,
Horizon 2020 Societal challenge 5:
Climate action, environment, resource
efficiency and raw materials

VERIFY

Observation-based system for monitoring and verification of greenhouse gases

GA number 776810, RIA

Deliverable number (relative in WP)	**D3.5**
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Responsible	Matthew McGrath
Contributor(s):	Raphael Ganzenmüller, Juraj Balkovic, Sophia Walther, Matthias Kuhnert, Matteo Vizzarri, Mart-Jan Schelhaas, Dmitry Schepaschenko, Andrey Krasovskii, Juraj Balkovic, Gert-Jan Nabuurs, Bas Lerink, Joao Paulo, Roberto Pilli, Viorel Blujdea, Giacomo Grassi
Internal reviewer:	Philippe Peylin

Changes with respect to the DoA

Delivery date was changes from 31/05/2020 to 30/06/2020 with the approval of the project officer from the EC.

Dissemination and uptake
(Who will/could use this deliverable, within the project or outside the project?)

The bottom-up simulation results are freely available (in some cases, registration is/will be necessary). The simulation results provide the initial guesses for top-down modeling approaches in WP3, in addition to be used in the synthesis product in WP5. The webpage for data download is listed later in this table.

Short Summary of results (<250 words)

Models play a crucial role in the quantification of GHG emissions. They can extrapolate and interpolate measurements spatially and temporally. Different models are designed for different purposes, from data-driven models that make the most efficient use of existing data, to process-based models which provide increased resolution of underlying driving mechanisms. VERIFY incorporates a wide variety of different model types to enable the system to respond to a far-reaching host of questions.

Therefore, the aim of this WP is to simulate terrestrial carbon fluxes in both natural and anthropogenic systems. Using harmonized input data collected and reported on in D3.2, WP3 produced a variety of gridded flux and stock estimates of carbon within Europe. This particular deliverable shows carbon dioxide emissions from croplands, grasslands, and forests across the continent, using a variety of approaches. These approaches include models making extensive use of country-level statistics, those aiming for comprehensive descriptions of ecosystem processes, and statistical upscaling of site-level results to the continental scale. This deliverable provides details about the results of the second round of simulations from the bottom-up land models. Simulation methods will be improved during the course of the project, reflecting new scientific and technical understanding.

Evidence of accomplishment
(report, manuscript, web-link, other)

All the simulation results will be accessible though the dedicated data THREDDS server:
https://verifydb.lsce.ipsl.fr/thredds/catalog/verify/WP3/catalog.html
Note that some of these data may be password protected during a consolidation phase and thus only accessible to the VERIFY partners (accessible through the internal share-point platform). To distinguish datasets submitted for this round of simulations, the identifier in the file name is changed from “V1” to “V2”, in addition to the submission date being generally later.

Version	Date	Description	Author (Organisation)
V0	19/07/20	Creation/Writing	Matthew McGrath (CEA)
V0.1	20/08/20	Writing/Formatting of methods	Sophia Walther (MPI-BGC), Raphael Ganzenmüller (LMU), Matthias Kuhnert (ABDN), Matteo Vizzarri (JRC), Juraj Balkovic (IIASA), Andrey Krasovskii (IIASA), Mart-Jan Schelhaas, Gert-Jan Nabuurs, Bas Lerink, Joao Paulo (WENR), Matthew McGrath (CEA)
V0.2	10/12/20	Writing/Formatting of results	Sophia Walther (MPI-BGC), Raphael Ganzenmüller (LMU), Juraj Balkovic (IIASA), Mart-Jan Schelhaas, Gert-Jan Nabuurs, Bas Lerink, Joao Paulo (WENR), Matthias Kuhnert (ABDN), Matteo Vizzarri, Roberto Pilli, Viorel Blujdea, Giacomo Grassi (JRC), Matthew McGrath (CEA)
V1	15/02/2021	Formatting/Delivery on the Participant Portal	Matthew McGrath and Aurélie Paquirissamy (CEA)

1. Glossary

Abbreviation / Acronym	Description/meaning
ABG	Aboveground biomass
BAU	Business as usual
CRF	Common reporting framework
DGVM	Dynamic global vegetation model
GPP	Gross primary product
KP	Kyoto Protocol
LULC	Land use and land cover
LULUCF	Land use and land cover change
NEP	Net ecosystem productivity
NPP	Net primary productivity
RS	Remote sensing
SOM	Soil organic matter
TRENDY	A model intercomparison project using DGVMs to look the carbon cycle

2. Executive Summary

National greenhouse gas inventories struggle to provide precise estimations of carbon dioxide emissions and uptake from land use, land use change, and forestry (LULUCF) activities. This is due to a variety of reasons, many related to the fact that LULUCF activities occur on highly heterogenous landscapes, where local conditions can dramatically impact the ability of plants to uptake and store carbon. In addition, LULUCF activities are spread across wide spatial areas which have traditionally been more difficult to monitor, as opposed to being point-sources of emissions like power plants. Finally, even classification of a parcel of land into a specific land use/land cover type is not always evident, which has led countries to use varying definitions of things like, "forest".

Over the years, a variety of approaches have developed to provide estimates of LULUCF emissions from ecosystems. These include data-driven approaches which make heavy use of national statistics; process-based models which simulate realistic ecosystem dynamics, parameterized by observations; and statistical upscaling techniques which take detailed site-level measurements and create "wall-to-wall" estimates covering entire regions. The challenge present in WP3 of VERIFY is to take all of these different approaches and use them to reduce the uncertainty in LULUCF CO_2 emissions.

For 2020, the work from 2019 was built-upon through the addition and refinement of the seven groups who submitted bottom-up results to WP3. In addition, progress was made on using standardized input data (meteorological and land use/land cover) to drive models, which greatly improves comparison of results. The goal of VERIFY WP3 is to run a harmonized model intercomparison using operational (i.e., up to the previous year) forcing data. Such a comparison is carried out on global scales for models of similar types (e.g., TRENDY), but much of the effort in WP3 is put into the best way to do this when the model structure and their approach to solving problems is different. This effort, and the CO_2 fluxes from ecosystems submitted to WP3 summarized in this deliverable, are fundamental to the synthesis efforts in WP5, and the increased use of harmonized datasets represents an important step towards that goal.

3. Introduction

D3.5 summarizes the second round of the bottom-up simulations for the project VERIFY, consisting of carbon dioxide fluxes coming from various human and natural ecosystems across Europe. VERIFY takes a different approach to standard model intercomparison projects, where simulation inputs are harmonized across many incarnations of a single model class in order to provide more robust estimates on flux uncertainty due to model structure. Instead, VERIFY begins with a wider collection of bottom-up model classes all capable of predicting the carbon dioxide net biome production (i.e., the net flux of carbon dioxide from an ecosystem, taking into account disturbances like wood harvest) but only uses one or two examples of each model type. In addition, sector-specific models are included, as these models often have much more detail than generally-applicable ecosystem models and can incorporate more observational data differentiating, for example, between tree species, crop varieties, and management practices. This provides the potential for more realistic constraints on the fluxes.

D3.5 is intricately related to other WPs in support of the overall VERIFY objective of advancing the development of accurate and robust observation-based methods for quantifying GHG emissions and sinks, in particular by providing a portfolio of synthesis products for land-based carbon dioxide emission in Europe. In this way, WP3 bottom-up simulations complement the high-resolution bottom-up fossil fuel and biofuel emission estimates of CO_2 produced in WP2, providing a complete picture of carbon dioxide emissions from the European land surface. Emissions and absorption of other strong greenhouse gases, notably methane and nitrous oxide, are covered in WP4, thus covering three gaseous species known to be highly important to climate processes. Results from bottom-up models such as those presented in this deliverable can serve as initial guesses for top-down approaches reported in other deliverables. Results highlighted in D3.5 will be merged with the rest of the project methods in the synthesis prepared in WP5 (as was done for D3.4), and when compared against WP1, can help identify common language between inventory-taking in accordance with IPCC guidelines and cutting-edge scientific results.

This deliverable is divided into sections for all bottom-up models expected to provide results to WP3 at some point during the VERIFY project. The first major section describes the models themselves, including updates made since the previous version of this report (i.e. last year) and directions for next year, while the second focuses on results achieved this year.

4. Model descriptions

The table below summarizes the key features of the different models that are participating to the VERIFY WP3 simulations, some of them with a contribution planed for the last year only. The selected models include a diversity of approaches (from process-based to data-driven).

Table 1: Models providing bottom-up carbon fluxes in the context of VERIFY.

Name/ model	Inst.	Spatial Coverage	Sector	Temporal Resolution	Time frame	Contact in the project
BLUE	LMU	Europe (35N:73N, 25W:45E), 0.25 degree	Land cover change	Annual	1950-2019	Pongratz, Julia[a]
CBM-CFS3	JRC	NUTS0/2	Forestry	Yearly	1990-2015	Matteo Vizzarri[b]
DAYCENT	UNIABDN	Europe	Crop and grass	Daily	To be chosen	Matthias Kuhnert[c]
ECOSSE	UNIABDN	EU28, 0.25 degree grid map	Cropland and grassland	Daily	2010-2015	Matthias Kuhnert[c]
EFISCEN Space	WENR	Selected European countries	Forestry	Annual	Average 2010-2018	Mart-Jan Schelhaas[d]
EPIC-IIASA	IIASA	1x1 km EU-33	Crops	Daily	1980-2019	Juraj Balkovic[e]
G4M/FLAM	IIASA	5 arc min	Forest	Monthly	2001-2019	Andrey Krasovskii[f]
ORCHIDEE	CEA	0.125 degree, 35N:73N, 25W:45E	Crops, forests, grasslands	0.5 hours	1700-2018	Matthew McGrath[g]
Fluxcom	MPI-BGC	Global	Biosphere	Hourly	1980-2018	Sophia Walther[h]
CCDAS-SDBM3	ULUND	Global	Biosphere	Sub-daily	To be chosen	Marko Scholze[i]

Email addresses of contact persons:
[a] julia.pongratz@geographie.uni-muenchen.de
[b] Matteo.VIZZARRI@ec.europa.eu
[c] matthias.kuhnert@abdn.ac.uk
[d] martjan.schelhaas@wur.nl
[e] balkovic@iiasa.ac.at
[f] krasov@iiasa.ac.at
[g] matthew.mcgrath@lsce.ipsl.fr
[h] swalth@bgc-jena.mpg.de
[i] marko.scholze@nateko.lu.se

4.1. BLUE

4.1.1. Model Description

BLUE is a bookkeeping model that provides an estimate of the net land use change carbon flux (Hansis et al., 2015). Transformation of natural vegetation to agriculture (cropland, pasture) and back, including gross transitions at the sub-grid scale (“shifting cultivation”) are considered, as well as wood harvesting. It is one of three bookkeeping models used in the Global Carbon Project’s annual carbon budget for estimating land use change emissions (Friedlingstein et al., in press).

For VERIFY, the underlying land use dataset has been updated to HILDA+ (Winkler et al., subm.) during the last year. Soil and vegetation carbon densities are currently biome-specific based on literature values, but will be replaced by newly produced spatially explicit data within the upcoming months. The currently submitted dataset has a resolution of 0.25°x0.25° degrees and provides annual data from 1950 to 2019.

4.1.2. Changes for next year

We are currently implementing spatially-explicit carbon densities in BLUE. So far bookkeeping approaches assume that carbon densities are biome-specific and/or country-specific. By combining newly available vegetation and soil carbon density data (Spawn et al., 2020, ISRIC, 2020) with land-use datasets (Winkler et al., subm., ESA-CCI, 2020), we are able to produce land cover specific carbon density maps at high resolution, which reflect local heterogeneities in soil and environmental conditions.

Thereafter, we will update and improve other input data, which limit current BLUE runs to the resolution of 0.25°x0.25° degrees. This includes (1) a new map product of potential vegetation types, (2) a revision of the response curves based on observational data from partners in VERIFY, which reflect the carbon development of carbon pools following transitions, and (3) the production of a new wood harvest dataset at high resolution for Europe by updating and improving former estimates (Hurtt et al., 2020, Ceccherini et al., 2020, McGrath et al., 2015). These improvements will enable us to run the model at much higher resolution (~1 km*1 km), and will result in more precise emission estimates.

4.1.3. References/link

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4.2. CBM-CFS3

4.2.1. Model Description

The Carbon Budget Model developed by the Canadian Forest Service (CBM-CFS3, hereafter CBM) can simulate the historical and future stand- and landscape-level C dynamics of forest ecosystems under different scenarios of harvest and natural disturbances (fires, storms), according to the standards described by the IPCC. Since 2009, CBM has been tested and validated by the JRC, and adapted to the European forest conditions. It is currently applied to 26 EU member states, both at the country and NUTS2 level.

Based on the model framework, each stand is described by area, age, land classes, up to 10 classifiers based on administrative and ecological information and on silvicultural parameters (such as forest composition and management strategy). A set of yield tables define the merchantable volume production for each species/forest types while species-specific allometric equations convert merchantable volume production into aboveground biomass at the stand level. For the initial year and any time step the model provides data on the net primary production (NPP), C stocks and fluxes as the annual C transfers between pools and to the forest product sector. With additional processing of the outputs, it can provide forestry-related indicators (e.g., standing volume and net annual increment of the standing volume).

