



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 N₂O 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 $0.160 \pm 0.020 \text{ kgC m}^{-2} \text{ yr}^{-1}$ (pine) and $0.138 \pm 0.062 \text{ kgC m}^{-2} \text{ yr}^{-1}$ (beech) and N₂O source of $0.285 \pm 0.125 \text{ kgN ha}^{-1} \text{ yr}^{-1}$ (pine) and $0.575 \pm 0.105 \text{ kgN ha}^{-1} \text{ yr}^{-1}$ (beech). The European av-

erage greenhouse gas potential of the carbon sink was 18 (pine) and 8 (beech) times that of the N₂O 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 N₂O 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 N₂O emission. N₂O 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 absorb about 10% of European CO₂ 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 $75 \pm 20 \text{ g C m}^{-2} \text{ yr}^{-1}$. 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 CO₂ (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 has 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 photo-

synthesis 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 CO₂ fluxes using forest chronosequences. They found that 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). However, Dieleman et al. (2010) found that soil nitrogen also influenced microbial activity and, thus, C decomposition and heterotrophic respiration, reducing the influence of increased N on soil C. 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 growth 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 CO₂ concentration stimulates growth and increases water-use efficiency, but trees may acclimate. Whilst N is limiting, changes in N deposition would be expected to influence 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 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; Dieleman et al., 2010). 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 consid-

ered. 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) 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 increased 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 N₂O and NO trace gases from soils (Pilegaard et al., 2006; Kesik et al., 2005) with N₂O being a harmful atmospheric gas contributing to climate change. Since N₂O is approximately 310 times as effective as CO₂ 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 N₂O 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 N₂O 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

To aid model comparison a table has been created (Table 1) summarising the main model characteristics and initialisation choices. In addition, descriptions of each model are given below.

2.1.1 BASFOR

The BASic FOReSt simulator, BASFOR, (Van Oijen et al., 2005) is a deterministic forest model. The model simulates carbon and nitrogen cycling in trees, soil organic matter and litter. 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-, CO₂- 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). Papers describing more recent model developments are Van Oijen and Thomson (2010) and Van Oijen et al. (2011).

To find the most plausible BASFOR parametrisation for use across Europe, we employed Bayesian calibration (BC) (Van Oijen et al., 2005), 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%. In addition, BASFOR was calibrated against observational data of averaged emissions of N₂O 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%. For the beech forest pa-

rameters 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 maximum a posteriori (MAP) parameter set was taken as the parametrisation for BASFOR.

2.1.2 DailyDayCent

The biogeochemical model DailyDaycent is a daily time step version of the CENTURY model (Parton and Rasmussen, 1994). DailyDaycent simulates decomposition, nutrient flows, soil water and soil temperature. DailyDaycent simulates the biogeochemical processes of C, N, phosphorus and sulphur cycling associated with SOM dynamics. 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, mineralisation of nutrients, N gas emissions from nitrification and denitrification, and CH₄ oxidation in non-saturated soils. 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. N gas fluxes from nitrification and denitrification are driven by soil NH₄ and NO₃ 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 at 2000, for age class 10–20 yr at 1990 and so on. Before this initialisation the areas which were assumed to be forests started growing from 1901. This previous forest was cleared 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.

2.1.3 INTEGRATOR

INTEGRATOR assesses N and GHG emissions from 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 emissions and N leaching and CO₂ emissions in agricultural and non-agricultural soils. This study is limited to the calculation of CO₂ and N₂O exchange fluxes from forests using the models EFISCEN and YASSO. The model EFISCEN is described in Sect. 2.4.

YASSO (Liski et al., 2003, 2005) is a dynamic soil carbon model consisting of decomposition and woody litter compartments. Allocation of non-woody litter to decomposition compartments is made according to its chemical composition. Woody litter is allocated to fine or coarse compartments based on size. Each woody litter compartment has a fractionation rate that determines the proportion of its contents to be

Table 1. Characteristics of the four models used in this study.

	BASFOR	DailyDayCent	INTEGRATOR/YASSO	LandscapeDNDC
Timestep	Daily	Daily	Annual	Daily
# State variables(tree, soil)	14(6, 8)	20(10, 10)	13(8, 5)	38(10, 28)
# Parameters	48	> 100	11	> 100
# Soil levels	1	12	1	Different for each NCU: three soil horizons split into 2 cm, 5 cm and 10 cm layers plus two litter layers.
Driving environment variables	Temperature, radiation, precipitation, humidity, wind speed, N-deposition, CO ₂ .	Temperature, radiation, precipitation, humidity, wind speed, N-deposition, CO ₂ .	Temperature, radiation, precipitation, humidity, N-deposition, CO ₂ .	Temperature, radiation, precipitation, vapour pressure, N-deposition, CO ₂ .
Plant growth	Light use efficiency based, limited by available N and soil water.	Functional dependence on genetic potential, phenology, nutrient availability, water/temperature stress, and solar radiation.	Model based on measured growth curves and age distribution, modified by climate (temperature and precipitation) and nitrogen effects.	Light use efficiency based, limited by available N and soil water.
Soil pools	Fast, slow and litter	Fast and slow	Two woody litter compartments and five decomposition compartments (extractives, celluloses and lignin-like compounds, humus1 and humus2).	Three litter pools (recalcitrant, labile, very labile) and two humus pools (active, non active).
Soil processes	Turnover depends on temperature.	Decomposition of litter and soil organic matter and nutrient mineralisation are functions of substrate availability, substrate quality (lignin %, C/N ratio), and water/temperature stress.	First order rate constants depending on temperature and precipitation minus potential evapotranspiration between May and Sep.	Decomposition depends on temperature, water, and the population of microbes which is N dependent.
N emissions	Calibrated fraction of mineral N.	Explicit nitrification and denitrification processes.	Empirical model or meta-model based on DNDC.	Explicit nitrification and denitrification processes.
Model initialisation forest	EFISCEN	From planting calibrated to EFISCEN.	EFISCEN	EFISCEN
Model initialisation soil	NitroEurope provided soil input	Initialised to equilibrium	NitroEurope provided soil input	NitroEurope provided soil input
Soil spinup	50 yr	> 110 yr	10–30 yr	5 yr
Pedo-transfer functions used in calculating the soil water profile	Derived from Robertson (1999, p. 45).	Derived from Gupta and Larson (1979); Rawls et al. (1982).	Not required	Derived using van Genuchten (1980) formula.
Thinning	Decadal 20 % thinning for trees aged 20 yr and over.	Decadal 20 % thinning for trees aged 20 yr and over.	EFISCEN	Decadal 20 % thinning for trees aged 20 yr and over.
Harvesting	Pine 80 yr, beech 100 yr	None	EFISCEN	Pine 80 yr, beech 100 yr.

