larger changes in CO$_2$ sink strength between decades for BASFOR and INTEGRATOR than for LandscapeDNDC and DailyDayCent.

Three of the models have larger N$_2$O emissions in the first decade than in the second whereas BASFOR is the opposite.

3.2 Forest carbon and nitrogen balance

To help understand the differences in GHG balance for species, decades and models it is informative to look at the full carbon and nitrogen budgets for both species (pine and beech) and for both decades (Fig. 2). Calculation of the full budget was only possible for two of the models BASFOR and LandscapeDNDC.

There are a number of similarities in the carbon and nitrogen budgets of the species, decades and models. There is agreement on the dominant fluxes, with NPP and litter being the main C fluxes in trees, and uptake and litter being the largest N fluxes in trees, with litter being more dominant in the N- than the C-cycle, where exported carbon is also significant. In the soil, the principal carbon fluxes are litter and respiration, with litter and uptake dominating the flux of N into and out from the soil similar to the trees.

3.2.1 Species differences

Carbon and nitrogen cycling is more vigorous in beech forests than pine, with a larger C and N litter flux to the soil and a larger soil respiration. The larger litter flux is perhaps to be expected, given the seasonal loss of foliage and regrowth in deciduous trees. In addition, exported carbon is greater for beech than pine and has a larger C / N ratio.

Soil carbon is fairly close to equilibrium for both species, though less so for beech. Both BASFOR and LandscapeDNDC have less NO and more N$_2$O emission in beech than in pine. In addition, soil N leaching is greater in beech than in pine. Lower evapotranspiration fluxes in the dormant vegetation period, the larger flux of nitrogen into the soil by litter and a greater nitrogen deposition in beech than pine forests may help explain the higher leaching and N$_2$O fluxes.

Differences between the two decades are less marked for beech than pine with larger imbalances in the second decade.

3.2.2 Decadal differences

As noted in Sect. 3.1, sequestration of carbon is reduced in the second decade. In the C and N budgets it is NPP and nitrogen uptake from the soil that have the largest reductions. While there are reductions in litter flux and soil respiration, these are generally less marked. The exception being soil respiration for LandscapeDNDC beech which has a comparable reduction to NPP. Thus changes in NPP are the major factor in changes in NEE and hence the greenhouse gas balance of the forest. Therefore,

understanding why NPP has changed is key to understanding how the greenhouse gas balance of forests changed with the environment. The exported carbon is greater in the second decade than in the first. In general, carbon and nitrogen in the soil are in closer balance in the second decade than in the first. The exception being for BASFOR beech which is closer to equilibrium in the second decade.

3.2.3 Model differences

Whilst what we have discussed so far are common to BASFOR and LandscapeDNDC, there are also important differences. Carbon and nitrogen cycling is more vigorous in BASFOR then in LandscapeDNDC, with greater NPP, but also a larger litter flux and hence a larger soil respiration.

As noted (Sect. 3.1), one model does not consistently have a greater carbon sequestration across species. Indeed, while NPP is clearly greater for pine than beech in BASFOR, it is more closely matched in LandscapeDNDC. While litter flux and thus soil respiration are larger for beech than pine for both models. This explains the lower carbon sequestration for LandscapeDNDC beech in Fig. 1 relative to pine and BASFOR. Further, LandscapeDNDC beech shows a net loss of carbon from the trees whereas pine and BASFOR have net gains. Indeed LandscapeDNDC beech also has a larger decadal reduction in NPP than pine and BASFOR but is counteracted by a larger reduction in soil respiration so the change carbon sequestration between the decades is smaller than for pine and BASFOR (Fig. 1).

Exported carbon is larger for BASFOR than LandscapeDNDC but exported N is smaller suggesting a larger C/N ratio in the stems for BASFOR. The litter flux is the opposite with BASFOR having a larger relative N to C flux than LandscapeDNDC suggesting a lower C/N ratio in the roots and leaves.

LandscapeDNDC has larger N_2O emissions and leaching in the first decade which reduces in the second decade. BASFOR shows increased N_2O emissions and leaching in the second decade, with larger emissions than LandscapeDNDC. The reduction in leaching is more dramatic for LandscapeDNDC pine than beech.

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In general, LandscapeDNDC has larger imbalances in the soil than BASFOR, with a net loss of N and C from the soil. As for NPP, the species are reversed with beech in closer balance in BASFOR and pine in closer balance in LandscapeDNDC. For LandscapeDNDC the model is in closer balance in the second decade than in the first for both soil C and N. Apart from soil N under pine BASFOR is in closer balance in the first decade. This helps explain the contrasting N_2O emissions noted above.

3.3 European averaged climate differences between decades

Before moving on to consider spatial variation between species and decades it is worth considering the European average climate.

In general, the environmental conditions are more favourable for beech forests than pine. Precipitation at beech stands was 14 % and temperature was 0.5 °C higher. Initial soil nitrogen was 23 % higher and nitrogen deposition was 58 % higher at beech than at pine sites. Further, the temperature was 1.2 °C closer to an optimum temperature of 10 degrees Celsius (defined as abs(temperature −10.)) than pine. This may indicate why NPP and NEE were significantly higher for beech than pine in BASFOR and INTEGRATOR although it does not explain the reverse for LandscapeDNDC and DailyDayCent.

Mean climate differences between the two decades were less than those for species, with temperature being 0.03 °C higher, precipitation 1.2 % lower in pine and temperature 0.06 °C lower and precipitation 2 % lower in beech. These changes seem small given the 10 % to 20 % changes in NPP/NEE already noted. This is indicative of a response to spatial variation hidden in the mean picture.

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4 Spatial variation in carbon sequestration

4.1 Scots pine

The models in general agree that the largest NEE (Fig. 3) is in central/southern Germany and Austria and northern Spain with lower values in Poland and S. Spain. There is, however, less agreement in the northernmost latitudes where BASFOR and INTEGRATOR have lower NEE over Scandinavia and England than DailyDayCent and LandscapeDNDC. Each model has spatial variation not found in the other models. DailyDayCent has very low values in SE Spain and Slovakia but otherwise has less spatial variation than the other models. BASFOR has lower values in central-southern France than the others. INTEGRATOR has homogeneous NEE values in Spain and low values in Bulgaria and LandscapeDNDC has lower values in N. Germany and negative values over NW Scotland. The homogeneous values of NEE in Spain for INTEGRATOR are likely to be due to Spain being averaged for this model.

That the spatial variation in NPP is important for NEE can be seen in Fig. 4. Linear regressions for the pine NCUs suggests that the strongest drivers of NPP for LandscapeDNDC are precipitation ($R^2 = 0.19$), temperature ($R^2 = 0.13$) and nitrogen deposition ($R^2 = 0.12$). For BASFOR nitrogen is more important with initial soil nitrogen ($R^2 = 0.65$) and deposition to a lesser extent ($R^2 = 0.11$) being important. Temperature has a similar relationship to NPP as LandscapeDNDC ($R^2 = 0.12$) but precipitation is weaker ($R^2 = 0.04$). For DailyDayCent the strongest driving factor was found to be precipitation ($R^2 = 0.25$) with the next largest influence being mineral soil N ($R^2 = 0.12$). The influence of temperature was less ($R^2 = 0.03$) than for the other models. Regressions for INTEGRATOR were with respect to NEE rather than NPP. Temperature was found to be more important ($R^2 = 0.11$) then precipitation ($R^2 = 0.07$) but N was less important than for the other models.