The model can support policy anticipation, formulation and evaluation under the LULUCF (Land Use, Land Use Change and Forest) sector, and it is used to estimate current and future forest C dynamics, both as a verification tool (i.e., to compare the results with the estimates provided by other models) and to support EU legislation on the LULUCF sector (Grassi et al. 2018). In the biomass sector, CBM can be used in combination with other models to estimate the maximum wood harvest potential and the forest C dynamics under different assumptions of harvest and land use change (Jonsson et al., 2018).

Methodology and data

CBM follows the IPCC reporting method 1 (Penman et al. 2003). The spatial framework coincides with the geographically referenced spatial units (SPUs), as relevant from the national forest inventories perspective. Each SPU can be identified with a forest stand characterized by tree species composition (i.e., forest type, FT), area, age, and other information, such as the correspondence with appropriate yield curves, the forest management system and management type (MT), and main wood use, i.e., solid or energy (which can be derived from model outcomes). National forest inventories (e.g., statistical sampling NFIs or stand-wise forest inventories) are the key data sources. In few cases, because of the lacking of country-specific information, some input parameters are obtained from literature or values reported by other countries under similar conditions (e.g., biogeographical region). Other relevant parameters are provided by Pilli et al. (2018). Table 2 summarizes the main characteristics of the modelling exercise.

Table 2: main characteristics of the modelling exercise.

Spatial coverage	**Time coverage for input data (NFIs)**	**Time step 0 (initial year of simulation)**	**Total forest land area (year=1990) (ha·10^6)**	**Considered natural events**	**Land use change**	**Main outcomes**
EU 26 Member States (excl. Cyprus and Malta) [NUTS 0; NUTS 3]	1992-2010	1992-2000	138 [0.1-22.6 for each individual Member State]	Fire (10 events); storm and sleet (16 events); insect attacks (2 events)	Afforestation; deforestation	NBP; C fluxes by pool

NFI standing volume and net annual increment data were used to build species-specific growth curves, combined with stand-level equations to convert merchantable volume per hectare into aboveground biomass, partitioned into merchantable stem wood, other wood components (stump, tops, branches, sub-merchantable size trees), foliage components (Pilli et al. 2013; Pilli et al. 2016a) and belowground biomass. The impacts of natural disturbances such as storms and sleets, fires and bark beetle attacks were also assessed (for background assumptions, please refer to Pilli et al. 2016a; 2016b). To define the decomposition rates of the DOM pools, 60 climatic units (CLUs) were created and associated with specific portions of country-level forest lands, based on the combination between maps of temperature and precipitation, and the CORINE land cover dataset (see Pilli, 2012 for further details).

In terms of outputs, CBM provides annual estimates of C stocks and fluxes, such as the annual C transfers between pools, from pools to the atmosphere and from forest pools to the forest product sector, as well as ecological indicators such as the net primary production (NPP), heterotrophic respiration (R_h) and net biome production (NBP). These variables were calculated as follows (see also Kurz et al. 2009):

$NPP = GPP - R_a$ [eq. 1]
where: NPP is the net primary productivity, i.e., net inputs of C from the atmosphere to the forest ecosystem; GPP is the carbon assimilated by plants during photosynthesis; R_a is the carbon released by plants through autotrophic respiration.

$NEP = NPP - R_h$ [eq. 2]
where: NEP is the net ecosystem productivity; NPP is the net primary production (see above); R_h is the heterotrophic respiration (i.e., decomposition).

$NBP = NEP - H - D$ [eq. 3]
where: NBP is the net biome production; H represents the direct biomass losses due to harvest; D represents the direct losses due to natural disturbances (e.g., fires).

Once the harvest demand was defined (BaU scenario), we applied CBM to (i) check if it is possible to harvest that amount for the period 2000 – 2015 and (ii) simulate the forest development under that harvest level from 2016 to 2030. The historical harvest (2000-2015) was inferred for each country, from the amount of roundwood removals reported by FAOSTAT, further distinguishing between industrial roundwood and fuelwood. Data on harvest were also compared, and corrected as needed, with other information from the literature (Pilli et al., 2015).

Land use change (i.e., afforestation and deforestation) was also taken into account. To be consistent with other studies, 1990 was used as the base year (see details in Pilli et al., 2016a). Afforestation was modelled through country-specific model runs, always beginning in 1990, applying the historical annual rate of afforestation/reforestation reported by each country up to 2012 (Pilli et al., 2016b). The total amount of afforestation/reforestation per year was distributed between different forest types (FTs), according to the proportional amount of the forest management area. Deforestation was modelled by decreasing the forest area since the base year (1990) until the time step 0 (when simulation starts), according to the total amount of forest area losses as reported by the countries (KP CRF tables, 2014).

For further details on the methodology, please refer to Pilli et al. (2017) and Grassi et al. (2018).

4.2.2. Changes for next year

For the purposes of the VERIFY project, ongoing modelling efforts by CBM are oriented to updating model simulations for NPP, NEP and forest biomass by forest types and climate units for the period 2000-2015 (extendable to 2020) at both the EU and country scale, using the latest available data (including from the National Forest Accounting Plans).

4.2.3. References/link

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4.3. DAYCENT

4.3.1. Model Description

The DAYCENT model was described in Deliverable 3.4. The exact version of the model has not yet been selected. Therefore, more detailed description will wait until next year when model results are available.

4.3.2. Changes for next year

Model results by DAYCENT will be included in the analysis. This will provide additional data for croplands and grasslands.

4.3.3. References/link

None.

4.4. ECOSSE

4.4.1. Model Description

The ECOSSE model was developed to simulate highly organic soils from concepts originally derived for mineral soils in the RothC (Jenkinson and Rayner, 1977; Jenkinson et al. 1987; Coleman and Jenkinson, 1996) and SUNDIAL (Bradbury et al. 1993; Smith et al. 1996) models. Following these established models, ECOSSE uses a pool-type approach, describing soil organic matter (SOM) as pools of inert organic matter, humus, biomass, resistant plant material and decomposable plant material (Figure 1). All processes of both carbon and nitrogen dynamics are considered (Smith et al., 2010a,b). Additionally, in ECOSSE, processes of minor relevance for mineral arable soils are implemented (e.g., methane emissions) to have a better representation of processes that are relevant for other soils (e.g., organic soils). ECOSSE can run in different modes and for different times steps. The two main modes are site-specific and limited-data. In the latter version, basis assumptions/estimates for parameters can be provided by the model itself instead of relying on user input. This increases the uncertainty but makes ECOSSE a universal tool that can be applied for large scale simulations even if the data availability is limited. To increase the accuracy in the site-specific version of the model, detailed information about soil properties, plant input, nutrient application and management can be added as available.

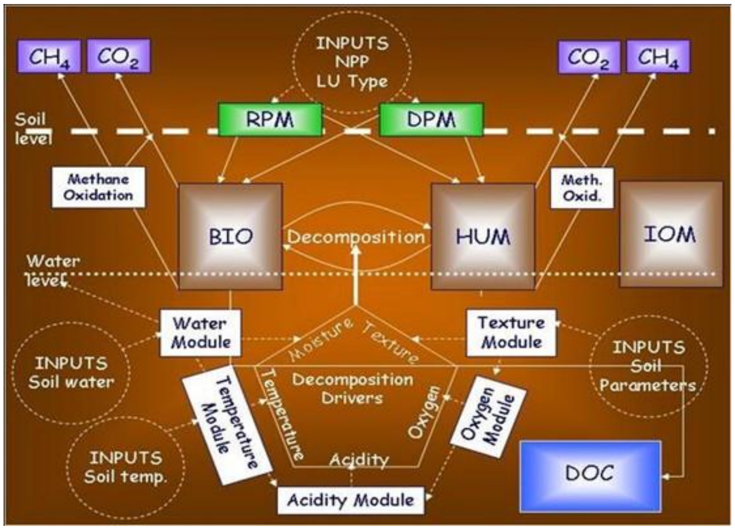

Figure 1. Structure of the carbon components of ECOSSE

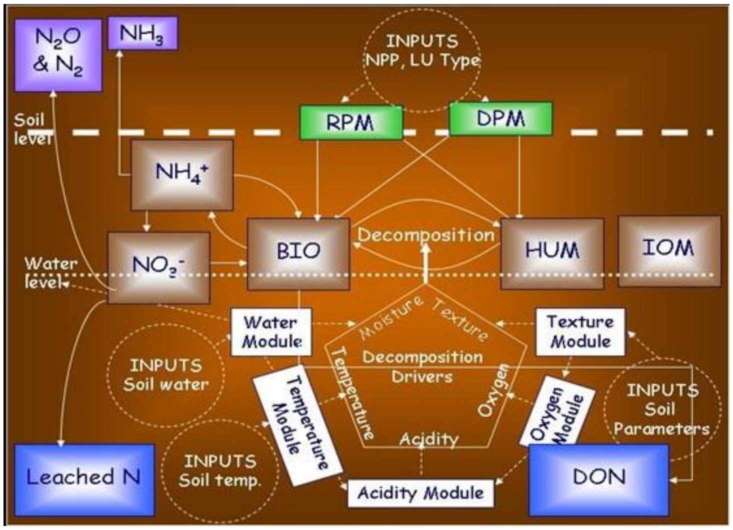

Figure 2. Structure of the nitrogen components of ECOSSE

The different processes are summarized in the ECOSSE user manual (Smith et al., 2011). During the decomposition process, material is exchanged between the SOM pools according to first order rate equations, characterised by a specific rate constant for each pool, and modified according to rate modifiers dependent on the temperature, moisture, crop cover and pH of the soil. Under aerobic conditions, the decomposition process results in gaseous losses of carbon dioxide (CO_2); under anaerobic conditions losses as methane (CH_4) dominate. The N content of the soil follows the decomposition of the SOM (Figure 2), with a stable C:N ratio defined for each pool at a given pH, and N being either mineralised or immobilised to maintain that ratio. Nitrogen released from decomposing SOM as ammonium (NH_4^+) or added to the soil may be nitrified to nitrate (NO_3^-). Carbon and nitrogen may be lost from the soil by the processes of leaching (NO_3^-, dissolved organic C (DOC), and dissolved organic N (DON)), denitrification, volatilisation or crop uptake; C and N may be returned to the soil by plant inputs, inorganic fertilizers, atmospheric deposition or organic amendments. The soil is divided into 5cm layers, so as to facilitate the accurate simulation of these processes down the soil profile.

For spatial simulations the model is implemented in a spatial model platform. This allows to aggregate the input parameters for the desired resolution. ECOSSE is a one-dimensional model and the model platform provides the input data in a spatial distribution and aggregates the model outputs for further analysis. While climate data are interpolated, soil data are represented by the dominant soil type or by the proportional representation of the different soil types in the spatial simulation unit (a grid cell in the context of the VERIFY project).

The former version of ECOSSE provided results for heterotrophic respiration for daily time steps. To meet the demand in VERIFY, the ECOSSE model was extended by modules to simulate NPP and yield by modification of model internal routines. Based on the available NPP module (MIAMI model; Lieth,1972) we were able to simulate the annual NPP, which was allocated to aboveground and belowground biomass based on the study by Neumann and Smith (2018). This study also provides a generic harvest index to estimate the yield. This enabled simulation of the NBP for croplands in order to be compare to other models/methods in the VERIFY project. For grassland simulations, the allocation factors were modified and the NPP simulations adapted for nutrient limitations. ECOSSE was run for monthly time steps, as this provided sufficient data for the target area and time steps.

4.4.2. Changes for next year

The analysis of the current results is still ongoing. Some results require additional analysis and addition of more input data or adding relevant management practices to be fully understood.

The cropland simulation will be extended for daily timesteps and include more detailed management information. This will potentially improve the simulation results, but it will also increase the uncertainty. A comparison with other results in the project will show if this more detailed simulation approach provides improved results.

The grassland simulation will be extended for grazing impacts. Similar to the cropland simulations, this additional data set will potentially improve the simulation results. Input data for grazing have already provided in the VERIFY project (see deliverable 3.2).

4.4.3. References/link

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4.5. EFISCEN Space

4.5.1. Model Description

EFISCEN Space is an empirical forest scenario simulator. It keeps track of the evolution of the diameter distribution of 20 tree species (groups) for individual plot locations (Nabuurs et al. 2006). For VERIFY we obtained initialisation data for ~200,000 plots from the national forest inventory data from 16 European countries (Figure 4, Table 3) (Nabuurs et al. 2010). Currently, a detailed dynamic growth module is included (Figure 3) (Schelhaas et al. 2018b), while natural mortality and harvesting are included as fixed regimes, depending on the region (Schelhaas et al. 2018a). Work is in progress to develop a dynamic natural mortality module, as well as a more flexible way to simulate harvesting. This work is developed in cooperation with the TreeMort project (Grant Nr. 758873 of the EU H2020 programme). Ingrowth of new trees is foreseen to be added over the coming years. From the number of trees per hectare, the model estimates volume and above- and belowground biomass, while growth in terms of timber volume as well as NEP can be derived. For a full carbon balance the soil model Yasso is added, but not yet properly parameterized. For VERIFY, individual plot results are aggregated to grid cells of 10 km resolution, both as a per hectare value as well as the total per grid cell.