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.

2.1.4 LandscapeDNDC

LandscapeDNDC (Haas et al., 2012) 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 recoded from the agricultural DeNitrification-DeComposition (DNDC) model and its forest adaptation PnET-N-DNDC (Li et al., 1992, 2000). For the present study, LandscapeDNDC used the PnET-N physiology module. In addition, the silvicultural tracking routine is called once a year (Grote et al., 2011). 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 and used for foliage and wood growth in the next year. In PnET-N (Li et al., 2000) the nitrogen concentration 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 considering retranslocation back into the plant before foliage shedding. Litter mineralisation and linked heterotrophic respiration as well as mineral N release are calculated as described earlier (Li et al., 2000). Ecosystem N turnover includes plant N uptake, mineralisation, microbial immobilisation, nitrification, denitrification or leaching considering aerobic as well as anaerobic pathways (Li et al., 2000).

2.2 NitroEurope classification units (NCUs)

To facilitate model computations across Europe, the EU25 plus Norway Switzerland and the Balkan countries (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.

Soil water profiles were calculated for each model separately as given in Table 1.

2.4 EFISCEN and initial forest data

Initial forest data were derived from EFISCEN. The European Forest Information Scenario model (EFISCEN V3.1)

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 time step, the national amount of wood to be produced from the forest is defined and allocated over the forest types according to the felling possibilities as defined by actual age class distributions and the management regime. Using factors to convert growing stock volumes to biomass (biomass expansion factors, BEFs) and turnover rates, EFISCEN is able to estimate carbon stocks and litterfall.

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

Trees which were initially aged above the rotation length were considered to be natural unmanaged forests and, therefore, not harvested. 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 initialised 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 (Nakicenović 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 Climate Data Operators (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 NH₃ 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 NH₃ and NO_x, derived from the EMEP model (Simpson et al., 2003; Tarasón et al., 2007). For 2020 the non-agricultural N emission scenario 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.

2.6.3 CO₂ timeseries

Future CO₂ 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 CO₂ sink is larger than the N₂O emission source (Fig. 1) although, the CO₂ sink for DailyDayCent pine is substantially larger than the others. Comparing the GHG balance for the two decades, there is generally a greater CO₂ sink in the first decade than in the second, although DailyDayCent pine has the opposite. All the models have larger N₂O emissions for beech than for pine forests.

There is, however, disagreement on whether pine or beech forests have a greater CO₂ sink, with LandscapeDNDC and DailyDayCent having a larger sink for pine forests than beech and BASFOR and INTEGRATOR vice versa. In addition, there are larger changes in CO₂ sink strength between decades for BASFOR and INTEGRATOR than for LandscapeDNDC and DailyDayCent.

Three of the models have larger N₂O 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

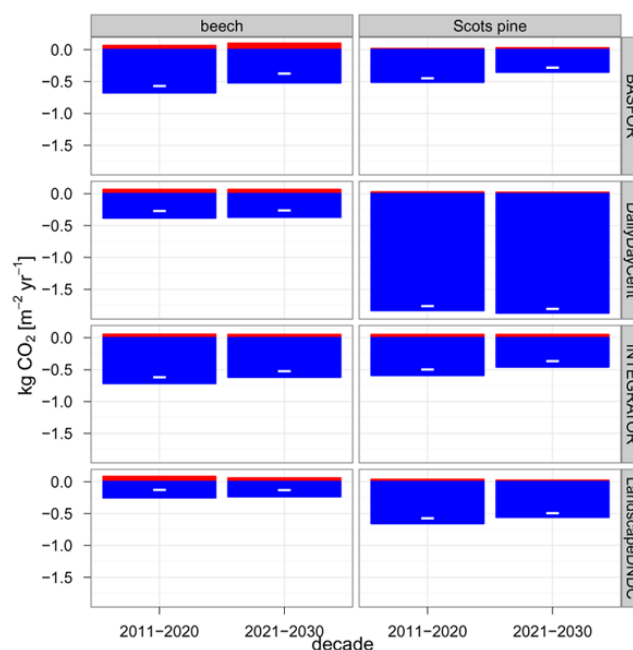


Fig. 1. European average greenhouse gas balance for two dominant forest species (Scots pine and beech) for decades (1) 2011–2020 and (2) 2021–2030. Positive is a source and negative a sink. N₂O has been scaled with a greenhouse gas warming potential (GWP) of 310 and is in red. CO₂ is in blue.

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. In this context, a lack of equilibrium or balance reflects a difference between incoming and outgoing fluxes of C and N from the trees or the soil and, therefore, implies a change in the stock of C and N in the same.

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 and uptake and litter being the largest N fluxes in trees. The litter flux is 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 caused by 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