It is also worth also noting that the influence of NPP was found to be particularly strong for soil respiration in DailyDayCent ($R^2 = 0.95$) and BASFOR ($R^2 = 0.86$) suggesting that the NPP-respiration coupling in these models is strong for pine. For

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LandscapeDNDC, NPP was still the largest influence on soil respiration but the correlation was weaker ($R^2 = 0.44$).

4.2 European beech

In general, all the models have highest NEE over central Europe (Fig. 3), although for BASFOR NEE is stronger to south and east of the centre, whereas in the other models NEE is higher in the north and Denmark and lower in Poland. All the models with the exception of INTEGRATOR predict higher NEE in the north of Spain and smaller or even negative NEE in the south. The models with the exception of DailyDayCent simulate higher NEE over N. Italy, S. Germany and Romania. BASFOR and DailyDayCent have smaller or even negative NEE in SE Spain, Sicily, the heel of Italy and easternmost Romania. DailyDayCent has higher NEE in SW France and LandscapeDNDC lower or even negative NEE over parts of France. BASFOR and LandscapeDNDC have smaller or even negative NEE in NW Scotland. There is again clear spatial correspondence between NEE and NPP (Fig. 4).

Linear regressions suggest that growth of beech in LandscapeDNDC has a dependence on temperature ($R^2 = 0.15$) similar to pine but little relationship with precipitation and a stronger relationship with soil nitrogen ($R^2 = 0.31$). DailyDayCent similarly shows a weaker relationship with precipitation ($R^2 = 0.04$) and a stronger relationship with temperature ($R^2 = 0.07$) than for pine, although the relationship with mineral soil N is weaker ($R^2 = 0.05$). However BASFOR shows a stronger relationship with precipitation ($R^2 = 0.08$) and a weaker relationship with temperature ($R^2 = 0.08$) than for pine. Where precipitation is very low there appears to be a yet stronger dependence in BASFOR beech. For very low soil water content there is a threshold response where growth is no longer possible giving very low values of NPP (for example in SE Spain). This threshold relationship with precipitation is also seen for both species in DailyDayCent in SE Spain. Growth in BASFOR has a weaker dependence on initial soil nitrogen ($R^2 = 0.16$) than pine. One possible reason this is that the C/N ratio of the trees are 35 % higher in BASFOR beech than in pine. Thus for each gram carbon growth, less

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nitrogen is required in the beech trees. Hence beech is less constrained by N than pine which along with the more favourable mean environmental conditions discussed in Sect. 3.3 may also suggest why NPP is higher in beech than in pine.

As for pine, soil respiration depends strongly on NPP for DailyDayCent ($R^2 = 0.96$) and is stronger for LandscapeDNDC (NPP $R^2 = 0.77$) and weaker for BASFOR (NPP $R^2 = 0.55$). This is significant since as discussed in Sect. 3.2 the litter flux is greater in beech trees than in pine. The closer coupling of soil respiration with NPP for LandscapeDNDC was also noted in Sect. 3.2 and was given as an explanation for the lower carbon sequestration for beech than pine despite the similarity of NPP.

5 Spatial differences between decades

5.1 Environmental drivers and management

Before looking at how NPP has changed between the two decades it is worth observing how the environment changed. Maps of temperature and precipitation and how they changed between the decades can be seen in Fig. 5. It is striking that the temperature and precipitation changes are negatively correlated, with higher precipitation and lower temperatures in central Europe and lower precipitation and higher temperatures in southern and high northern latitudes. This helps explain the small European average changes noted in Sect. 3.3.

Nitrogen deposition is higher in Eastern Europe and Italy and lower in central Europe and Germany, in particular, with N deposition reducing by 1.3 % in pine and increasing by 2.7 % in beech forests. Due to ageing and clearfelling, at 80 yr for pine and 100 yr for beech, the mean age of the forest has also changed between the decades with pine forests 3 % older and beech forests 7 % older.

5.2 Decadal differences in net primary productivity

As discussed above, changes in NPP, are the major contributor to changes in NEE so this section will consider how NPP has changed between the decades.

Decadal differences in NPP are shown in Fig. 6.

5.3 Scots pine

NPP has increased according to LandscapeDNDC across considerable areas of northern central Europe. Average values for the main environmental drivers have been calculated for the NCUs where NPP increased in LandscapeDNDC pine. In this region temperature is 0.8 °C lower than the European average, although it is 1.5 °C closer to an optimal temperature of 10 °C than average. Initial N is 15 % higher than the European average while precipitation is 9 % lower. In the second decade the temperature fell by 0.3 °C and is 0.2 °C further away from optimal while precipitation increased by 11 %. This indicates that it was the increase in precipitation in this area that gave rise to the higher NPP. This is consistent with a larger sensitivity to precipitation than temperature noted in Sect. 4, so for LandscapeDNDC the rise in precipitation overcomes the reduction in temperature, leading to higher production. This suggests that growth in LandscapeDNDC is sensitive to non-optimal water availability. In southern latitudes there is a general reduction in growth, suggesting that the combination of lower precipitation and higher temperatures is not conducive to growth in LandscapeDNDC. The largest reduction in NPP is in the north of Spain where NPP was highest in the first decade. Whilst no single factor has clearly reduced in this region there are modest reductions in temperature, precipitation and soil nitrogen, suggesting that the combined effect of all of these may account for reduced NPP in this area.

Similarly, DailyDayCent NPP has increased in the second decade but for an even wider area than for LandscapeDNDC. As for LandscapeDNDC, the difference in NPP was found to have a strong relationship with precipitation ($R^2 = 0.37$). The stronger

dependence on precipitation than temperature or N deposition is consistent with the analysis made for DailyDayCent in Sect. 4.

For BASFOR, unlike LandscapeDNDC and DailyDayCent, NPP has generally reduced in central and northern Europe, although there is a slight increase in Poland and patches of increase in Bulgaria where deposition has increased in the second decade (Fig. 5). That BASFOR has a greater sensitivity to temperature and nitrogen, as opposed to precipitation, is consistent with the spatial relationships highlighted in Sect. 4. In southern latitudes, NPP is reduced over southern France and northern Spain where soil nitrogen is also reduced (not shown). Over southern and central parts of Spain NPP has increased. That NPP increases in some of the driest regions in southern Spain where further reductions in precipitation have occurred, but temperature has increased, further confirms that growth in BASFOR is relatively insensitive to non-optimal water availability.

5.4 European beech

The largest decadal reduction in NPP was for LandscapeDNDC beech. Firstly this is because NPP increases in a smaller area than for pine. This only occurs where the increase in precipitation is large and where and N deposition has also increased (the Netherlands and Poland) and is consistent with the relative insensitivity to precipitation versus pine noted in Sect. 4. Secondly over much of the rest of Europe NPP decreases. This is particularly marked where soil nitrogen also decreased, for example in NW Spain and parts of central Europe. Although soil N is generally lower throughout Europe in the second decade. Indeed the change in NPP was found to have an R^2 of 0.18 with the change in soil N. In addition, there was clearfelling in beech in the first decade, especially in parts of France which did not occur for pine leading to further reductions in NPP.

Whilst DailyDayCent has increased NPP in central Europe in the second decade, similar to pine, the area of large increase is less extensive so that in central and southern France and Spain the increase is either smaller or is a reduction in NPP. Similar to

the analysis in Sect. 4 the change in NPP has a weaker relationship with the change in precipitation ($R^2 = 0.17$) and is now similar to that for the change in temperature ($R^2 = 0.17$) suggesting that the decrease in temperature may be counteracting the increase in precipitation to a greater extent for beech than for pine.