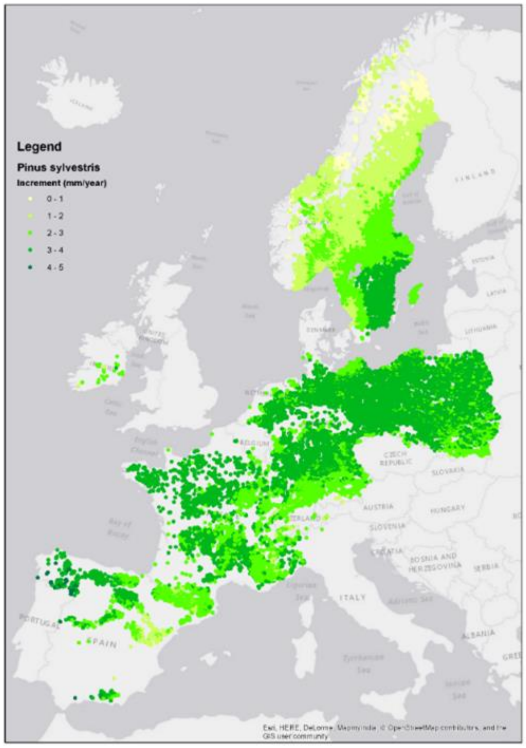

Figure 3: Increment of a median tree (mm/yr) in each plot where Pinus sylvestris occurs.

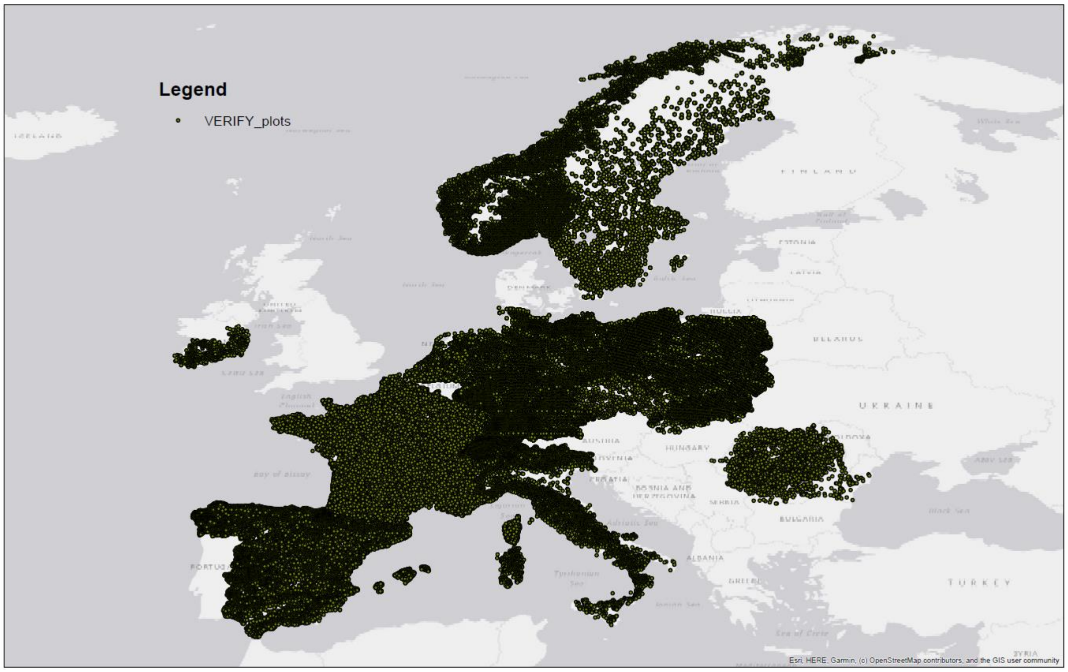

Figure 4: Locations of plots with initialization data for EFISCEN Space

Table 3: Acknowledgement of data sources used to initialise EFISCEN Space

	NFI	Date	Source	Contact person
Ireland	NFI-2	2009-2012	State Forest Service	John Redmond
Norway		2014-2018	NIBIO	Rasmus Astrup
Sweden		2015-2017	SLU	Jonas Fridman
Poland	NFI-2	2010-2014	Bureau for Forest Management and Geodesy, Poland	Andrzej Talarczyk
Germany	NFI-3	2012	online	
Netherlands	NFI-6	2012-2013	online	
Belgium - Flanders	NFI-2		INBO	Leen Govaere
Luxembourg	NFI-2	2009-2011	Ministère de l'Environnement, du climat et du développement durable / Administration de la nature et des forêts, Luxembourg	Thierry Palgen
France	NFI-5/6	2005-2012	online	
Spain	NFI-3	1996-2008	online	
Switzerland	NFI-3	2004-2006	WSL	Esther Thürig
Italy		2005	online	
Czech Republic		2014-2015	IFER	Emil Cienciala
Slovak Republic	NFI-2	2015-2017	National Forest Centre	Vladimír Šebeň
Romania	NFI-2		Department of Forest Management Planning and Terrestrial Measurements, Universitatea Transilvania Brasov	Viorel Blujdea
Ukraine	NFI pilot	2015	Ukrainian Research Institute of Forestry and Agroforestry Melioration (URIFFM)	Igor Buksha

Last year's results (Deliverable D3.4) only included NBP and lacked harvesting and mortality patterns for most countries included. This year's activity has focused on developing an approach that makes it possible to run the EFISCEN Space model everywhere in Europe with fixed management and mortality regimes, even if no data is available to determine the local regimes. We used the forest management intensity map developed by Nabuurs et al. (2019) as a basis, which estimates management intensity based on a number of predictors like elevation, soil type, distance to cities, etc. in a Bayesian Belief Network (Figure 5). From the data collection in the TreeMort project we obtained repeated observations for permanent NFI plots in 9 countries. All plots were assigned a forest management intensity class according to the map, and management and mortality patterns were extracted for all combinations of species, countries and management intensity classes. Harvesting probabilities showed a positive correlation with management intensity classes (Figure 6), which provides a good basis for extrapolation to other countries. Based on the TreeMort dataset, management and mortality sets were derived for the 20 species groups in EFISCEN Space for each of the countries, for three management intensity classes: low, (combining strict nature management, close-to-nature management and low-intensity management), medium (multifunctional management) and high (intensive and very intensive management). In addition, a set was derived for all observations together for application in case the management class was unknown. For all plots in the VERIFY dataset, the management intensity class was derived based on the Nabuurs et al. (2019) map. For each of the countries in the VERIFY simulations, the nationally-derived management and mortality regime were applied. If not available for a country, the best (subjective) match from the available countries was taken (Table 4). For Ireland and the Netherlands we used results from other studies containing more detailed applications of the EFISCEN Space model for the country.

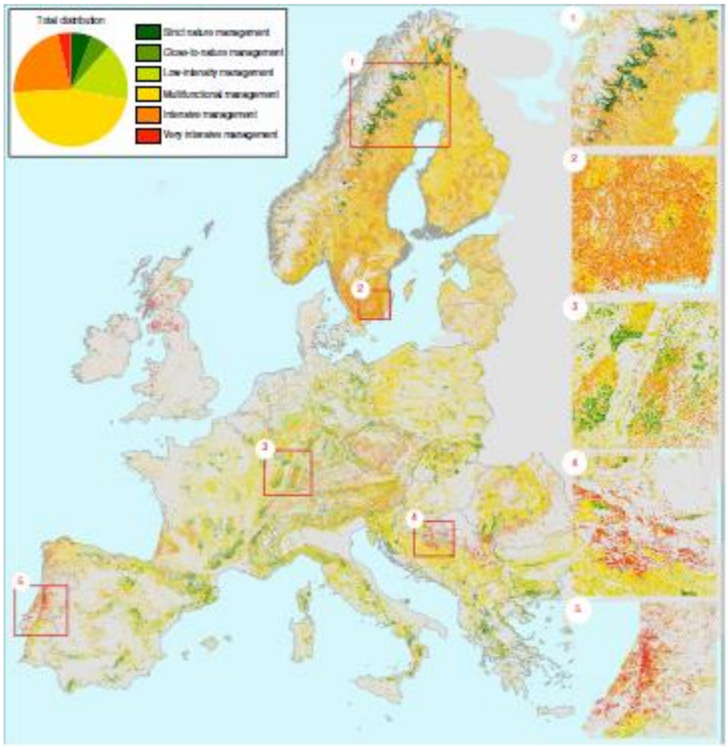

Figure 5: Forest management intensity map (Nabuurs et al. 2019).

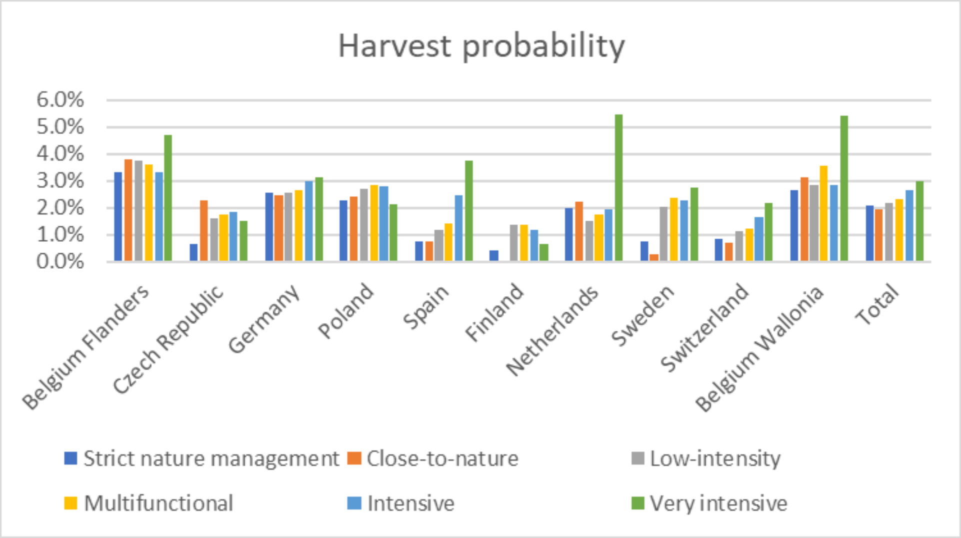

Figure 6:Annual harvest probability per management class as derived from the TreeMort dataset.

Table 4: Management and mortality regimes applied to country simulations for Verify, and NFI datasets and contact persons from TreeMort for data used to derive the regimes.

VERIFY dataset	management&mortality dataset applied	TreeMort contact person
Norway	Sweden	
Sweden	Sweden (2008-2012/2013-2017)	Jonas Fridman
Netherlands	As published in Arets and Schelhaas (2019)	
Ireland	As published in Schelhaas et al. 2018	
Belgium Flanders	Belgium Flanders (1997-1999/2009-2019)	Leen Govaere
Luxembourg	Germany	
France	Germany	
Germany	Germany (2000-2003/2011-2013)	
Poland	Poland (2005-2010/2010-2014)	Andrzej Talarczyk
Czech Republic	Germany	
Slovakia	Germany	
Switzerland	As published in Schelhaas et al. 2018	
Spain	Spain (1981-1999/1997-2008)	
Italy	Spain	
Romania	Germany	
Ukraine	Germany	

4.5.2. Changes for next year

Introduction of a dynamic mortality module; parameterisation of the soil module; better routines to produce gridded output maps. When possible, generating annual results with real weather data rather than an average over years.

4.5.3. References/link

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4.6. EPIC-IIASA

4.6.1. Model Description

The EPIC-IIASA model was integrated with VERIFY weather forcing covering the period 1980-2019. The CRUHAR v.3.1 dataset was used for the whole period and all variables except for solar radiation, for which the version 3.2 was used. In addition, a new version of atmospheric CO_2 concentration data was included. As in previous year, each cell of the 1-km simulation grid in EPIC-IIASA has been forced by underlaying daily meteorological inputs, including solar radiation, minimum and maximum temperature, precipitation, relative humidity, and wind speed.

In this version, a new parameterization of soil organic carbon routine (Balkovič et al., 2020) was implemented. This routine provides a better response of SOC dynamics and heterotrophic respiration to crop management, foremost to the residue handling, crop fertilization, and organic amendments.

As in the previous version, the following input data and assumptions were implemented:

- *Terrain:* each 1-km grid cell was represented by a 50-ha field with a mode elevation and slope derived from the Shuttle Radar Topographic Mission Data (SRTM) digital elevation model (Werner, 2001).
- *Soils:* soil inputs derived from the European Soil Bureau Database (version 2.0) https://esdac.jrc.ec.europa.eu, the Map of organic carbon content in the topsoil (Lugato et al., 2014), and the Database of Hydraulic Properties of European Soils (Wösten et al., 1999).
- *Crops*: crop calendars of the main European crops, including barley, corn maize, winter rapeseed, rice, winter rye, soybean, sunflower, winter wheat, sugar beet, and potatoes were adopted from Balkovič et al. (2018)
- *Fertilization*: crop specific nitrogen and phosphorus fertilizer application rates were adopted from Balkovič et al. (2018, 2013)
- *Irrigation*: crop specific irrigation was based on the European Irrigation Map (Wriedt et al., 2009).
- *Crop residue handling*: 20% of crop residues were harvested in case of cereals (excluding maize), while no residues were harvested for other crops (Köble, 2014).
- *Soil cultivation*: tillage consisting of two cultivation operations and moldboard ploughing prior to sowing, and an offset disking after harvesting of cereals, was implemented. Two row cultivations during the growing season were assumed for maize and one ridging operation for potatoes.

Daily simulations of the respective state variables and fluxes over the period 1980-2019 were aggregated with monthly resolution. See Table 5 for the list of simulated outputs and the rules applied for temporal aggregation.

Table 5: EPIC-IIASA output variables of carbon cycle. Output variables are organized according to the VERIFY simulation protocol.