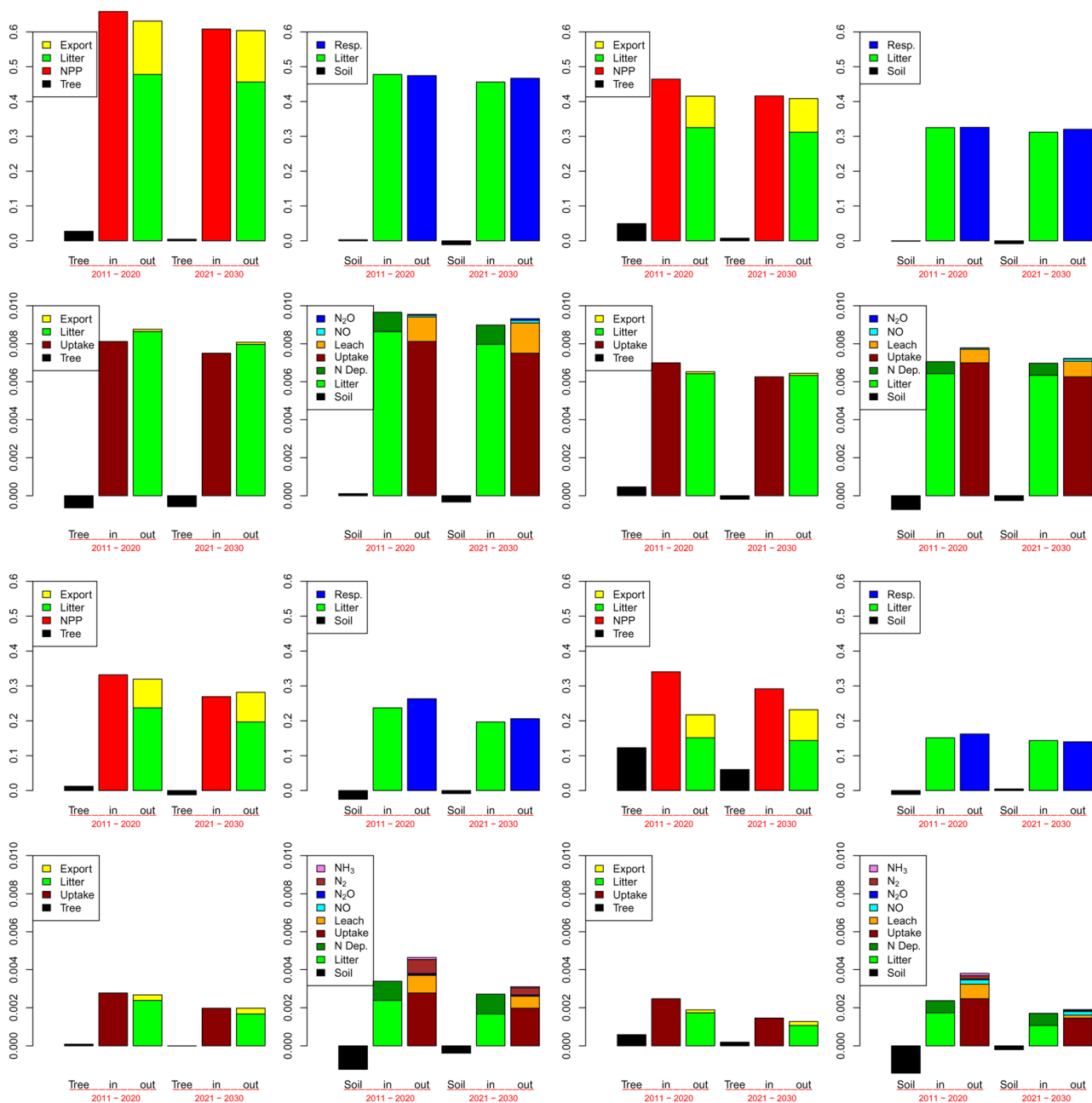


Fig. 2. European average carbon and nitrogen budgets. The plots are grouped in sets of four in which the top and bottom rows are carbon and nitrogen budgets, respectively. The left plots are for trees and the right plots soil. The top set of plots are for BASFOR and the bottom set for LandscapeDNDC. The units are kg C or $\text{N m}^{-2} \text{yr}^{-1}$.

LandscapeDNDC have less NO and more N_2O 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_2O 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 is 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 how 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. An exception is BASFOR beech which is closer to equilibrium in the second decade.

3.2.3 Model differences

Carbon and nitrogen cycling is more vigorous in BASFOR than in LandscapeDNDC, with greater NPP, but also a larger litter flux and hence a larger soil respiration.

As noted (Sect. 3.1), the models do not agree on 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. In contrast, 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 this is counteracted by a larger reduction in soil respiration so the change in 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 N₂O emissions and leaching in the first decade which reduces in the second decade. BASFOR shows increased N₂O emissions and leaching in the second decade, with larger emissions than LandscapeDNDC. The reduction in leaching is more dramatic for LandscapeDNDC pine than beech.

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 N₂O emissions noted above.

3.3 European averaged climate differences between decades

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. 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.

4 Carbon sequestration

4.1 Spatial variation in carbon sequestration

Maps of carbon sequestration and growth averaged over the models present in this study and their standard deviation have been created for pine (Fig. 3) and beech forests (Fig. 4) to highlight model agreement and disagreement and, thus, uncertainty. INTEGRATOR results were not included in the growth maps since unlike the other models, INTEGRATOR does not calculate NPP and plant respiration. INTEGRATOR NEE is the sum of tree carbon sequestration calculated by EFISCEN and soil carbon sequestration calculated by YASSO. While the inclusion of INTEGRATOR results for NEE, but not NPP makes direct comparison of NPP and NEE more opaque, of primary concern for this work was to estimate the structural uncertainty in NPP and NEE by including the maximum number of models possible in our results. In addition, given the large and very probably unrealistic values of NPP and NEE for DailyDayCent pine forests, as noted in Sect. 3.1 it was decided not to include this model's results into the pine model averages and standard deviations.

4.1.1 Scots pine

Similarities in the geographical variation of NEE and NPP suggests that growth dominates sequestration. The largest growth and sequestration is in central/southern Germany, Austria, northern Bulgaria and northern Spain. The smallest growth and sequestration is in high northern latitudes, Poland and southern Spain.

For growth, the largest uncertainties between models are in areas where both models have high growth, but there is a magnitude difference (central Europe and NW Spain). However, there are also areas of large uncertainty where only one