For BASFOR beech, the sensitivity to precipitation and optimal temperature is more closely matched (Sect. 4) so that while NPP is generally lower in central and northern latitudes there are small areas where NPP increases. Though as for pine, there are large reductions where temperature has fallen the most (southern Germany and Austria). As for LandscapeDNDC NPP has decreased in central France where clearfelling occurred. Reductions in soil nitrogen are more modest for BASFOR than for LandscapeDNDC and pine and the relationship to soil N is weaker than for pine so that reductions in NPP are smaller for BASFOR beech. In climates where reductions in precipitation and increases in temperature have been more modest, for example the northern western coast of Spain, and where N deposition has increased, such as over Italy and Romania and Bulgaria, there are patches of modest increase in NPP in the second decade. As discussed in Sect. 4, beech has a particular sensitivity to very dry conditions which is not seen for pine. So where precipitation decreased in an already dry area NPP dropped significantly for instance over southern Spain and Sardinia. This suggests a difference between the species vulnerability to drought.

5.5 Decadal differences in net ecosystem exchange

The decadal difference plots for NEE can be seen in Fig. 7. For LandscapeDNDC and BASFOR NEE has often increased more than NPP. This is because the simulations have a general decadal soil respiration decrease. There are particular areas where soil respiration has reduced more than others. For BASFOR beech, where NPP was already very low in the first decade, litter flux to the soil is very low leading to a greater net loss of carbon from the soil in these locations (SE Spain, Sicily, heel of Italy, eastern Romania and Bulgaria). Thus by the second decade soil carbon has reduced so that there is less carbon available to be respired than in the first decade. Since NPP

is already very low in these areas and soil respiration is reduced, the change in NEE in these areas is positive. Similarly, where NPP has decreased in the second decade, the litter flux to soil will also have reduced, leading to less soil carbon and a smaller respiration compensating for the reduction in NPP. Changes in soil respiration are particularly marked for LandscapeDNDC beech in Poland and NW Spain. This has the effect of increasing NEE in both of these areas, reducing the effect of the loss of NPP in NW Spain and boosting further NEE where NPP increased over Poland. For LandscapeDNDC pine, while NPP increased over northern and central Europe soil respiration decreased. As for beech, this has the effect of adding to the positive change in NPP in NEE. It is significant that while soil respiration was found to vary with litter flux for BASFOR pine ($R^2 = 0.27$) this was not found for LandscapeDNDC pine ($R^2 = 0.03$). For DailyDayCent, soil respiration has generally increased this compensates for the increased NPP so that NEE increased less than NPP. For INTEGRATOR, the spatial variability of the response to the change in environmental variables was less than for the other models. The largest drivers of change were temperature ($R^2 = 0.42$) and N deposition ($R^2 = 0.14$).

6   Spatial variation in N$_2$O emissions

Maps of N$_2$O are shown for each of the models in Fig. 8. As can be seen there are large spatial differences between the models for both pine and beech. BASFOR and LandscapeDNDC the have highest emissions in central Europe for beech and pine although, BASFOR has high emissions over Spain for beech while LandscapeDNDC has lower emissions over Spain but higher emissions over N. Italy and Romania. INTEGRATOR has highest emissions in N. Sweden and low emissions where BASFOR and LandscapeDNDC have high emissions in Austria, the Czech Republic and E. Germany. DailyDayCent has highest emissions in SE Spain and Slovakia for pine and Bulgaria, Romania and Slovakia for beech. Whilst there are large differences between

the models, the strongest spatial relationships as identified by linear regressions are for somewhat similar variables for each of the models.

BASFOR pine has highest emissions where the initial soil N is high ($R^2 = 0.48$) with the next strongest relationship being with NPP ($R^2 = 0.24$). Similarly for LandscapeDNDC pine the strongest relationship in the first decade is with soil N ($R^2 = 0.15$) although, by the second decade the strongest relationships are with NPP ($R^2 = 0.21$) and N deposition ($R^2 = 0.24$). The strongest relationship for DailyDayCent pine is also NPP ($R^2 = 0.46$). Indeed it is clear from the maps that DailyDayCent emissions are highest in SE Spain and Slovakia where NPP was found to be very low. This indicates that smaller growth leads a smaller N demand from the soil (as can be seen in Sect. 3.2) shifting the balance so that more N is available to be emitted. Mineral soil N was found to have the next highest relationship ($R^2 = 0.12$) similar to BASFOR and LandscapeDNDC. For INTEGRATOR the strongest relationship was found for precipitation ($R^2 = 0.09$).

For BASFOR beech, initial soil N is again dominant ($R^2 = 0.35$) but not NPP. This supports the suggestion in Sect. 4.2 that N is less limiting for growth in BASFOR beech. For DailyDayCent beech as for pine the strongest relationship is with NPP ($R^2 = 0.20$) which is also clear from the NPP maps Fig. 4. The strongest linear relationship for LandscapeDNDC beech is with soil N ($R^2 = 0.15$), NPP ($R^2 = 0.13$) and N deposition ($R^2 = 0.1$) being the next strongest. For the log(N$_2$O) the strongest relationship is with NPP ($R^2 = 0.46$) and also clitter ($R^2 = 0.43$) where the relationship unlike BASFOR and DailyDayCent is positive as can be seen in Fig. 4. Thus for LandscapeDNDC, N$_2$O emissions are less sensitive to N limitation in the soil due to uptake and more sensitive to the N available to be emitted in the litter layer which is larger for beech than pine.

6.1   Decadal differences in N$_2$O emissions

For both beech and pine, LandscapeDNDC has widespread lower emissions in the second decade (Fig. 9) with spatial similarities to changes in soil nitrogen (not shown). It was noted in Sect. 3.2 that the outgoing flux of N in the first decade was not matched

by incoming N to the soil. Thus during this decade the soil was depleted of N so that in the second decade there was less soil N available to be emitted. A linear regression of changes in N_2O against changes in soil nitrogen suggest that they are highly correlated ($R^2 = 0.67$). This indicates that the lower N_2O emitted in the second decade is related to depleted soil N.

In BASFOR soil N is also out of balance in the first decade, but to a lesser extent and N_2O emissions generally increase across Europe for pine and to a lesser extent for beech (Fig. 9). In addition, comparing the difference maps of NPP (Fig. 6) with those of N_2O suggests that they may be correlated. Indeed, linear regressions would suggest a significant relationship ($R^2 = 0.24$) between the change in $logN_2O$ and NPP. This is perhaps unsurprising given the relatively strong relationship between N_2O emissions and NPP identified for BASFOR.

The decadal differences in N_2O was smaller for INTEGRATOR and DailyDayCent suggesting that they were less sensitive to environmental changes. This may suggest that the N available for emission was not greatly perturbed in these models.

7 Discussion

7.1 Average results for Europe

This study was concerned with quantifying the greenhouse balance of European forests considering not only CO_2 but also N_2O. Taking the average over the models we found a European average carbon sink for 2011–2020 of $0.160 \pm 0.020\,kgC\,m^{-2}\,yr^{-1}$ for pine (excluding the large DailyDayCent pine C sink) and $0.138 \pm 0.062\,kgC\,m^{-2}\,yr^{-1}$ for beech. This is comparable to the values for "ecological sites" ($0.200 \pm 0.052\,kgC\,m^{-2}\,yr^{-1}$) and national forest inventories ($0.160 \pm 0.020\,kgC\,m^{-2}\,yr^{-1}$) found in Luyssaert et al. (2010) (henceforth L10). In the remainder of this discussion we will refer to "ecological sites" as termed in L10 as observational sites and will refer to national forest inventories from L10 as just inventories.