Variable	**Unit**	**Description**	**Temporal aggregation**
mrso	kg m^{-2} $month^{-1}$	Total Soil Moisture Content	1st day of month
mrro	kg m^{-2} $month^{-1}$	Total Runoff, Drainage, and Subsurface Runoff	Monthly sum of daily fluxes
evapotrans	kg m^{-2} $month^{-1}$	Total Evapo-Transpiration	Monthly sum
cVeg	kg C m^{-2} $month^{-1}$	Carbon in Vegetation	1st day of month
cLitter	kg C m^{-2} $month^{-1}$	Carbon in Litter	Monthly sum
cSoil	kg C m^{-2} $month^{-1}$	Carbon in Soil	1st day of month
npp	kg C m^{-2} $month^{-1}$	Net Primary Production - total	Monthly sum
npp(a)	kg C m^{-2} $month^{-1}$	Net Primary Production – aboveground	Monthly sum

npp(b)	kg C m^{-2} $month^{-1}$	Net Primary Production – belowground	Monthly sum
rh	kg C m^{-2} $month^{-1}$	Heterotrophic Respiration	Monthly sum
fHarvest	kg C m^{-2} $year^{-1}$	C Flux to Atmosphere from harvested crop biomass consumption	Last day of year
yoc	kg C m^{-2} $month^{-1}$	soil carbon loss with sediments (water erosion)	Monthly sum
clch	kg C m^{-2} $month^{-1}$	leached soluble carbon	Monthly sum

Aggregation of simulated outputs

The EPIC-IIASA simulation outputs were aggregated to represent carbon fluxes and stocks on managed cropland. First, crop-specific output variables were calculated in each grid cell as a mean value from rainfed and irrigated simulations, weighted by the area of irrigated and rainfed production based on the European Irrigation Map. Second, monthly variables from Table 5 were calculated in each grid cell as a mean value of the crop-specific output variables, weighted by harvested areas of crops reported by EUROSTAT. Third, harvested carbon (fHarvest) represents carbon exported with crop yield and harvested residues, again calculated as a weighted mean from the NUTS2-specific crop harvested areas. Finally, for conversion purposes, we assume that dry matter crop biomass contains 42% of carbon where applicable.

Re-gridding

Simulation outputs from Table 5 were spatially aggregated and re-gridded from 1-km layout projected in ETRS_1989_LAEA coordinate system to a 0.125 x 0.125° CRUHAR v.3.1 grid in WGS84 coordination system. Mean values from all underlying EPIC-IIASA grid cells in a 0.125 x 0.125° cell were calculated.

4.6.2. Changes for next year

1. EPIC-IIASA will include atmospheric nitrogen deposition.
2. EPIC-IIASA will include harmonized soil information provided within the VERIFY project.
3. EPIC-IASA will include updated meteorological forcing prepared for the new version of simulations.

4.6.3. References/link

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4.7. G4M+FLAM

4.7.1. Model Description

IIASA’s G4M and FLAM models were linked with IIASA-EPIC via similar infrastructure based on simulation units. A geographical grid of regular grid cells with spatial resolution of 5 x 5 arc min (about 8 km at equator) covers geographical Europe. The resolution was increased compared to simulations carried out in the previous year of the VERIFY project. Each grid cell provided soil information preprocessed by the IIASA-EPIC group from the Harmonized World Soil Database. In particular, the available water capacity (AWC) parameter is used by G4M for the water balance calculations to take into account water stress on forest growth. The infrastructure also includes landscape parameters used in the modeling (e.g., elevation, slope).

For model calibration and validation, we used aboveground biomass maps from GlobBiomass project, burned areas from the MODIS CCI dataset, and MODIS net primary productivity (NPP).

For the climate inputs we use the HARMONIE dataset provided by the VERIFY project. The data on meteorological inputs including solar radiation, minimum and maximum temperature, precipitation, relative humidity, wind speed, and is used for simulations covering 2010-2019. The data is preprocessed to fit the spatial resolution of 5 x 5 arc min. In addition, we used land-cover maps provided by the VERIFY project, i.e., the Hilda+ dataset.

See Table 6 for the list of simulated outputs.

Table 6: G4M/FLAM output variables of carbon cycle. Output variables are organized according to the VERIFY simulation protocol.

Variable	Unit	Description	Temporal aggregation
FCO2_NPP_FOR	kg C m^{-2} yr^{-1}	FCO2_NPP_FOR / Fluxes per square meter of forest	Annual
AGB	kg C m^{-2}	Above Ground Biomass	Annual

Re-gridding

Simulation outputs from Table 6 were spatially re-gridded to a 0.125 x 0.125° CRUHAR v.3.2 grid in WGS84 coordination system.

4.7.2. Changes for next year

- G4M/FLAM will include updated land cover forcing provided within the VERIFY project.
- G4M/FLAM will include updated meteorological forcing prepared for the new version of simulations.
- G4M/FLAM will include heterotrophic respiration to permit modelling NBP.

4.7.3. References/link

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4.8. ORCHIDEE

4.8.1. Model Description

ORCHIDEE is the land surface model of the IPSL (Institut Pierre Simon Laplace) Earth System Model. Hence, by conception, the ORCHIDEE model can be run coupled to a global circulation model (Figure 7). In a coupled set-up, the atmospheric conditions affect the land surface and the land surface, in turn, affects the atmospheric conditions. Coupled land-atmosphere models thus offer the possibility to quantify both the climate effects of changes in the land surface and the effects of climate change on the land surface. However, when a study focuses on changes in the land surface rather than on the interaction with climate, ORCHIDEE can be run off line as a stand-alone land surface model (Figure 7b). The stand-alone configuration receives the atmospheric conditions such as temperature, humidity and wind, to mention a few, from the so-called “forcing files”. Unlike the coupled set-up, which needs to run at the global scale (but with the possibility of a regional zoom), the stand-alone configuration can cover any area ranging from the global domain to a single grid point. The stand-alone configuration is what is used for VERIFY.

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

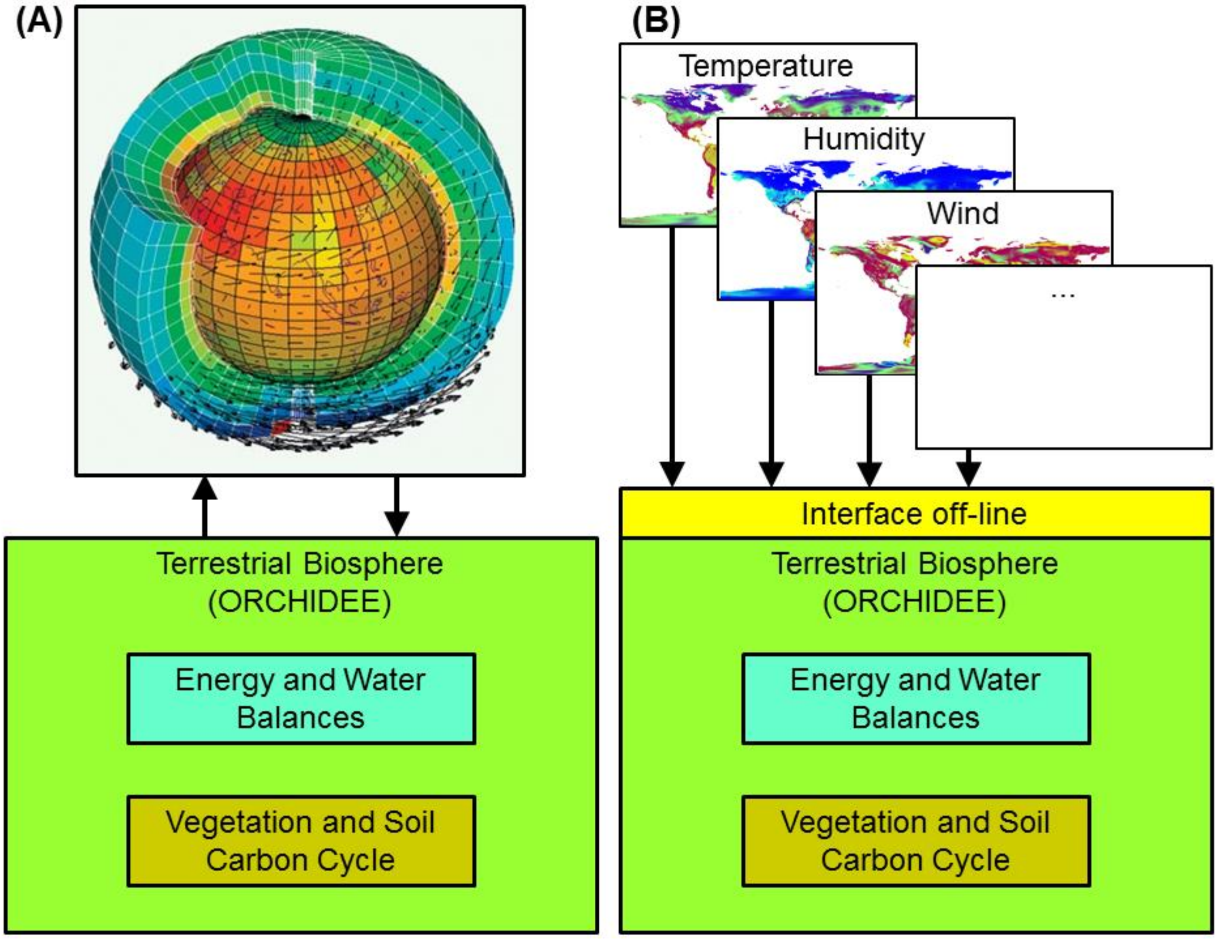

Figure 7 : Overview of the ORCHIDEE model.

The processes included in the early versions of ORCHIDEE were aimed at quantifying the terrestrial water (Figure 8a) and the energy balance (Figure 8b). Later versions of the model were extended with biogeochemical processes (Figure 8c), and the current version simulates the interference of anthropogenic activities with natural biogeochemical processes (Figure 8d). The biophysical process include latent (denoted ‘evaporation and transpiration’ in Figure 8a or LE in Figure 8b), sensible (denoted H in Figure 8b), and kinetic energy exchanges at the surface of soils (G in Figure 8b). Heat dissipation and water fluxes are vertically distributed in the soil (“drainage” in Figure 8a and G in Figure 8b) and the runoff (Figure 8a) is collected in rivers and lakes. The simulated processes that affect the global carbon cycle (Figure 8c) include photosynthesis, carbon allocation, litter decomposition, soil carbon decomposition, maintenance and growth respiration and vegetation dynamics. The anthropogenic interference (Figure 8d) includes land cover changes, fire, crop irrigation, and forest and grassland management. Land cover changes are included in the 2020 simulations for VERIFY, while the rest may be included in future years.

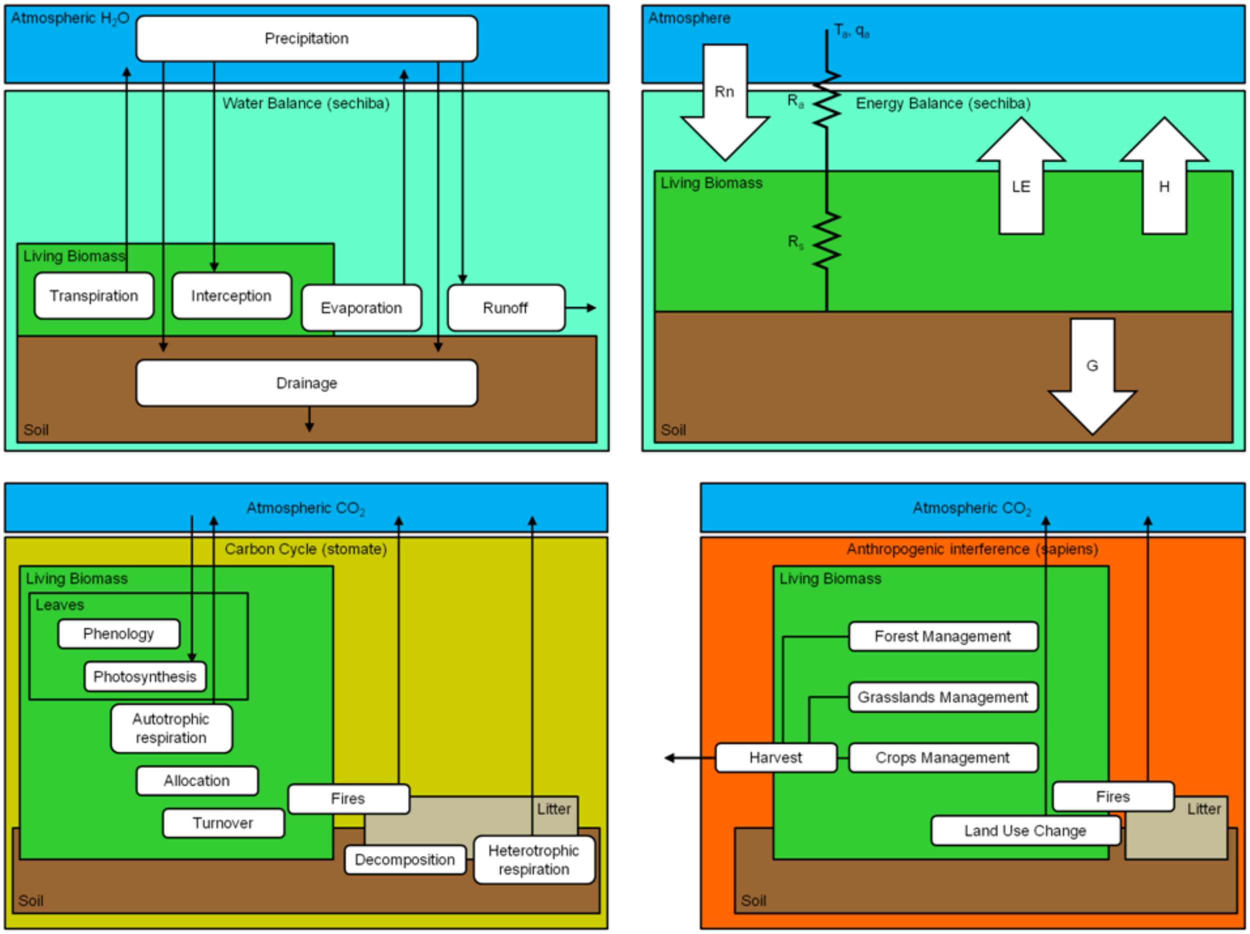

Figure 8: Processes represented in the ORCHIDEE model

ORCHIDEE calculates its prognostic variables (i.e., a multitude of C, H_2O and energy fluxes) from the following environmental drivers: air temperature, wind speed, solar radiation, air humidity, precipitation and atmospheric CO_2 concentration. In off-line mode, the user provides these drivers, and ORCHIDEE simulates their impact on ecosystem production, ecosystem respiration, the energy budget of ecosystems, the soil water budget and the surface run–off at a wide range of temporal and spatial scales. When coupled to an atmospheric model, ORCHIDEE follows an implicit approach. The prognostic variables of ORCHIDEE at each timestep are therefore simultaneously calculated with the atmospheric drivers in the planetary boundary layer (Fig. 3.8.1a). For both setups, the user needs to provide files describing the boundary conditions, namely the (initial) vegetation distribution (that may change with time if the dynamic vegetation module is activated) and a soil map. The meteorological drivers used for VERIFY were taken from those listed in D3.2. None of the optional maps were used.