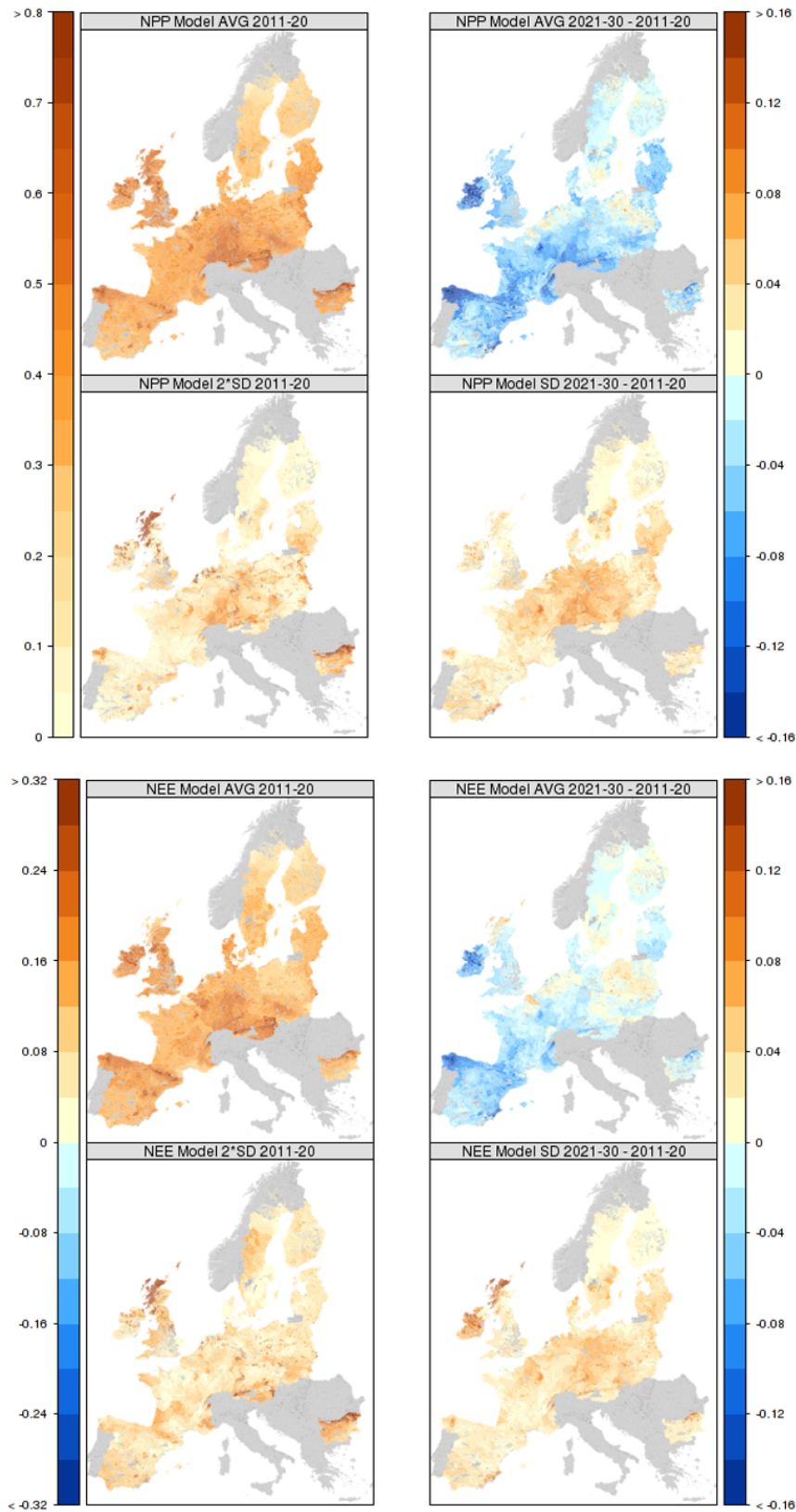


Fig. 3. NPP (top four plots) and NEE (bottom four plots) ($\text{kg C m}^{-2} \text{ yr}^{-1}$) for Scots pine. The first and third rows are averages over the models. The second and fourth rows are standard deviations (right column) or two times standard deviations (left column) over the models. The left column is the decadal average 2011–2020. The right column is the difference in decadal average 2021–2030 minus 2011–2020.

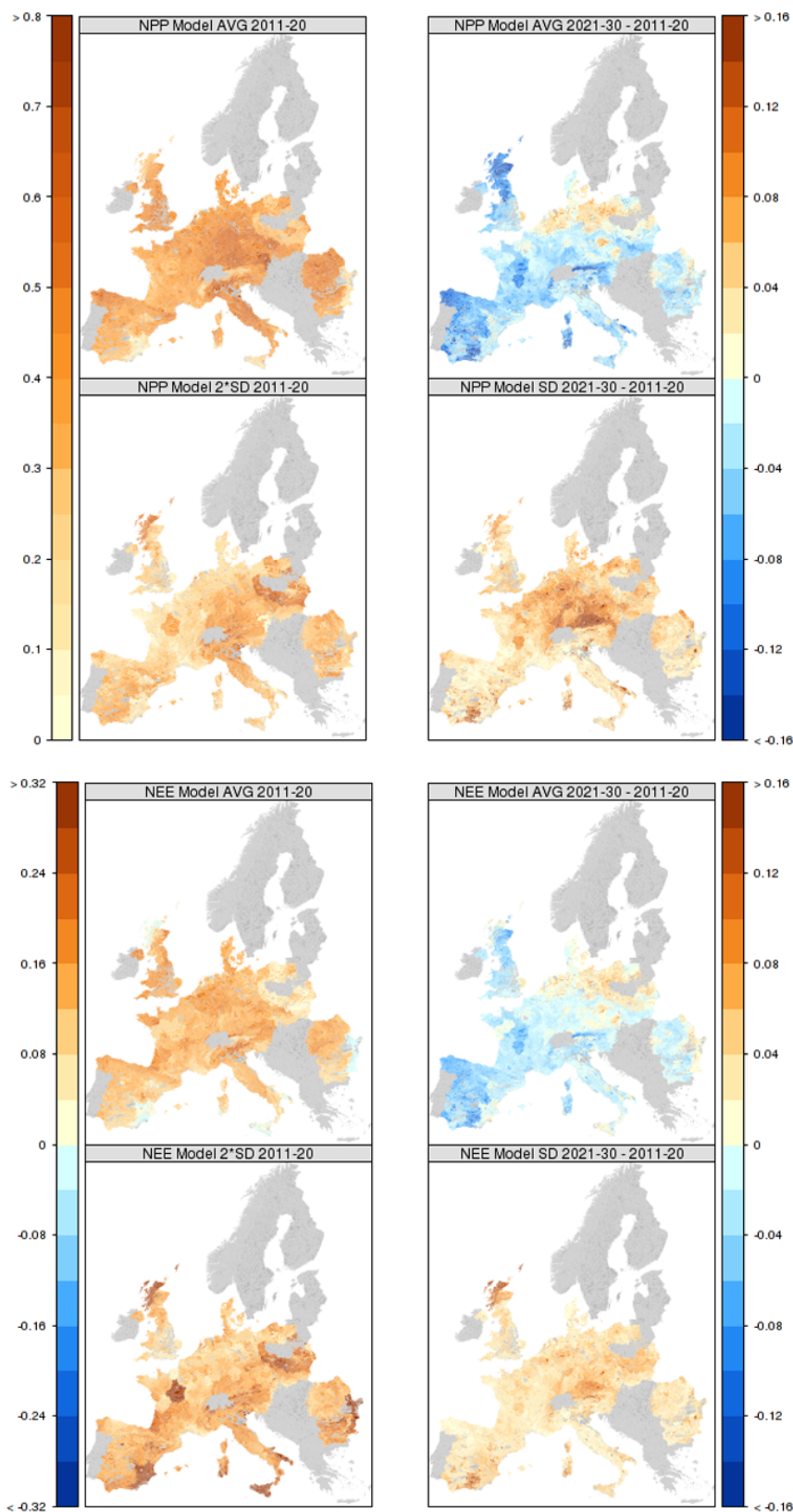


Fig. 4. NPP (top four plots) and NEE (bottom four plots) ($\text{kg C m}^{-2} \text{ yr}^{-1}$) for European beech. The first and third rows are averages over the models. The second and fourth rows are standard deviations (right column) or two times standard deviations (left column) over the models. The left column is the decadal average 2011–2020. The right column is the difference in decadal average 2021–2030 minus 2011–2020.