In addition, we found a European average N_2O source for 2011–2020 of 0.285 ± 0.125 $kgN\,ha^{-1}\,yr^{-1}$ for pine and 0.575 ± 0.105 $kgN\,ha^{-1}\,yr^{-1}$ for beech. This is comparable to the range of 0.55 to 0.62 $kgN\,ha^{-1}\,yr^{-1}$ found for all forest species in the modelling and observational study of European N_2O reported in Kesik et al. (2005). Although given that the model used in that study (PnET-N-DNDC), is closely related to LandscapeDNDC, it is perhaps unsurprising to have found similar values. We found that the sink through uptake of CO_2 was dominant over the source of N_2O by a factor 18 (pine) and 8 (beech). This is consistent with the prevailing assertion that age structure and management practices in Europe are continually changing such that forests overall are currently sequestering carbon (Nabuurs et al., 2003) and that C sequestration dominates over forest soil N_2O emissions (de Vries et al., 2011a). It was also found that there was a greater imbalance between tree growth and litter fall than between litter flux into the soil and respiration. Hence more of the carbon sink is sequestered by the trees than the soil. This is consistent with L10 who found an 78/22 % split between carbon sequestered by the trees and the soil.

LandscapeDNDC and DailyDayCent had larger carbon sequestration for pine than beech trees whereas INTEGRATOR and BASFOR showed the reverse. The N- and C-budgets presented in Sect. 3.2 help explain these differences. For BASFOR a more favourable climate and less N limitation for beech contributed to higher NPP. For LandscapeDNDC the higher litter flux for beech than pine led to higher soil respiration and lower NEE. Indeed litter flux and soil respiration was generally higher for beech forests which is perhaps unsurprising given the seasonal defoliation in deciduous forests.

It was also found that N_2O emissions were larger from beech forests than pine which is in agreement with results from field observations (e.g., Butterbach-Bahl et al., 2011). This is likely to be related to higher inputs of nitrogen to the soil from nitrogen deposition and litter in beech forests and differences in soil moisture during the dormant period (Butterbach-Bahl et al., 2002). In contrast, emissions of NO where found to be higher in pine than beech forests for LandscapeDNDC but not for BASFOR. This is consistent with Pilegaard et al. (2006) who found higher emissions from coniferous

forests than deciduous forests. They suggested that nitrification favouring NO emissions is more likely from coniferous forests, where soil moisture is lower and litter is thick and well aerated, and denitrification favouring N_2O emissions is more likely from deciduous forests with a more compact moist litter layer.

Since both L10 and the first decade of this study, while not for the same years, are both close to present day we consider that they can be usefully compared. In the following discussion, Table 3 from L10 will be compared with our Tables 1 and 2 for pine and beech respectively. For NPP the values for the models in this study are generally lower than those for the models in L10. This is consistent with the lower NPP value for the model BIOME-BGC in L10 which was the only one to include the influence of N and is consistent with the assertion that European forests are N limited. For pine, BASFOR is closest to the observational sites and inventory values. As already noted DailyDayCent pine values are approximately double of those both in this study and in L10. For beech, BASFOR had higher and LandscapeDNDC and DailyDayCent lower values than those found in inventories and observational sites. For soil respiration, the model values here are generally significantly lower than those for models in L10. The difference is due to a lack of management in the L10 models since managed removal of carbon cannot be respired from the soil. Thus NEE values for the models in this study are generally higher than those in L10. In general, the values of carbon sequestration found here are similar to the range 0.16–0.20 $kgC\,m^{-2}\,yr^{-1}$ found in L10 for inventories and observational sites. The exceptions are LandscapeDNDC and DailyDayCent beech which had lower values and DailyDayCent pine which had a far higher value. L10 calculate the split in NPP between soil respiration and NEE for the inventories, observational sites and each of the models in their study. These values are given in Table 3 of their paper and will be compared with the values for the models in this study. For pine, BASFOR has a 70/30 split which is closer to the split found in L10 for observational sites than inventories (65/35) whereas LandscapeDNDC and DailyDayCent are close to a 50/50 split. For beech, BASFOR and DailyDayCent are close to a 70/30 split consistent with observational sites whereas LandscapeDNDC has an 80/20

split which is closer to a model (Modified LPJ) in L10 which included management. Whilst exported carbon values themselves are either slightly higher or not dissimilar to those of L10 the percentage of NPP that is exported is closer to 20 % for pine and 17–25 % for beech whereas inventory and ecological site percentages are between 10–16 %. This higher fraction of NPP exported partially explains the lower percentage of soil respiration for LandscapeDNDC and DailyDayCent pine. For BASFOR pine and LandscapeDNDC and DailyDayCent beech the higher fraction of exported C is offset by a higher percentage of NPP which becomes litter than the 50 %and 60 % found for inventories and observational sites indicated in Ciais et al. (2008). In general, the percentage of NPP which is sequestered in the models in this study which included the influence of N and management are closer to those for inventories and observational sites than the models in L10. This supports the conclusion in L10 that management practises and N deposition rather than changes in CO_2 and climate control the carbon sequestration ratio (NEE/NPP).

7.2 Interaction of geographical and species differences with environmental factors

We found that carbon sequestration was generally highest in central/southern Germany and Austria and northern Spain with lower values in Poland and S. Spain. We found that the geographical variation in NPP was more important than soil respiration for this. This is consistent with Ciais et al. (2008) who found a linear relationship between carbon sequestration and growth. There were also significant differences between the geographical variability of NEE shown by the models suggesting significant remaining uncertainty. These differences are likely to be due to differences in model's sensitivities to environmental variables. Indeed there were important differences between the models as to which weather variables were most important for the geographical variation in NPP. BASFOR had temperature as most significant for pine and precipitation as most important for beech whereas LandscapeDNDC and DailyDayCent showed the opposite sensitivity. Geographical variations in growth for BASFOR, DailyDayCent and

LandscapeDNDC was found to be sensitive to nitrogen (either soil N or atmospheric deposition). Further, species also were found to have different sensitivities to nitrogen although the models differed on this. In BASFOR pine growth was more sensitive than beech to soil nitrogen. This is likely to be due to a lower C/N ratio found for pine trees, thus requiring more nitrogen for growth than beech coupled with a lower average soil N for pine than beech trees. This is consistent with Solberg et al. (2009) who found that the fertilizing effect of N deposition was most clear for pine and spruce forests and where the C/N ratio of the soil was higher than 25. In LandscapeDNDC and DailyDay-Cent, beech growth was found to have a stronger relationship with soil nitrogen than pine, so that species differences are uncertain.

There was considerable uncertainty about the geographical location of N_2O emissions. Two of the models BASFOR and LandscapeDNDC had largest emissions in central Europe where nitrogen deposition and soil nitrogen were largest. There was more similarity between the models in the sensitivities of geographical variations of N_2O to drivers. For BASFOR and LandscapeDNDC the largest driver was soil nitrogen and for BASFOR, LandscapeDNDC and DailyDayCent NPP was also important. Indeed, N_2O emissions had a negative spatial relationship with NPP for BASFOR and DailyDayCent so that N uptake from the soil was influenced the N available to be emitted. For LandscapeDNDC, NPP was also important for N_2O emissions but the relationship was positive so that where growth was higher the litter flux of N to the soil was greater providing more available N for emission.

7.3 Geographical and species differences in response to environmental changes

Of particular interest in this study was in which locations we expect environmental changes to cause the largest changes in forest productivity, carbon sequestration and greenhouse gas balance. In addition, which environmental drivers would be the main cause of those changes.

It was found that changes in carbon sequestration were dominated by NPP. This is consistent with Ciais et al. (2008) who found a linear relationship between carbon sequestration and growth. No overall one driver dominated changes in NPP with precipitation, temperature, nitrogen deposition and management (through clearfelling), all being significant factors.