The version of ORCHIDEE used for this deliverable is TAG2.1.

4.8.2. Changes for next year

The Covid19 pandemic delayed finalization of the two new revisions of the ORCHIDEE model discussed in the last deliverable. However, those versions have made significant progress, and therefore the ORCHIDEE model for next year will likely include the full nitrogen cycle, as well as hopefully a vertically-resolved canopy and detailed forest management routines. In additional, we hope to use more of the input data provided by the VERIFY project. In particular, land cover and land use maps from Hilda+ are currently undergoing reformatting for use in VERIFY. Discussions are on-going around the best way to transform the land cover categories in Hilda+ into those required by ORCHIDEE.

4.8.3. References/link

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4.9. Statistical upscaling of eddy covariance fluxes (Fluxcom)

The contribution of MPI-BGC to this work package is the delivery of net and gross natural terrestrial carbon flux estimates based on machine-learning methods (Tramontana et al., 2016, Jung et al., 2017, Bodesheim et al., 2018, Jung et al. 2020, www.fluxcom.org). In this, statistical relationships between insitu observations of carbon fluxes and environmental conditions from the La Thuile eddy-covariance flux database are learned and transferred to global gridded estimates using satellite observations and meteorological data of the same predictors. They represent a complementary approach to process-based models.

4.9.1. Model Description

Modelled carbon fluxes based on two complementary set-ups were provided last year: the ‘RS+meteo’ and the ‘RS only’ set-up, where RS stands for “remote sensing”. The former produces carbon flux estimates at hourly and 0.5deg spatial resolution. Regarding model drivers The ‘RS+meteo’ set-up is based on meteorological reanalysis data and a mean seasonal cycle of several remotely-sensed land surface indicators. This set-up uses random forest as a machine-learning method (for details please refer to last year’s report).

The ‘RS only’ set-up uses only remotely-sensed information to drive the models and comes at a resolution of 8 days and 1/12 deg spatially, making use of artificial neural networks and random forest as machine-learning methods. Monthly averages of the gross and net biogenic carbon flux estimates from both set-ups were created for this work package deliverable. For the synthesis activities in Verify it is important to note that the statistical upscaling produces estimates of net ecosystem exchange and not of net biome productivity.

The initial intercomparisons of the results from the statistical upscaling with each other and also other flux estimates from different models in this work package revealed suspicious behaviour of the RS+meteo simulation results, which after closer inspection led to a necessary correction of the same. While spatial and temporal patterns remain unchanged, magnitudes of the net fluxes were affected by this correction. Still, the focus of the evaluation activities is henceforth on the ‘RS only’ flux estimates for two reasons: The ‘RS only’ flux estimates have a higher and more suitable (for the purposes of Verify) spatial resolution than the ‘RS+meteo’ data, and a new simulation set-up that would be able to produce ‘RS+meteo’ estimates at a finer spatial resolution is not yet production-ready.

The high spatial resolution of the ‘RS only’ biogenic fluxes allowed the estimation of not only ecosystem totals but also of plant-type-specific flux estimates at slightly coarser spatial resolution. The total as well as the plant type specific carbon exchange for forests, grasses and crops are submitted to the project at 0.25deg for both net and gross ecosystem fluxes, both machine-learning and flux-partitioning methods and all years covering Europe. Clear differences in the estimated net ecosystem exchange between artificial neural networks and random forest as machine-learning methods are illustrated in Figure 9, underlining the importance of diversity in model set-ups, in this case regarding statistical methods.

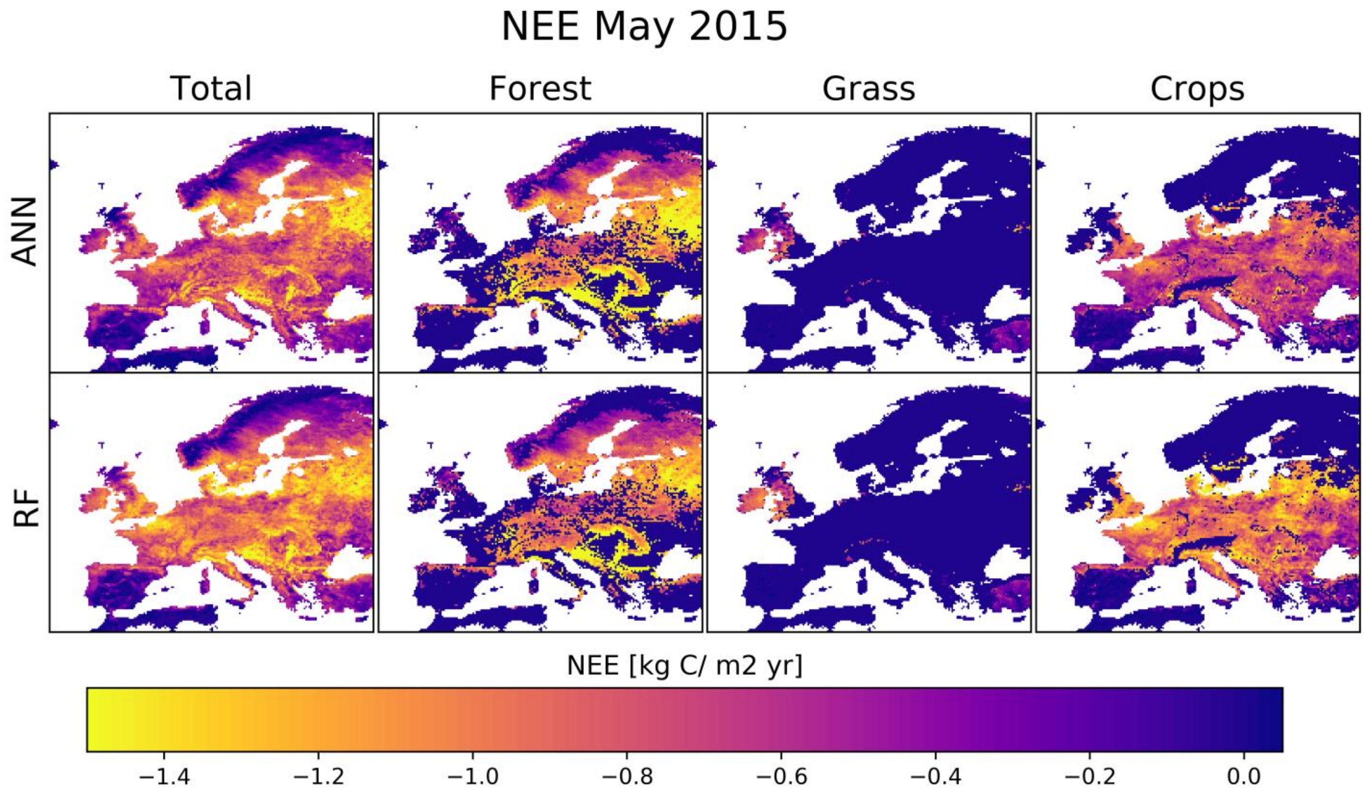

Figure 9 :Net ecosystem exchange estimates in May 2015 from the 'RS only' set-up for specific ecosystem types and the total ecosystem and for two different machine-learning methods (RF: random forest, ANN: artificial neural networks)

4.9.2. Changes for next year

Efforts are ongoing to prepare the setup such that meteorological reanalysis and land cover data can be ingested at finer spatial resolutions than the currently 0.5deg and that this way, a meteorological forcing data according to the common simulation protocol can be ingested and the data delivered accordingly.

4.9.3. References/link

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Jung, M., et al. Compensatory water effects link yearly global land CO2 sink changes to temperature, Nature, 541(7638), 516-520 (2017)

Bodesheim, P., et al. Upscaled diurnal cycles of land–atmosphere fluxes: a new global half-hourly data product, Earth System Science Data, 10 (3), 1327-1365 (2018)

Jung, M., et al. Scaling carbon fluxes from eddy covariance sites to globe: synthesis and evaluation of the FLUXCOM approach, Biogeosciences, 17, 1343–1365, https://doi.org/10.5194/bg-17-1343-2020 (2020)

4.10. CCDAS-SDBM3

4.10.1. Model Description

CCDAS is a comprehensive data assimilation system for the global carbon cycle (Kaminski et al, 2013). It has been operating since the early 2000s both with SDBM (Knorr and Heimann, 1995; Kaminski et al, 2002), a diagnostic model using remotely sensed "greenness", or BETHY (Rayner et al. 2005), a process-based terrestrial biosphere and land surface model, as the underlying terrestrial biosphere component. SDBM3 is a new development that aims at exploiting the now much richer global set of eddy covariance data (FLUXNET2015 Tier1, https://fluxnet.fluxdata.org/data/fluxnet2015-dataset/). SDBM3 is a semi-empirical model that incorporates process understanding of photosynthesis and plant and soil respiration in a simplified manner, but bases parameterisation of the model and its dependence on vegetation type on the available training data. It will produce hourly fluxes of photosynthesis (gross- primary productivity), plant respiration (Raut) and soil resporiation (Rhet), as well as evapotranspiration and plant-available soil moisture. In its global configuration, it will be run by hourly re-analysis data as well as remotely sensed FAPAR.

4.10.2. Changes for next year

We expect first global results to be available early next year. Due to personnel changes, focus of our group has been on completing top-down inversions for VERIFY, which are less-well represented than bottom-up models in WP3.

4.10.3. References

Kaminski, T., W. Knorr, M. Heimann, and P. Rayner (2002), Assimilating atmospheric data into a terrestrial biosphere model: A case study of the seasonal cycle, Global Biogeochemical Cycles, 16(4), 1066, doi:10.1029/2001GB001463.

Kaminski, T., W. Knorr, G. Schürmann, M. Scholze, P. J. Rayner, S. Zaehle, S. Blessing, W. Dorigo, V. Gayler, R. Giering, N. Gobron, J. P. Grant, M. Heimann, A. Hooker-Strout, S. Houweling, T. Kato, J. Kattge, D. Kelley, S. Kemp, E. N. Koffi, C. Köstler, P.P. Mathieu, B. Pinty, C. H. Reick, C. Rödenbeck, R. Schnur, K. Scipal, C. Sebald, T. Stacke, A. Terwisscha van Scheltinga, M. Vossbeck, H. Widmann, and T. Ziehn. The BETHY/JSBACH Carbon Cycle Data Assimilation System: experiences and challenges, J. Geophys. Res., 118, 1-13, 2013.

Knorr, W., and M. Heimann (1995), Impact of drought stress and other factors on seasonal land biosphere CO2 exchange studied through an atmospheric tracer transport model, Tellus B, 47, 471-489.

Rayner, P. J., M. Scholze, W. Knorr, T. Kaminski, R. Giering, and H. Widmann (2005), Two decades of terrestrial carbon fluxes from a Carbon Cycle Data Assimilation System (CCDAS), Global Biogeochemical Cycles, 19, GB2026, doi:doi:10.1029/2004GB002254.

5. Model Results

5.1. BLUE

Replacing LUH2, which is the land-use change forcing used in the Global Carbon Project's annual global carbon budget, with the newest HILDA+ dataset (v201101) in the BLUE model results in significant temporal and spatial differences of LULC emission estimates.

While the total land use and land cover (LULC) emission estimates since 1980 are comparable in size and trends, the single component fluxes from crop, pasture, harvest and abandonment generally differ significantly (Figure 10). For Europe, the estimates based on HILDA+ reflect a larger sink from abandonment compared to the ones based on LUH2 (on average 74.8 TgC*yr^{-1} for the time period 1950-2019). Similarly, emission estimates, primarily from cropland expansion but also to some degree from pasture expansion and forestry harvests, are higher based on HILDA+; the average emissions are 31.8 TgC*yr^{-1} (cropland expansion), 22.3 TgC*yr^{-1} (pasture expansion), and 7.4 TgC*yr^{-1} (forestry harvest) for the time period 1950-2019. Since HILDA+ does not provide forestry harvest information, we used the LUH2 harvested area. The fact that the resulting net forestry harvest flux is significantly different between the two simulations reveals strong interactions between different land-use activities. The elimination of extreme values (i.e., 1960, 2015) in the BLUE runs with the LUH2 forcing, which were most likely artifacts, suggests a higher reliability of estimates based on HILDA+.