Table 2. R^2 of linear regressions for NPP of Scots pine and European beech forests.

Scots Pine	BASFOR	LandscapeDNDC	DailyDayCent
Precipitation	0.04	0.19	
Temperature	0.12	0.13	
Initial soil N	0.65	0.02	
N deposition	0.11	0.12	
European Beech	BASFOR	LandscapeDNDC	DailyDayCent
Precipitation	0.08	0.00	0.04
Temperature	0.08	0.15	0.07
Initial soil N	0.16	0.03	0.00
N deposition	0.22	0.06	0.01

model has high growth for example NW Scotland and Bulgaria.

The large uncertainties in the areas where there are magnitude differences in NPP are less apparent for NEE suggesting that opposing magnitude differences in soil respiration compensate for model differences in growth. The smaller interval in the uncertainty plots of NEE allows us to see a greater geographical heterogeneity in the model uncertainty although this is also affected by the inclusion of output from INTEGRATOR. Indeed greater model uncertainty over Spain is largely due to the absence of any variation in NEE in Spain in INTEGRATOR. This is due to Spain being averaged for this model, caused by a lack of more detailed spatial data.

Linear regressions can give a first indication of which drivers are most important for growth in each of the models. Linear regression for the pine NCUs (Table 2) suggests that the strongest drivers of NPP for LandscapeDNDC are precipitation, followed by temperature and nitrogen deposition. For BASFOR nitrogen is more important with temperature and N deposition being less important. Unlike LandscapeDNDC temperature is more important than precipitation.

The influence of NPP was found to be particularly strong for soil respiration in BASFOR ($R^2 = 0.86$) suggesting that the NPP-respiration coupling in this model is strong for pine. For LandscapeDNDC, NPP was the largest influence on soil respiration, but the correlation was weaker ($R^2 = 0.44$).

4.1.2 European beech

There are similarities with pine with highest sequestration over central and southern Germany and Austria. There are differences with greater sequestration over SE France, N Germany, Denmark and the Netherlands than for pine, but lower sequestration and growth over Poland, SE Spain and NW Scotland.

Linear regression (Table 2) suggests that unlike pine temperature is more important than precipitation for beech according to LandscapeDNDC and DailyDayCent. Whereas for BASFOR precipitation is relatively more and temperature less important for beech than for pine. BASFOR has a

weaker relationship with soil N than for pine which may suggest that N is less limiting for growth in BASFOR beech.

These regression differences help explain greater model uncertainty for beech than for pine for growth and NEE. Greater uncertainty over Poland is due to differences in sensitivity to N. Differences over specific areas in northern France are due to differences in harvesting. Particularly marked are differences in NEE in more extreme climates (NW Scotland, SE Spain, Sicily, the heel of Italy and E. Romania). BASFOR and DailyDayCent have no or very low growth in dry areas of the Mediterranean and negative NEE, whereas LandscapeDNDC does not show a marked drought response in these areas.

Soil respiration in LandscapeDNDC has a larger dependence on NPP for beech than pine (NPP $R^2 = 0.77$) opposite to that of BASFOR (NPP $R^2 = 0.55$). This stronger coupling for LandscapeDNDC helps explain the lower C sequestration for similar growth for beech than pine noted in Sect. 3.2.

4.2 Decadal differences in carbon sequestration

4.2.1 Environmental drivers and management

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.

4.2.2 Scots pine

In general, both growth and NEE decrease over time although there are significant areas such as over Poland and the Netherlands where growth and to a greater extent NEE have increased. Over Poland and the Netherlands N deposition has increased, leading to higher growth whereas soil respiration has reduced due to lower temperatures. The largest reduction in growth is in Ireland, where temperature and precipitation have modestly increased but N deposition has fallen significantly, and NW Spain where a reduction in soil N in BASFOR and LandscapeDNDC has combined with modest falls in temperature and precipitation.

As for NPP the largest uncertainty in the change in NPP is in southern Germany. To the north of this region in Belgium, the Netherlands NE Germany and northern Poland uncertainty is high for both NPP and sequestration. This is due to