Environmental changes had largest impact where they had previously been low, limiting growth in that area. For example, in regions where precipitation was below average (northern Germany and Poland) an increase led to increased growth in pine in LandscapeDNDC. However beech forests LandscapeDNDC in were less sensitive to increased precipitation in central and northern Europe. Where precipitation decreased in an already dry area there was a threshold response from beech forests in BASFOR and DailyDayCent, with growth collapsing, for example in dry southern areas of Europe such as SE Spain, Sicily, Sardinia, southern tip of Italy and eastern fringes of Romania/Bulgaria. This was not found for pine forests in BASFOR indeed, pine forest growth increased in parts of dry southern Spain. Where soil N was lower and so limiting, for example in Poland, an increase in nitrogen deposition was found to promote growth. It is known that N deposition has multiple effects on vegetation. It may cause direct damage to plant cuticles and cells, leading to dieback and mortality (Ulrich and Pankrath, 1983). Further, N deposition may lead to soil N saturation and acidification (Aber et al., 1989; Ågren and Bosatta, 1988; Matson et al., 2002; Butterbach-Bahl et al., 2011). However, because most terrestrial ecosystems are N-limited (LeBauer and Treseder, 2008; Vitousek, 1982) and particularly the temperate and boreal forests (Vitousek and Howarth, 1991), N deposition tends to increase tree growth and carbon sequestration (Solberg et al., 2009; Sievering et al., 2000; Townsend et al., 1996). A major source of uncertainty in analyses of the whole forest ecosystem response to atmospheric nitrogen deposition is the soil. Whereas the influx of carbon into the soil tends to be enhanced by additional N, as indicated above, the decomposition rate of soil organic matter may respond in different ways. In nutrient poor systems, or those already receiving high N inputs, increased N availability appears to reduce rates of decomposition,

whilst in nutrient rich systems or systems with low N deposition there is an increase (Berg et al., 2000, 2001; Jandl et al., 2007). Jandl et al. (2007) found that N fertilization stimulated forest biomass production, but microbial decomposition of SOM was sometimes stimulated, leading to a net C loss from the soil and formation of nitrogen oxides.

Growth was also particularly affected where there was a change in a environmental factor that was larger, dominating the effect of others such as temperature which suppressed growth in BASFOR and in LandscapeDNDC beech in central Europe. In regions where other factors, such as precipitation and nitrogen deposition, were also changing the impact was reduced or even reversed (for example in northern Germany, Denmark and northern Poland). Thus identification of key drivers from spatial patterns of forest dynamics is hampered by the fact that many variables covary at the European scale. Climatic variables are correlated with each other and to some extent with N deposition as well, with the lowest values of deposition being found in the northernmost, coldest regions. Likewise, soil N-content reflects to some extent the past history of N-deposition, although that causal relationship is likely only important in areas where previously both deposition and soil fertility were extremely low, such as Scandinavia (Hyvönen et al., 2008). More modest changes in environmental variables could also have a larger impact where they act in concert. For example, the large decrease in growth in LandscapeDNDC pine forests in northern Spain was due to the combined effect of reductions in temperature, precipitation and soil nitrogen.

7.4 Sensitivity of different biogeochemical processes to environmental change

We were also interested in which parts of the nitrogen and carbon balance were most perturbed and thus contributed most to changes in carbon sequestration and greenhouse gas balance. The largest sensitivity to decadal differences in the trees was NPP. This was accompanied by changes in nitrogen uptake from the soil, which was responsible for the largest change in soil nitrogen balance. Whilst there were also reductions in litter flux and soil respiration, these were more modest suggesting that they are less

sensitive to environmental change. The exception to this was where NPP was already very low due to low soil water availability leading to depletions in soil carbon and a larger reduction in soil respiration to restore the soil C balance. Similar to the geographical variations in N_2O discuss above, we found where decadal NPP decreased in BASFOR this changed the soil N balance through reduced uptake so that so that more nitrogen was available to be emitted. Thus N_2O emissions increased as growth decreased. In LandscapeDNDC there was a general reduction in emissions in the second decade after large emissions due to a larger soil N imbalance in the first decade.

7.5 Evaluation of methodology and outlook to future work

The tendency for soil nitrogen, and to a lesser extent carbon to be more out of balance in the first decade was found for BASFOR pine and in LandscapeDNDC. It is suggested that is due to imbalances between the initial soil and tree data. As this imbalance decreases during a model run (spinup) this creates a spurious factor in the time evolution. This was found to be particularly significant for C in LandscapeDNDC beech in Poland and for N in LandscapeDNDC and BASFOR in the NW corner of Spain, where the imbalance was largest, affecting the GHG balance in these areas. For N_2O reduced fluxes in the second decade were related to soil nitrogen changes but not changes in nitrogen uptake and growth. Likewise larger reductions in soil respiration in LandscapeDNDC were not related to reductions in litter flux and growth but were instead found to be more consistent with changes due to soil spinup. This suppressed the sensitivity of NEE to decadal change in LandscapeDNDC. The issue of spinup in models is not a new one (Yeluripati et al., 2009) but its effects need to be recognised so that false interpretations are not made and where possible reduced. Whilst one solution is to initialise with tree data and to run the model for a number of years to allow the soil to come into balance, this is not ideal since information in the soil data will be lost. A better solution would be to calibrate the initial values of the model to both the initial tree and soil data at each site where the model is run. However where many thousands of sites are computed, as in this study, such a calibration may not be practical.

The analysis in this study relied mainly on simple linear regressions. This is despite our understanding that many forest processes are likely to be nonlinear and as discussed above are affected by covarying environmental drivers. Whilst looking for linear relationships is a useful first step, model sensitivity studies varying the environmental drivers across Europe and analysing the responses will allow a deeper nonlinear analysis and understanding of the important underlying mechanisms.

In their study, L10 highlighted a number of factors which they identified as being potentially important for future growth in forests which have not been considered in this study. They suggested that factors such as management induced increases in fertility of soils, forest area expansion, aw well as changes to more productive species such as Sitka spruce will contribute to increased growth. However factors such as limitation in nutrients, increases in ozone concentration, climate change induced changes in species composition, increased frequency of insect outbreaks (Aber et al., 1998; Brumme and Khanna, 2008), increased frequency and intensity of forest fires will reduce growth. Such factors should be included in a future studies if our uncertainty in the future contribution of forests to the greenhouse gas balance is to be further reduced.

Uncertainty in model structure has been considered in this study through the use of four different forest models. Parameter uncertainty has not been quantified although recent studies would suggest that it is smaller than model structural uncertainty (van Oijen et al., 2011). Future modelling work should aim to quantify uncertainty in all inputs to the model including soil and tree initialisation, parameter and structural uncertainty. The large differences found between the models in this study highlight how differences in model implementation result in different predictions of forest dynamics across Europe. There is a clear need for future model development to reduce uncertainty in predictions of how environmental changes will impact on the future C- and N-cycle of European forests.

8 Conclusions

- This study found a European average carbon sink for 2011-2020 of $0.160 \pm 0.020\,\text{kgC m}^{-2}\,\text{yr}^{-1}$ for Scots pine and $0.138 \pm 0.062\,\text{kgC m}^{-2}\,\text{yr}^{-1}$ for European beech. The European average N_2O source for 2011–2020 was $0.285 \pm 0.125\,\text{kgN ha}^{-1}\,\text{yr}^{-1}$ for Scots pine and $0.575 \pm 0.105\,\text{kgN ha}^{-1}\,\text{yr}^{-1}$ for European beech.