Spatial patterns reveal great local differences (Figure 11). Main differences are located in Eastern and Southern Europe, where the sink for LULC fluxes is larger for the estimates based on HILDA+. Differences in Western and Northern Europe are visible but comparably small. However, breaking down emissions from each of the four primary activities reveals large differences (Figure 12). The differences for abandonment are especially striking. Overall, the estimates based on HILDA+ seem to capture heterogeneity better and provide a more detailed picture of local sources and sinks.

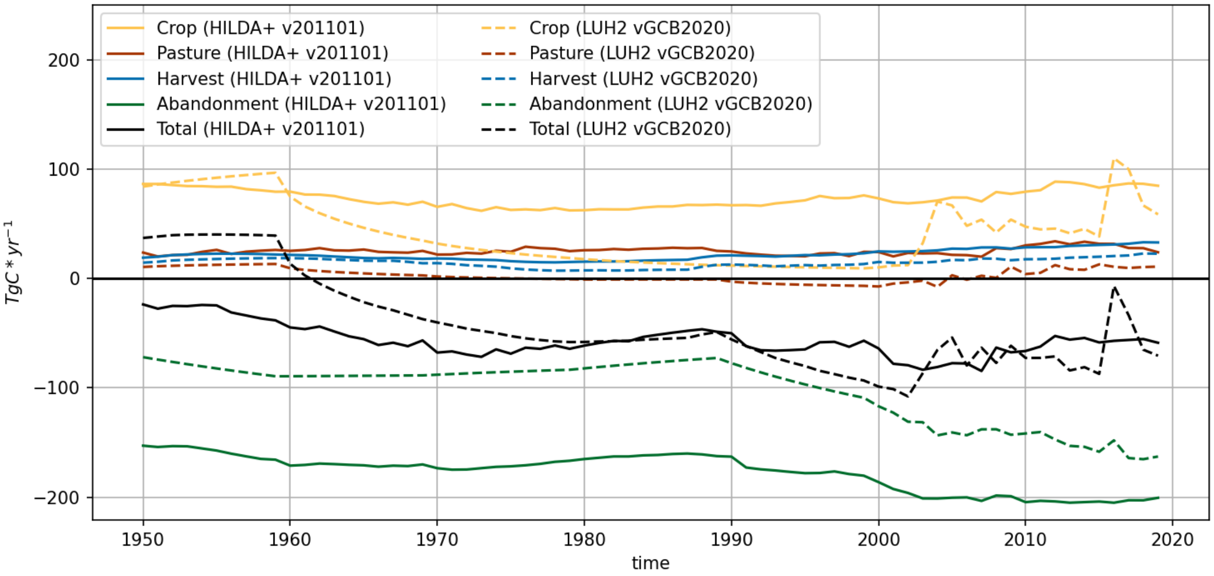

Figure 10: LULC emission estimates for Europe based on HILDA+ and LUH2.

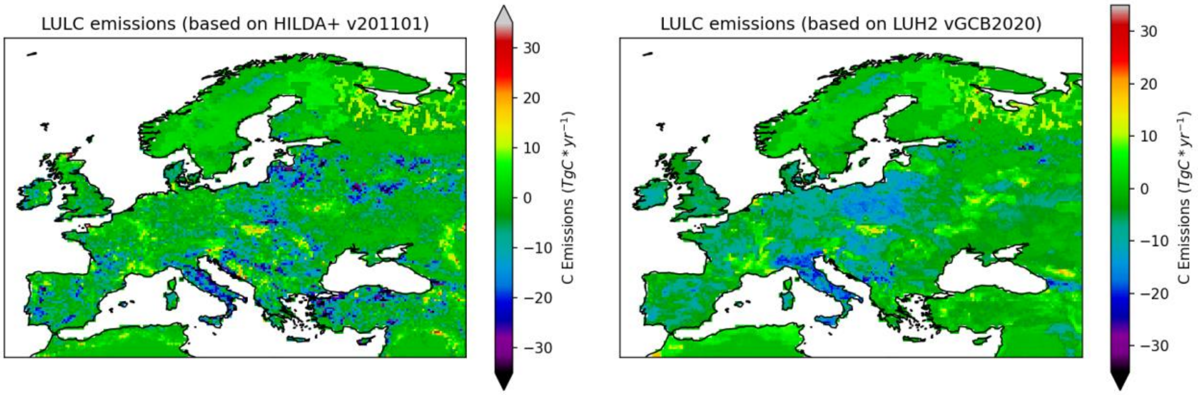

Figure 11: LULC emission estimates for the time period 1990-2019 based on HILDA+ (left) and LUH2 (right)

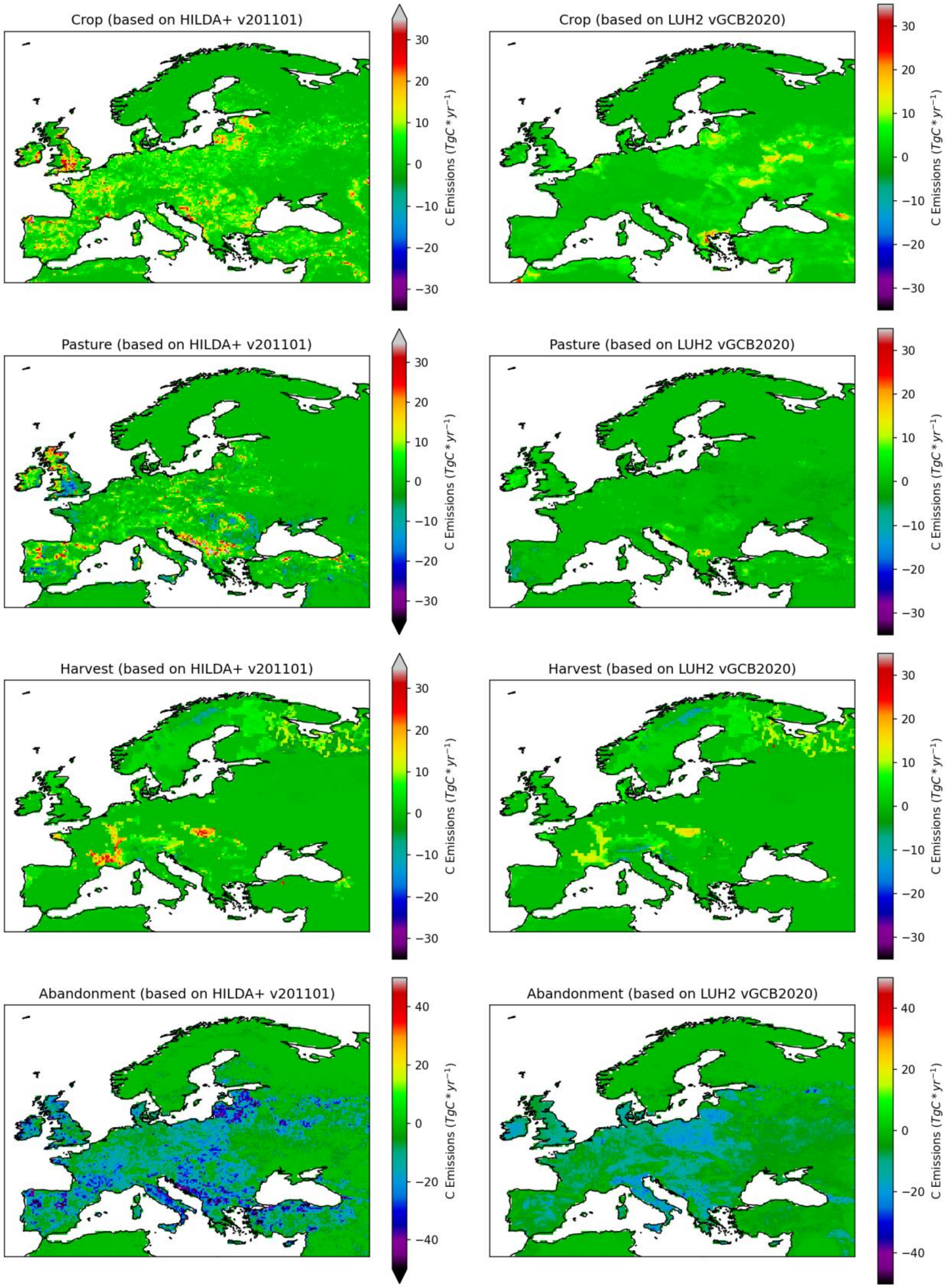

Figure 12: Emission estimates from crop, pasture, harvest, and abandonment for the time period 1990-2019 based on HILDA+ (left) and LUH2 (right).

5.2. CBM-CFS3

Results from CBM show that the forest NBP for the period 2000-2015 for EU-26 is on average 0.61 Mg C ha^{-1} year^{-1}, ranging from about 0.18 Mg C ha^{-1} year^{-1} for Hungary to about 1.93 Mg C ha^{-1} year^{-1} for Ireland (see Figure 13). The NBP was calculated for a total forest area of about 158 million ha.

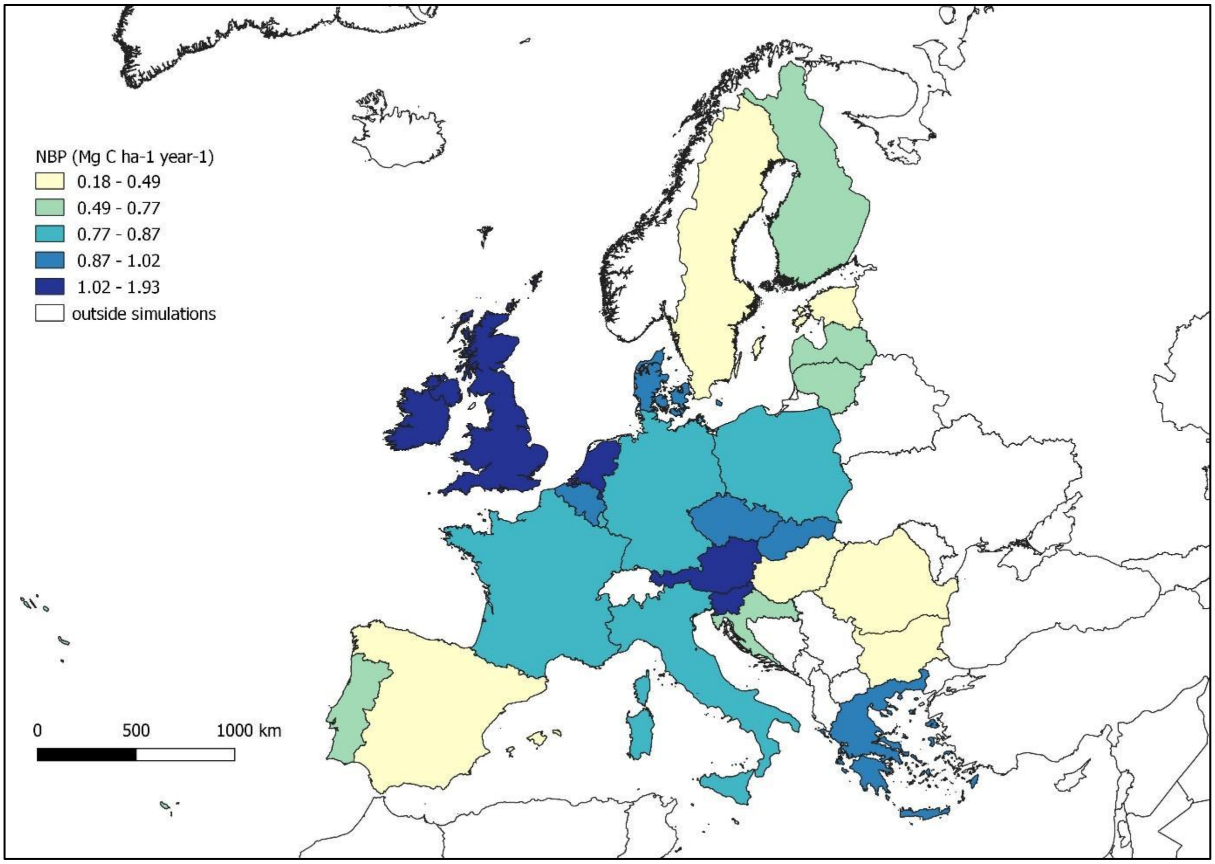

Figure 13: distribution of forest NBP (Mg C ha^{-1} year^{-1}) for EU-26 (NUTS-0 level).

There are regional differences in terms of NBP (range for the period 2000-2015): 0.55 ± 0.91 Mg C ha^{-1} year^{-1} in Central and Eastern Europe; 0.43 ± 0.66 Mg C ha^{-1} year^{-1} in Northern Europe; 0.64 ± 0.79 Mg C ha^{-1} year^{-1} in Southern Europe; 0.91 ± 1.23 Mg C ha^{-1} year^{-1} in Western Europe.

During the period 2000-2015, the forest NBP in EU-26 declines by about 22.5%, with highest drop for Central and Eastern Europe (-37%) and lowest for Southern Europe (-7%) (see Figure 14).