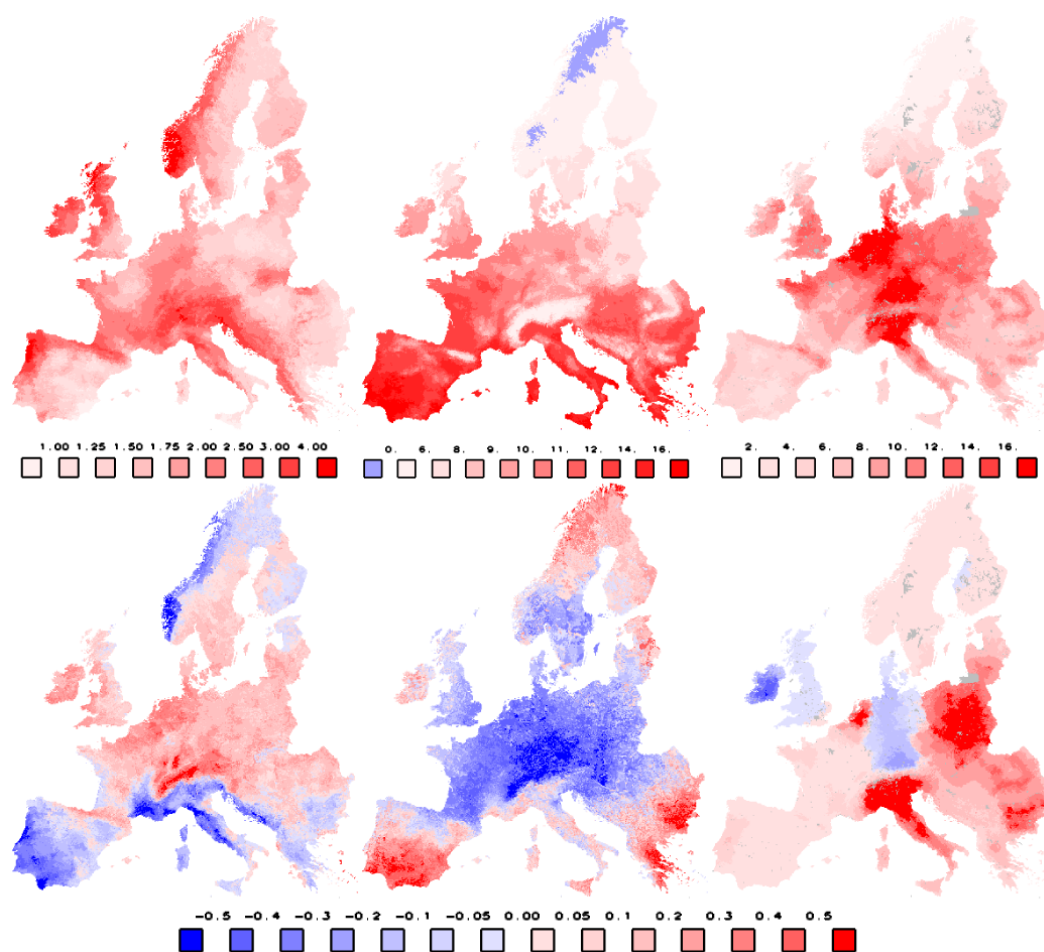


Fig. 5. The top row shows decadal average environmental drivers 2011–2020. The bottom row are differences in decadal average environmental drivers 2021–2030 minus 2011–2020. The left column is precipitation (mm day^{-1}), the middle is temperature ($^{\circ}\text{C}$) and the right is nitrogen deposition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

BASFOR and LandscapeDNDC having opposite responses to the decadal climatic changes. Taking an average in this area temperature was 0.8°C lower than the European average in the first decade and precipitation was 9 % lower. In the second decade temperature fell by 0.3°C while precipitation increased by 11 %. As noted in Sect. 4.1.1 growth in BASFOR is more sensitive to temperature than precipitation whereas LandscapeDNDC has the opposite sensitivity. Uncertainty is larger for NEE in Ireland than NPP due to the inclusion of results from INTEGRATOR which is less sensitive to changes in N deposition than the other two models.

4.2.3 European beech

For beech there is greater similarity between the change in growth and NEE than for pine. There is an area of increased growth and NEE in the Netherlands, northern Germany and Poland greater than that found for pine largely due to the inclusion of results from the DailyDayCent which similar to

LandscapeDNDC has a greater sensitivity to changes in precipitation than to temperature. However, like pine, the area where growth and sequestration have decreased is greater. This is particularly marked over the northern UK, particular areas in France (due to a lack of strong growth in recently harvested areas) and southern Spain where reduced precipitation and greater temperatures increase the already weak growth in this area due to drought.

As found before there are larger model uncertainties for beech than pine. These uncertainties are greatest over southern Germany and Austria where BASFOR and LandscapeDNDC have reduced growth and NEE, whereas DailyDayCent has strong increased growth and NEE cancelling somewhat the influence of the other models in the mean in this region. There is also greater uncertainty in southern Spain where not all models have as strong a reduction in growth as BASFOR. For NEE there are larger uncertainties over Poland where larger reductions in soil respiration in this region for LandscapeDNDC are not found for the other models.

Table 3. R^2 of linear regressions for N_2O and the logarithm of N_2O of Scots pine and European beech forests.

Scots Pine	BASFOR	log(BASFOR)	LandscapeDNDC	log(LandscapeDNDC)	DailyDayCent	INTEGRATOR
Precipitation	0.00	0.00	0.00	0.04	0.06	0.09
Soil N	0.48	0.35	0.15	0.17	0.12	0.04
N deposition	0.02	0.11	0.01	0.15	0.01	0.03
NPP	0.24	0.35	0.00	0.02	0.46	
European Beech	BASFOR	log(BASFOR)	LandscapeDNDC	log(LandscapeDNDC)	DailyDayCent	INTEGRATOR
Precipitation	0.04	0.24	0.00	0.00	0.00	0.08
Soil N	0.35	0.17	0.15	0.09	0.00	0.01
N deposition	0.00	0.01	0.10	0.18	0.00	0.03
NPP	0.00	0.00	0.13	0.41	0.20	

5 N_2O emissions

5.1 Spatial variation in N_2O emissions

Maps of N_2O for pine Fig. 6 show highest values in high northern latitudes SE Spain and eastern Europe with lower values in northern and western Spain, Austria, the Czech Republic and SE Germany. Model differences are largest over Sweden where INTEGRATOR has high emissions, but the other models do not. It is harder to see a clear pattern of uncertainty for the rest of Europe although there is a general tendency to have higher uncertainty where N_2O emissions are higher such as in Austria, the Czech Republic and SE Germany and parts of northern Spain. In general, there appears to be less agreement between models than for carbon sequestration.

For N_2O emissions in pine forests BASFOR, LandscapeDNDC and DailyDayCent have similar relationships to driving variables (Table 3). Soil N has the strongest relationship for BASFOR and LandscapeDNDC and mineral N has second strongest relationship for DailyDayCent. NPP has the strongest relationship for DailyDayCent and the second strongest relationship for BASFOR and by the second decade NPP is also important for LandscapeDNDC ($R^2 = 0.21$) along with N deposition ($R^2 = 0.24$). The strong relationship of N_2O with NPP indicates that smaller growth leads to 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.

As already noted N_2O emissions are higher for beech forests than pine. The pattern of highest emission is somewhat similar to that of pine forests with higher values over SE Spain, eastern regions such as Romania, Bulgaria, Slovakia and Poland although there are now also higher values over southern Germany, northern France and Italy. Similar to pine there are lower values over northern and western Spain, SW France and parts of the Alps. There is a greater discernible pattern of uncertainties for beech than pine with higher uncertainties over Austria, the Czech Republic, Eastern Germany, NW Scotland, Bulgaria, eastern Spain and southern Italy. There is a split in the models with BASFOR and Land-

scapeDNDC having higher emissions in central Europe and Italy than DailyDayCent and INTEGRATOR.

Similar to pine DailyDayCent emissions from beech forests have their strongest relationship with NPP (Table 3). However, for BASFOR the relationship with NPP is weaker than for pine supporting the suggestion in Sect. 4.1.2 that N is less limiting for growth in BASFOR beech. Similar to DailyDayCent NPP is one of the most significant factors for LandscapeDNDC. The importance of NPP increases yet further if we carry out a linear regression on $\log(N_2O)$ rather than N_2O and there is also a strong relationship with carbon litter flux ($R^2 = 0.43$). Indeed unlike BASFOR and DailyDayCent there is a positive correlation between NPP and N_2O emissions. Thus, for LandscapeDNDC, N_2O 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.