- The GHG gas balance of forests was a sink with the uptake of CO_2 being dominant over the source of N_2O by a factor 18 (pine) and 8 (beech) and the sink of C in the trees larger than that for the soil.

- The models disagreed about whether pine or beech sequestered more carbon, with differences in growth rate dominating this.

- Carbon sequestration was highest in central Europe and lowest in high northern latitudes and Southern Spain. This geographical variation was primarily determined by spatial variation in tree growth rate.

- There were differences between the models and species about which weather variables accounted the most for geographical variation in growth. Some models identified precipitation as the main weather driver behind spatial variation in Scots pine with temperature driving the variation in beech. Other models had the opposite sensitivity.

- Most of the models were sensitive to soil N but there was disagreement about whether Scots pine or European beech forests were more sensitive to nitrogen availability.

- No single environmental driver dominated the response to changes between the decades 2011–2020 and 2021–2030. Growth was found to change more than

respiration. Forest growth was found to be most sensitive to change in environmental drivers in those parts of Europe where the drivers were limiting growth, where changes were particularly large or where changes acted in concert.

– In particular, some models were sensitive to modest changes in precipitation while others had a threshold response to very low soil water content due to low precipitation. European beech forests were found to be more vulnerable to drought than Scots pine although Scots pine forests were more sensitive to more modest changes in precipitation.

– N_2O emissions from soil were larger for European beech forests than Scots pine while NO emissions showed the reverse. This is likely to be due to differences in moisture content of the litter layer and differences in litter fall by Scots pine and European beech.

– Soil N and atmospheric deposition were found to be important for N_2O emissions from soils in most of the models. NPP was also important either through limiting the N available to be emitted or in the opposite sense by leading to enhanced litter fall and thereby increasing the N available for emission.

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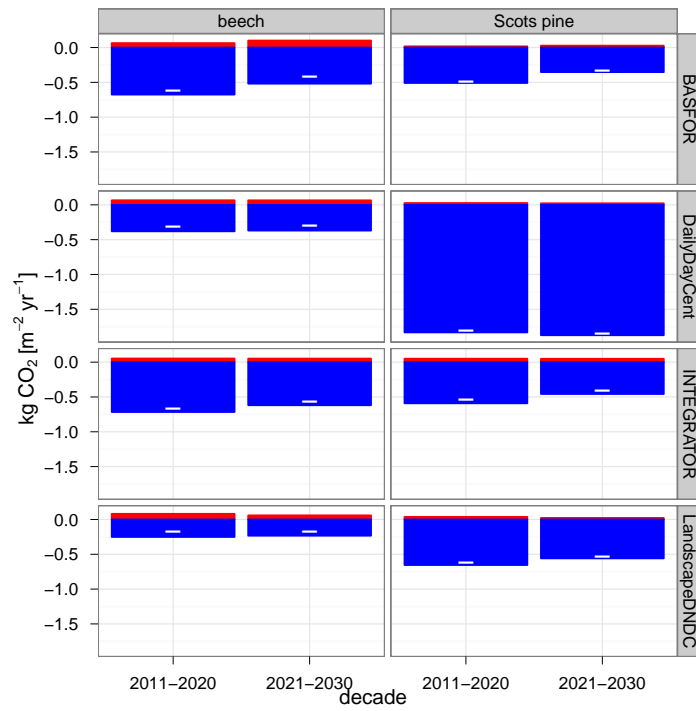**Table 1.** Area weighted decadal average European average values for Scots pine forests (kg C m^{-2} yr^{-1}) for years 2011–2020. N_2O has units kg N ha^{-1} yr^{-1}.

	BASFOR	LandscapeDNDC	DailyDayCent	INTEGRATOR	Mean	Standard Deviation
NPP	0.465	0.341	0.962		0.589	0.329
Soil Respiration	0.326	0.162	0.463		0.317	0.151
Exported C	0.090	0.066	0.216		0.124	0.081
Litter C	0.325	0.151			0.238	0.123
NEE	0.139	0.179	0.499	0.161	0.244	0.170
N_2O	0.146	0.329	0.227	0.438	0.285	0.126

Table 2. Area weighted decadal average European average values for European beech forests (kg C m^{-2} yr^{-1}) for years 2011–2020. N_2O has units kg N ha^{-1} yr^{-1}.

	BASFOR	LandscapeDNDC	DailyDayCent	INTEGRATOR	Mean	Standard Deviation
NPP	0.659	0.332	0.354		0.448	0.183
Soil respiration	0.475	0.263	0.250		0.329	0.126
Exported C	0.153	0.082	0.062		0.099	0.048
Litter C	0.478	0.237			0.357	0.170
NEE	0.184	0.068	0.103	0.195	0.138	0.062
N_2O	0.556	0.712	0.574	0.458	0.575	0.105

Fig. 1. European average greenhouse gas balance for two dominant forest species (Scots pine and beech) for decades (1) 2011–2020 and (2) 2021–2030. Positive is a source and negative a sink. N_2O has been scaled with a greenhouse gas warming potential (GWP) of 310 and is in red. CO_2 is in blue.
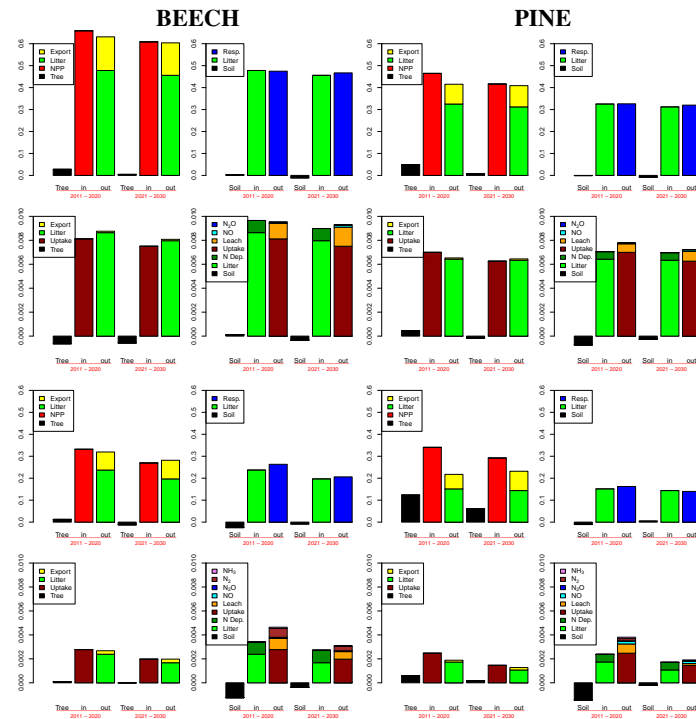
Fig. 2. European average carbon and nitrogen budgets. The plots are grouped in sets of four in which the top and bottom rows are carbon and nitrogen budgets respectively. The left plots are for trees and the right plots soil. The top set of plots are for BASFOR and the bottom set for LandscapeDNDC. The units are kg m^{-2} yr^{-1}.