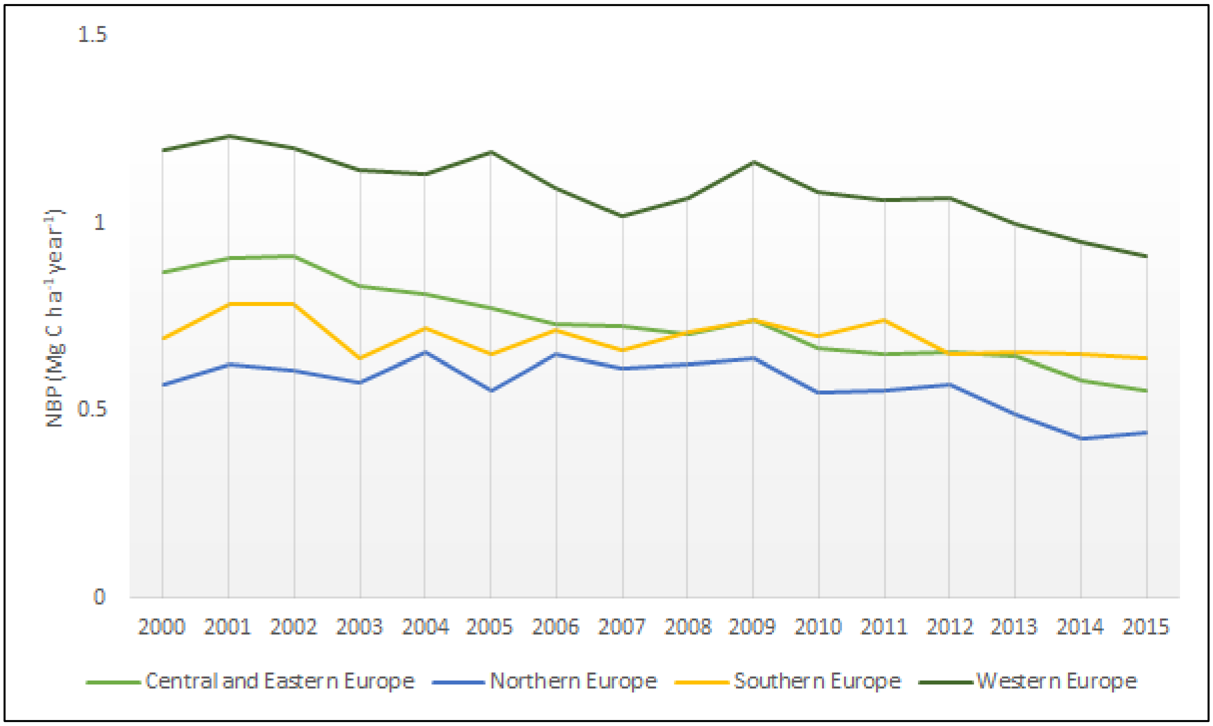

Figure 14: trend in forest NBP (Mg C ha^{-1} year^{-1}) by geographic region in EU-26 from 2000 to 2015.

According to Pilli et al. (2017), the NBP corresponds to 16% of the NPP in managed forest land for the period 2000-2012. Uncertainties are only available for NPP. The overall uncertainty related to the living biomass stock is about 6.6% (based on simulations in Pilli et al. 2017). When compared to other models, the forest NPP from CBM is -17% than from EFISCEN, -8% than from BIOME-BGC, -16% than from ORCHIDEE, +24% than from JULES (see Pilli et al. 2017).

References/link

Pilli, R., Grassi, G., Kurz, W. A., Fiorese, G., and Cescatti, A.: The European forest sector: past and future carbon budget and fluxes under different management scenarios, Biogeosciences, 14, 2387–2405, https://doi.org/10.5194/bg-14-2387-2017, 2017.

5.3. DAYCENT

Not yet available. DAYCENT results will be included in the next deliverable.

5.4. ECOSSE

The extension of the model described in the Methods section allows provision of the net primary production (NPP) data to calculate the net biome production (NBP). Figure 15 shows the results for the cropland NPP. The values are higher for western-facing exposed areas, which can be explained by high precipitation values and sufficient temperature. For other areas (e.g., Italy), the high NPP values can be explained by high temperatures, but still sufficient amounts of precipitation. For too cold (North-Eastern Europe) or too dry (Spain, Eastern Europe) conditions the NPP understandable drops.

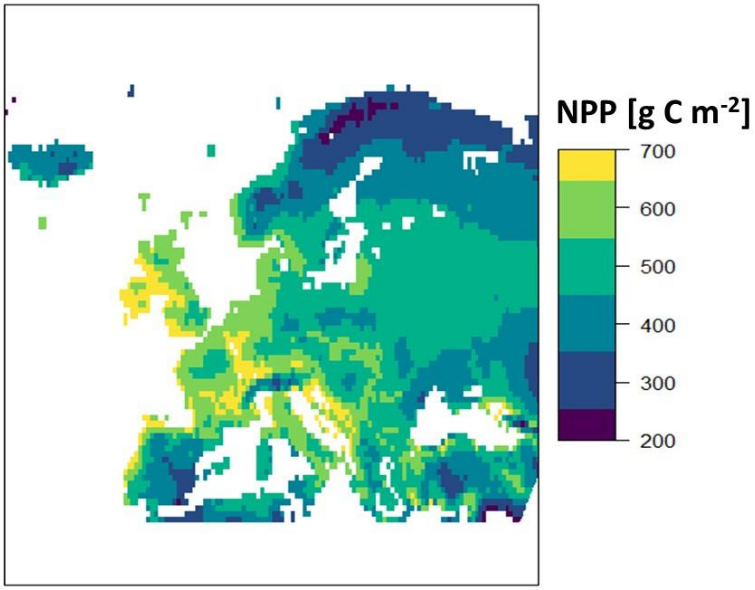

Figure 15: Simulated NPP for croplands (including all grid cells).

The changes in the model allowed simulation of all relevant variables to calculate NBP:

$$\boldsymbol{NBP = R_h - NPP + Yield + RR}$$

with R_h as the heterotrophic respiration and RR as removed residues (all variables have the units g C m^{-2}). The results for croplands and grasslands (29 year average - 1990-2018) show an average carbon sink over all grid cells (Figure 16). Values lower than -100 g C/m^{-2} are masked out, as this is a suspiciously strong sink and they will therefore require a more detailed analysis. Some management practices are not yet included in the simulation. For example, grazing impacts are not yet considered, which results in an overestimation of carbon gains for intensive grazed areas (e.g., Ireland).

Overall, the NBP results (Figure 17) follow the spatial pattern of the NPP simulation results (Figure 15). This can be expected, as NPP, yield and amount of residues are correlated. Therefore, the primary production is the main driver for the strong sink for croplands. The results for grassland are within the range of estimates by Janssens et al. (2003), who estimate about -66 g C m^{-2} yr^{-1}, but they overestimate the sink compared to improved estimates by Chang et al. (2015), who quantified the carbon sink at 15 ± 7 g C m^{-2} yr^{-1}. In addition, the cropland results do not represent literature values, as Ciais et al. (2010) estimated the croplands to be a weak carbon source, rather than a sink. The results presented here show the croplands as a stronger sink than the grasslands, which is unlikely and contradicts both expectation and the literature. The analysis showed that the simulated respiration rates for croplands are quite low, which requires an additional analysis. For the grasslands, besides the intensive grazing (which will move the overall average towards a source), the fertilization of grasslands (which will move the overall average towards a stronger sink) is not yet included.

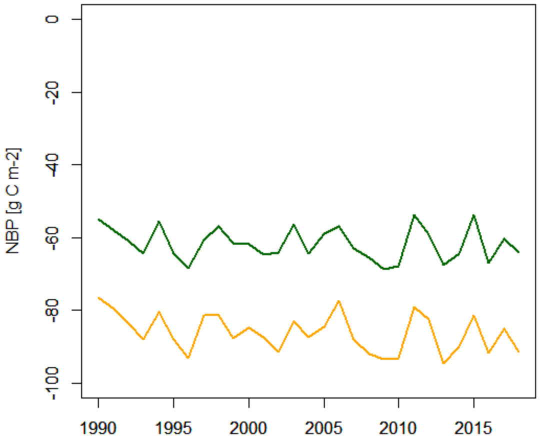

Figure 16: Simulated NBP for cropland (orange) and grassland (green) as overall average.

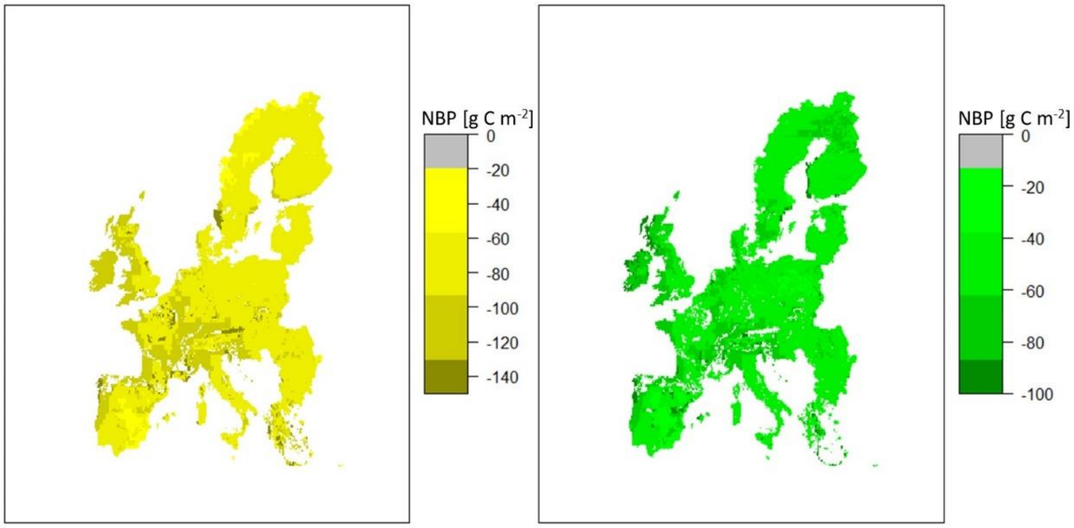

Figure 17: Simulated NBP for all grid cells. The maps show the NBP for cropland (left, yellow) and grassland (right, green).

References

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5.5. EFISCEN Space

We obtained monthly observed weather at 25 km resolution from the Agri4Cast website of the JRC (http://agri4cast.jrc.ec.europa.eu/) for the period 1979-2018. The reason for using this dataset is that the increment model (Schelhaas et al. 2018b) was derived including this dataset, and using the meteorological forcing as provided within the VERIFY project may result in biases in the simulations. For the current simulations of forests carbon budget, we used the average observed weather for the years 2011-2018. In the next year we will try to produce annual output, as the model has this year been adapted to incorporate this capability. All countries have been simulated as a first try, but work is still ongoing to check and finetune total harvest, mortality and increment.

In contrast to last year, the model setup now includes mortality and harvest, and the biomass expansion factors are based on European data (Forrester et al. 2017). The model produces wood volumes and biomass per plot for 20 species groups, for live trees, for mortality and for harvest. Subtracting the consecutive whole-tree biomass estimates yields the net increase in tree biomass after mortality and harvest, which can be considered to be the tree Net Biome Production (NBP). Harvest is defined as the biomass in the stems that are removed, and possibly extracted residues. Tree NEP is calculated as tree NBP plus harvest. Please note that stock changes in deadwood and soil are not (yet) considered in this approach.

Output is delivered as annual values (kg C m^{-2} yr^{-1}), repeated for each month, following the requested simulation output format, assuming 365 days in a year. Please note that there will be a clear annual cycle in the NEP which will not be reflected by this method; therefore these data should only be used at the annual scale.

For the creation of the NetCDF file, a simple average was taken of the individual plot values available in the grid cell (based on the meteorological forcing grid), irrespective of the available number of plots (see for an example Figure 18). Norway was left out of the simulation results due to unexpectedly high increment values in some regions. Results are delivered as one NetCDF file for all countries together, containing total tree carbon stock, NPP, NBP and harvest flux (Figures 19-22).