5.2 Decadal differences in N_2O Emissions

The decadal change in N_2O depicted in Fig. 6 and the large uncertainty can best be understood as a difference plot between BASFOR and LandscapeDNDC which generally predicted opposite responses of N_2O to the environmental changes. The decadal differences in N_2O were 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.

For both beech and pine, LandscapeDNDC has widespread lower emissions in the second decade 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.

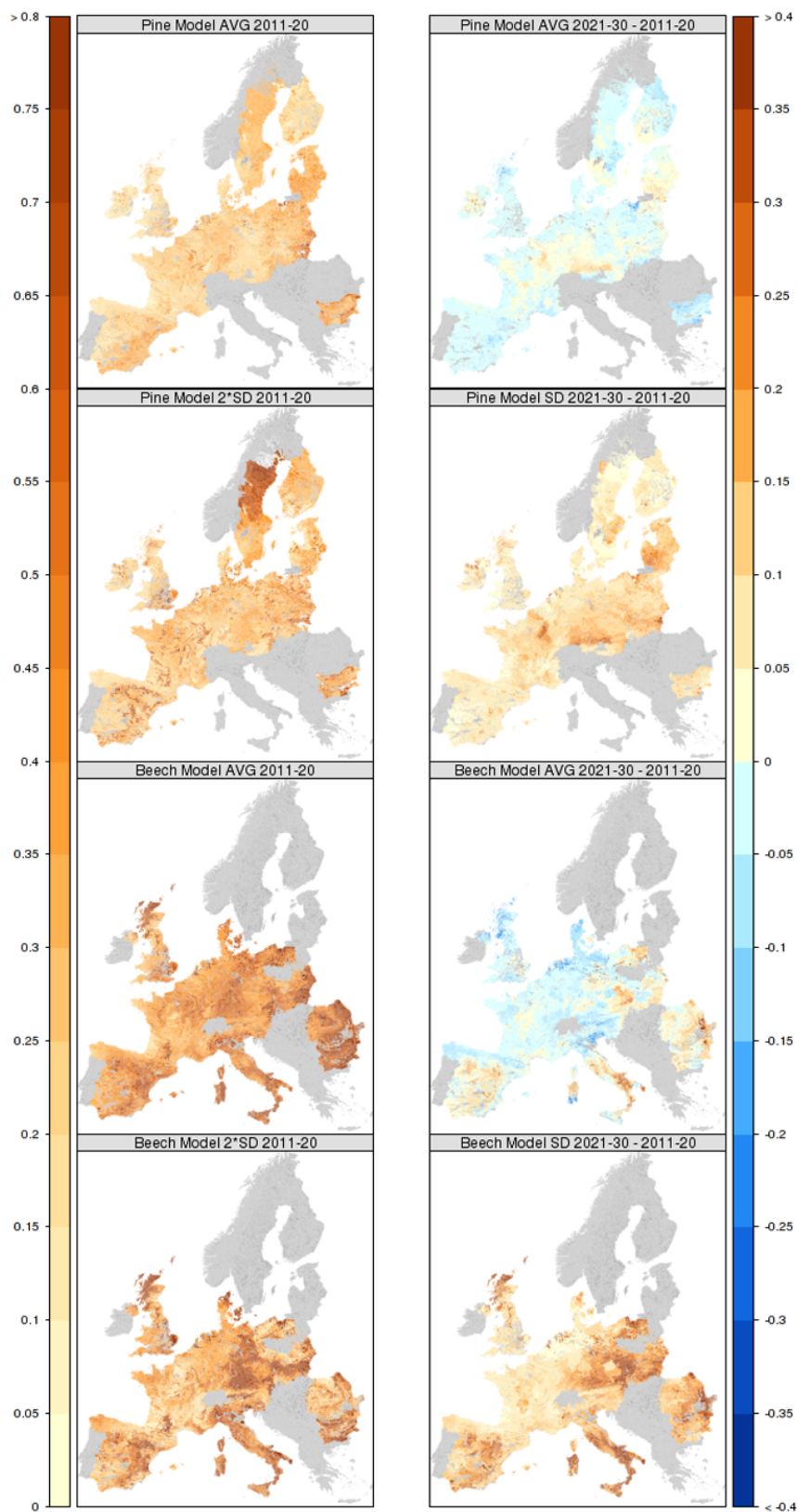


Fig. 6. N_2O ($\text{kg N ha}^{-1} \text{yr}^{-1}$) for Scots pine and European beech. The first and third rows are averages over the models. The second and fourth rows are standard deviations (right column) or two times standard deviations (left column) over the models. The left column is the decadal average 2011–2020. The right column is the difference in decadal average 2021–2030 minus 2011–2020.

In BASFOR soil N is also out of balance in the first decade, but to a lesser extent and N₂O emissions generally increase across Europe for pine and to a lesser extent for beech. In addition, comparing the difference maps of NPP with those of N₂O (not shown) suggested that they may be correlated. Indeed, linear regressions would suggest a significant relationship ($R^2 = 0.24$) between the change in logN₂O and NPP. This is perhaps unsurprising given the relatively strong relationship between N₂O emissions and NPP identified for BASFOR above.

6 Discussion

6.1 Average results for Europe

This study was concerned with quantifying the greenhouse balance of European forests considering not only CO₂, but also N₂O. Taking the average over the models we found a European average carbon sink for 2011–2020 of $0.160 \pm 0.020 \text{ kgC m}^{-2} \text{ yr}^{-1}$ for pine (excluding the large DailyDayCent pine C sink) and $0.138 \pm 0.062 \text{ kgC m}^{-2} \text{ yr}^{-1}$ for beech. This is comparable to the values for ‘ecological sites’ ($0.200 \pm 0.052 \text{ kgC m}^{-2} \text{ yr}^{-1}$) and national forest inventories ($0.160 \pm 0.020 \text{ kgC m}^{-2} \text{ yr}^{-1}$) found in Luysaert 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 N₂O source for 2011–2020 of $0.285 \pm 0.125 \text{ kgN ha}^{-1} \text{ yr}^{-1}$ for pine and $0.575 \pm 0.105 \text{ kgN ha}^{-1} \text{ yr}^{-1}$ 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 N₂O reported in Kesik et al. (2005). Given that the model used in that study (PnET-N-DNDC), is closely related to LandscapeDNDC, it is perhaps unsurprising that we found similar values. We found that the sink through uptake of CO₂ was dominant over the source of N₂O 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 N₂O 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 were generally higher for beech forests which is perhaps unsurprising given the seasonal defoliation in deciduous forests.