BASFOR　　**DailyDayCent**　　**INTEGRATOR**　　**LandscapeDNDC**

-0.24 -0.20 -0.16 -0.12 -0.08 -0.04 0.00 0.04 0.08 0.12 0.16 0.20 0.24
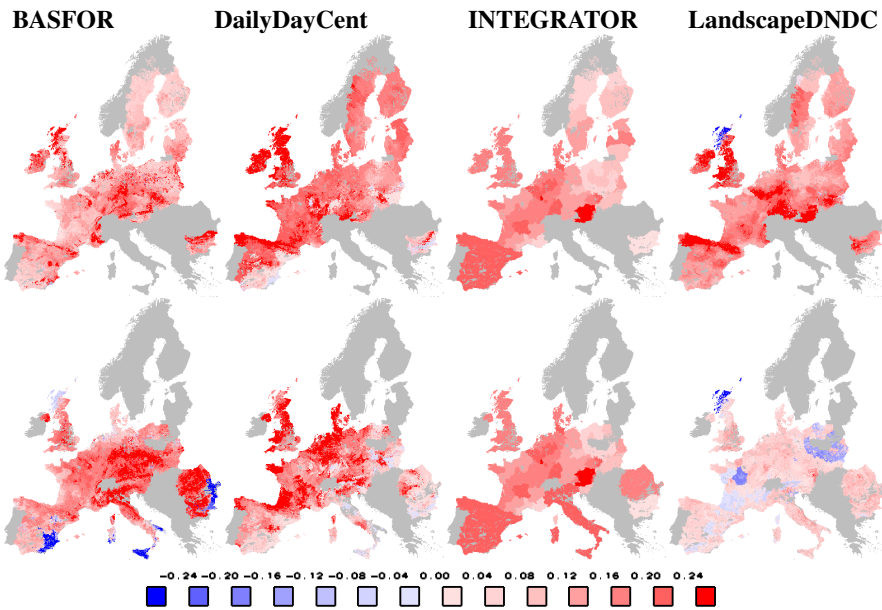
Fig. 3. Decadal average NEE (kg C m^{-2} yr^{-1}) 2011–2020 for Scots pine (top row) and beech (bottom row). The interval for DailyDayCent Scots pine is three times that shown in the legend.
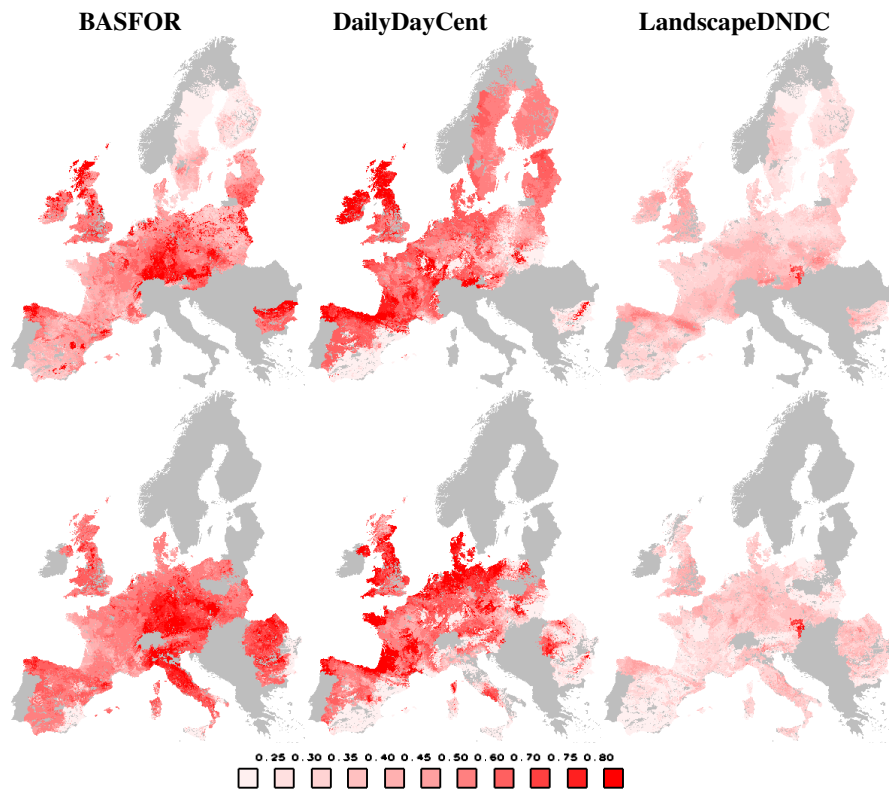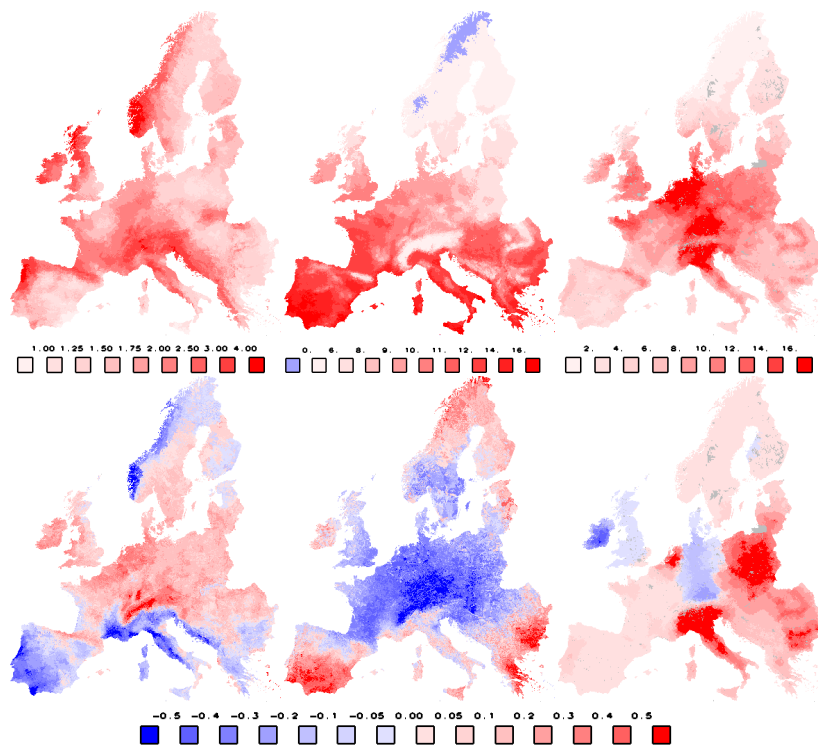
BASFOR　　　**DailyDayCent**　　　**LandscapeDNDC**

0.25 0.30 0.35 0.40 0.45 0.50 0.60 0.70 0.75 0.80

Fig. 4. Decadal average NPP (kg C m^{-2} yr^{-1}) 2011–2020 for Scots pine (top row) and beech (bottom row). The interval for DailyDayCent Scots pine is twice that shown in the legend.

1.00 1.25 1.50 1.75 2.00 2.50 3.00 4.00   0. 6. 8. 9. 10. 11. 12. 14. 16.   2. 4. 6. 8. 10. 12. 14. 16.

−0.5 −0.4 −0.3 −0.2 −0.1 −0.05 0.00 0.05 0.1 0.2 0.3 0.4 0.5

Fig. 5. The top row shows decadal average environmental drivers 2011–2020. The bottom row are difference in decadal average environmental drivers 2021–2030 minus 2011–2020. The left column is temperature (°C), the middle is precipitation (mm day^{-1})) and the right is nitrogen deposition (kg N ha^{-1} yr^{-1}).