It was also found that N₂O 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 were 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 N₂O 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 Table 4. For NPP the values for the models in this study are generally lower than those for the models in L10. However, this is consistent with the lower NPP value for the only model in L10 to include the influence of N (BIOME-BGC) 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 largely 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

Table 4. European area weighted average values for Scots pine and European beech forests ($\text{kg C m}^{-2} \text{yr}^{-1}$) averaged over years 2011–2020. N_2O has units $\text{kg N ha}^{-1} \text{yr}^{-1}$. Missing values in the table are where a model output was unavailable.

Scots Pine	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
European Beech	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

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).

6.2 Interaction of geographical and model 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 N. Scandinavia, Poland and southern 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 significant differences between the geographical variability of growth and NEE given by the models and, thus, giving significant uncertainty in model predictions. The

uncertainty was larger for beech than for pine forests although this will be at least partly due to the inclusion of DailyDayCent in beech, but not pine results.

Uncertainty tended to be larger where growth was greatest, as might be expected, due mainly to magnitude differences which are related to differences in the models sensitivity to driving variables. For example BASFOR was more sensitive to soil N than LandscapeDNDC. Compensating model differences in soil respiration led to lower NEE uncertainty in NW Spain, southern Germany and Austria than might have been expected from NPP.

Uncertainties were also greater in areas where initial soil N was particularly high, perhaps unrealistically so. For example, NW Scotland, NW Spain and Bulgaria where growth was high in BASFOR and significantly lower in LandscapeDNDC since BASFOR has a greater sensitivity to soil N.

Similarly uncertainty was larger in regions where driving variables were very low for example in the low rain areas of SE Spain, Sardinia, the heel of Italy and E. Romania the models responded differently to low soil water conditions. BASFOR and DailyDayCent beech forests had no or very low growth and negative NEE compared to LandscapeDNDC and INTEGRATOR.

In some areas where uncertainties were high, deficiencies in a particular model were important. For example larger uncertainties in Spain were in part due to homogeneous carbon sequestration in INTEGRATOR.

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, N₂O emissions had a negative spatial relationship with NPP for BASFOR and DailyDayCent because N uptake from the soil reduced the N available to be emitted. For LandscapeDNDC, NPP was also important for N₂O 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.

6.3 Geographical and species differences in response to environmental changes

Of particular interest in this study was locations in which we expect environmental changes to cause the largest changes in forest productivity, carbon sequestration and greenhouse gas balance. In addition, environmental drivers which would be the main cause of those changes. It was found that changes in carbon sequestration were dominated by NPP. This is consistent with what was found above.

No overall driver dominated changes in NPP with precipitation, temperature, nitrogen deposition and management (through clearfelling), all being significant factors.

Environmental changes had the largest impact where environmental drivers 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. Where soil N was lower and so limiting, for example, in Poland an increase in nitrogen deposition was found to increase growth. 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.

Growth was also particularly affected where there was a change in an environmental factor that was larger, dominating the effect of others such as decreased temperature which reduced 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 Belgium, the Netherlands, northern Germany and Poland). Indeed 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 important only 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 acted 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.

Model uncertainty about responses to changes in environmental drivers was important since these were large relative to the changes being predicted so we need to be cautious about taking these model results as future predictions. As already discussed in Sect. 6.2, a significant reason for model differences was differences in the sensitivities of the models to changes in environmental drivers. For example, growth in BASFOR pine forests had a greater sensitivity to temperature than precipitation and the opposite for beech forests whereas LandscapeDNDC had the reverse. As discussed, above this was particularly important for model uncertainty in Belgium, the Netherlands, northern Germany and Poland and in dry S. Spain, Sardinia and the heel of Italy. Differences in model sensitivity to changes in N deposition also led to uncertainties in Ireland. Uncertainties in specific regions in France were due to DailyDayCent and INTEGRATOR having different harvesting than the other models.

Similar to Sect. 6.2 compensating model differences in soil respiration led to less uncertainty in Belgium, the Netherlands, northern Germany and Poland than might have been expected from growth differences. However, where respiration had decreased due to reduced soil carbon which had been respired in the first decade by LandscapeDNDC in NW Scotland and Poland, but not in the other models NEE model uncertainty increased.

6.4 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. Consistent with the geographical variations in N₂O discussed above, we found that areas where decadal NPP decreased in BASFOR changed the soil N balance through reduced uptake so that more nitrogen was available to be emitted. Thus, N₂O 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.

6.5 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 pine forests in BASFOR and in both forests in LandscapeDNDC. This is likely due to imbalances between soil and tree initialisations. As this imbalance decreases during the 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 N₂O 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, as 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 about 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. Whilst the models in this study are well known and have been evaluated in many previous studies their application has generally been to individual forest sites rather than the whole of Europe. Indeed only one model was specifically recalibrated for use across Europe and even this was only against a number of observational sites which may or may not be a good representation of the whole of Europe. It is perhaps then unsurprising that model differences and, hence, uncertainty was found to be high. This is our current state of C- and N-cycle forest modelling in Europe and this study had been able to make a first attempt at quantifying this uncertainty and highlighting possible reasons for the model differences found. While some of the differences will be due to model structural differences and, therefore, reflect our current uncertainty about how best to model forest processes some of the uncertainty could be reduced by improving the parameterisation of the models for use across Europe. This could be aided by use of increasing available remote-sensing data which may have greater errors, but can be usefully represented in calibration techniques which allow for inclusion of observational uncertainty such as Bayesian calibration.

7 Conclusions

In recent years there has been considerable activity aiming to quantify the present and future contributions of forests to the GHG balance of Europe. Indeed there has been considerable controversy over the importance of nitrogen for this balance. Our study is one of the first in which N effects, thinning and harvesting are included in a range of models, ranging from simple to complex.

- 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 N₂O 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 CO₂ being dominant over the source of N₂O 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.
- N₂O 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 N₂O 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.
- There were large differences found between the model predictions. Model uncertainty was greater for European beech than Scots pine forests and for N₂O emissions than for carbon sequestration. Differences in the sensitivity of the models to environmental drivers can help explain these uncertainties. For prediction at the European scale, differences between models may be reduced if data with good spatial coverage, such as from remote sensing, are used to calibrate each model.

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