BASFOR　　　　**DailyDayCent**　　　　**LandscapeDNDC**

−0.12 −0.10 −0.08 −0.06 −0.04 −0.02 0.00 0.02 0.04 0.06 0.08 0.10 0.12
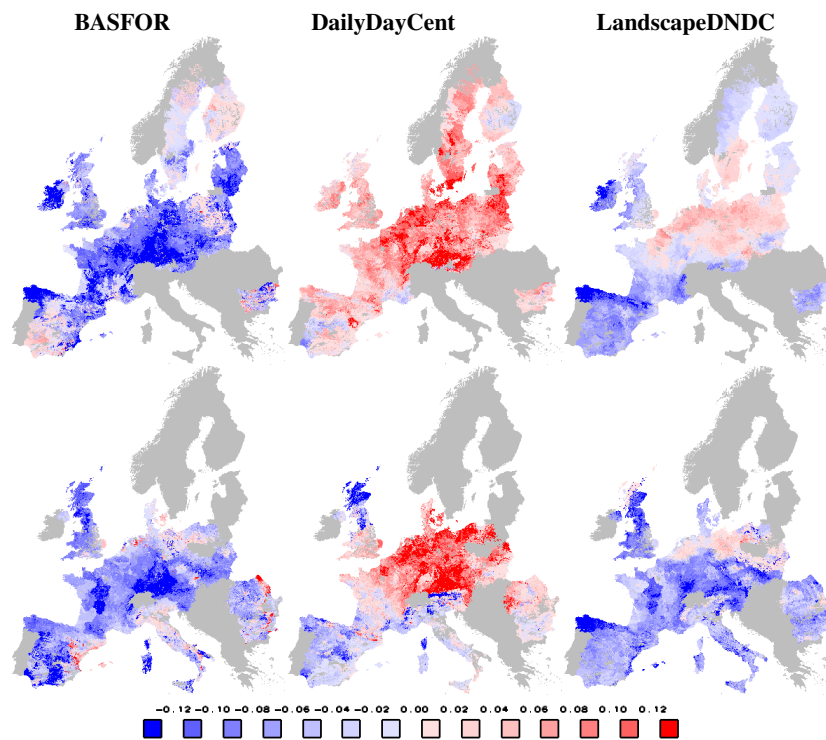
Fig. 6. Difference in decadal average NPP (kg C m^{-2} yr^{-1}) 2021–2030 minus 2011–2020 for Scots pine (top row) and beech (bottom row). The interval for DailyDayCent Scots pine is twice that shown in the legend.
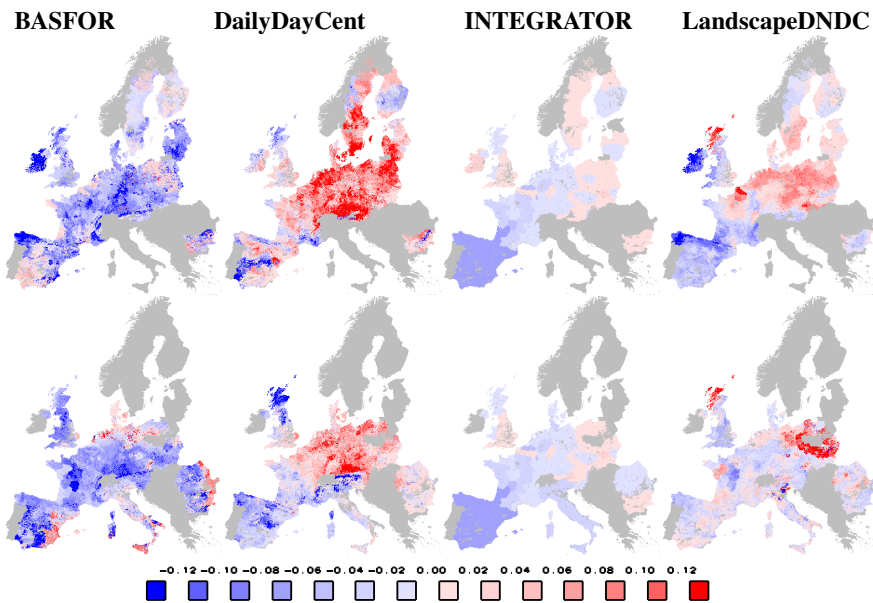
Fig. 7. Difference in decadal average NEE (kg C m^{-2} yr^{-1}) 2021–2030 minus 2011–2020 for Scots pine (top row) and beech (bottom row).
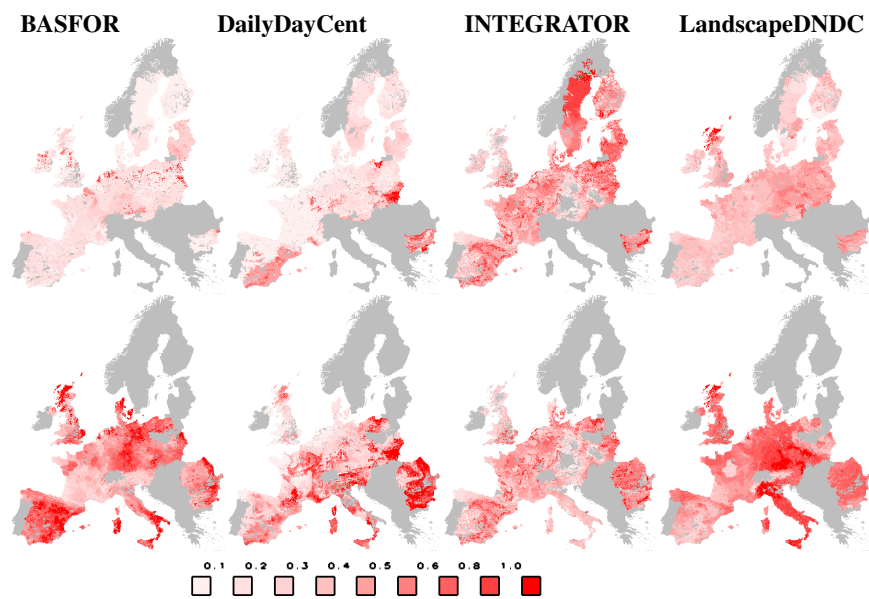
Fig. 8. Decadal average N$_2$O (kg N ha^{-1} yr^{-1}) 2011–2020 for Scots pine (top row) and beech (bottom row).

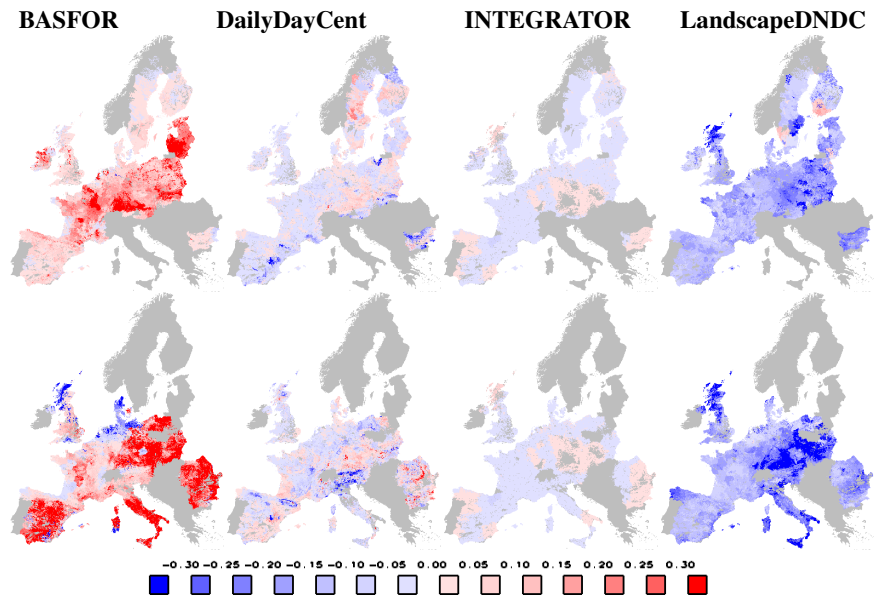**Fig. 9.** Difference in decadal average N_2O (kg N ha^{-1} yr^{-1}) 2021–2030 minus 2011–2020 for Scots pine (top row) and beech (bottom row).