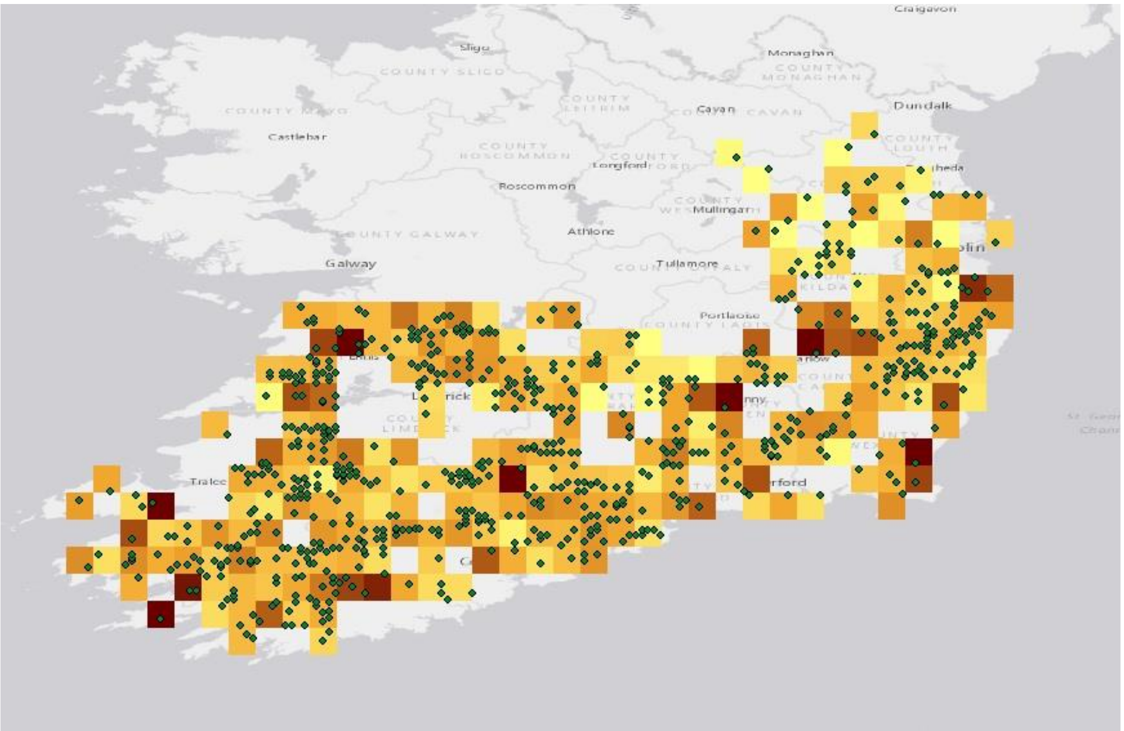


Figure 18: Grid values are based on the average of the available forest plots per grid cell, with varying number of plots per cell.

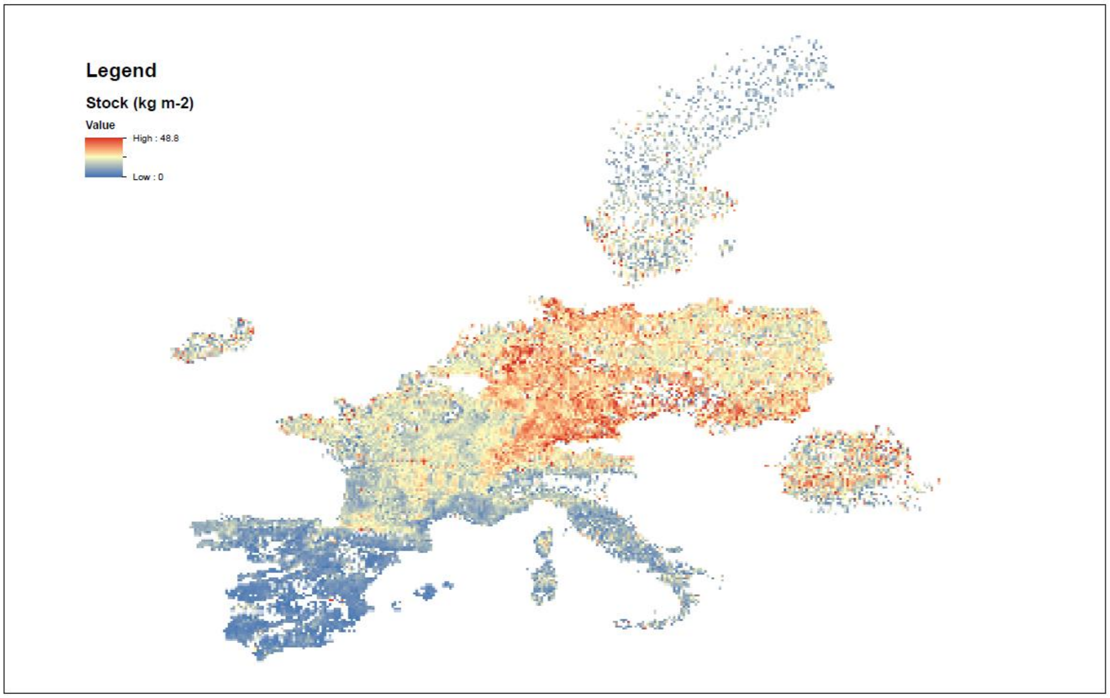


Figure 19: Pattern of forest carbon stocks over Europe over the simulated countries (kg C m^{-2}).

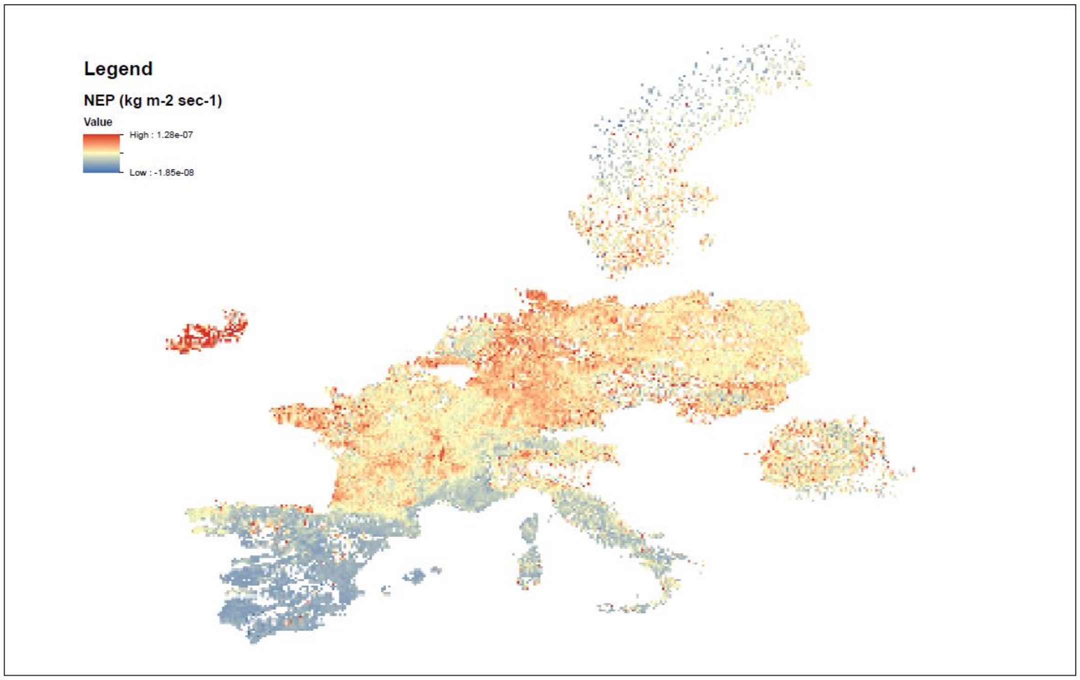


Figure 20: Pattern of forest NEP over Europe over the simulated countries.

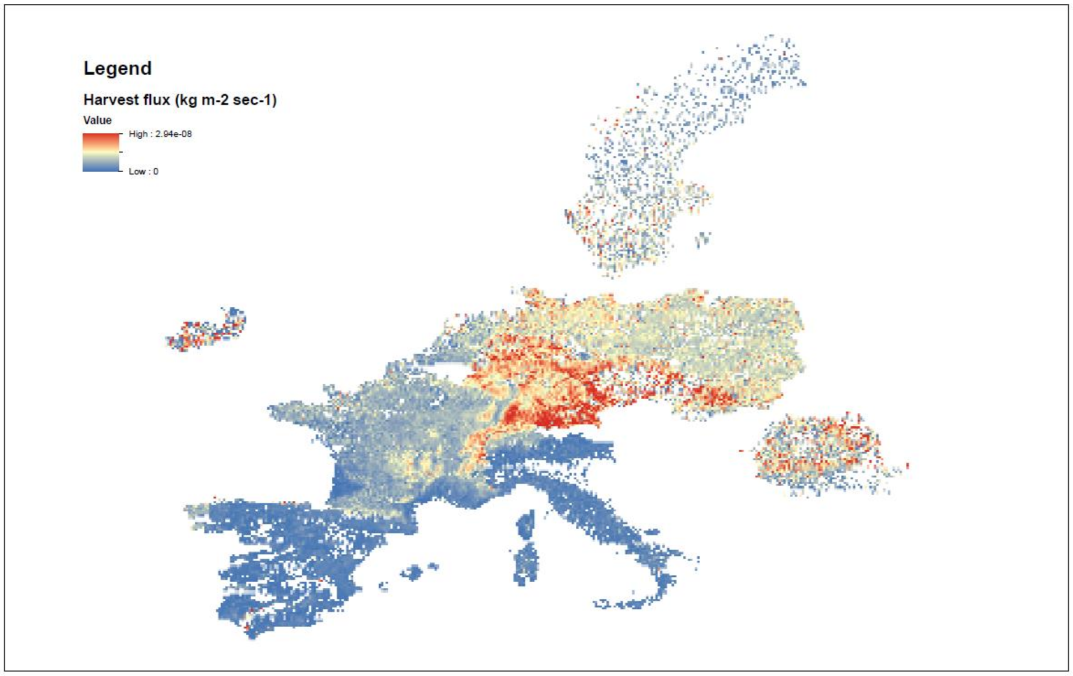


Figure 21: Pattern of forest harvest flux over Europe over the simulated countries.

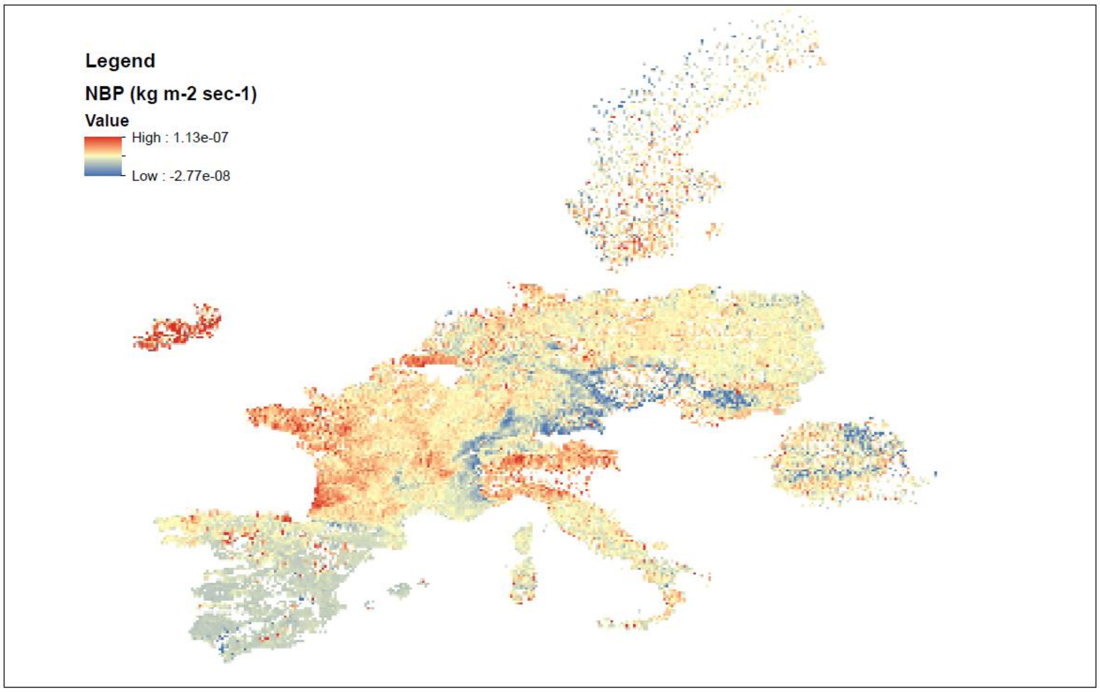
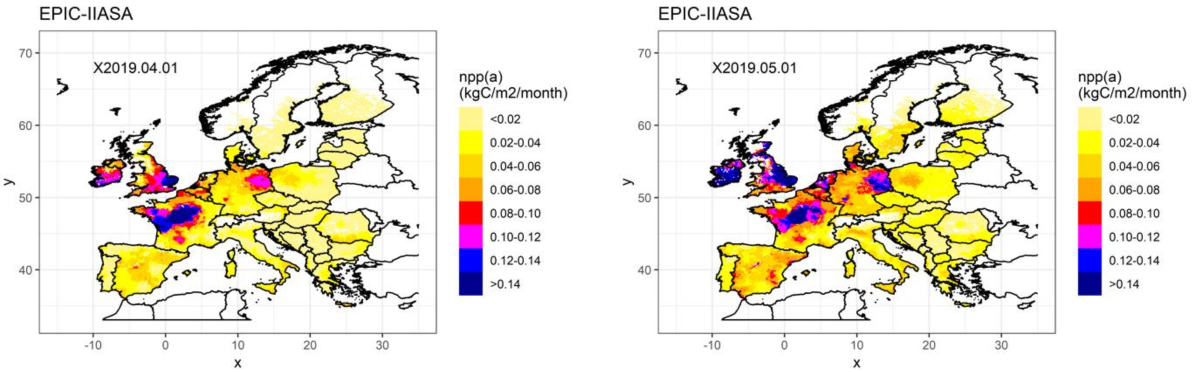


Figure 22: Pattern of forest NBP over Europe over the simulated countries.

5.6. EPIC-IIASA

We present example results from the re-gridded EPIC-IIASA simulations for the year 2019 as driven by the CRUHAR v.3.1 meteorological forcing: the above-ground NPP (npp(a), in kg C m^{-2} $month^{-1}$), heterotrophic respiration (rh, in kg C m^{-2} $month^{-1}$), and carbon in vegetation (cVeg, in kg C m^{-2} $month^{-1}$) in Figures 23 to 25.



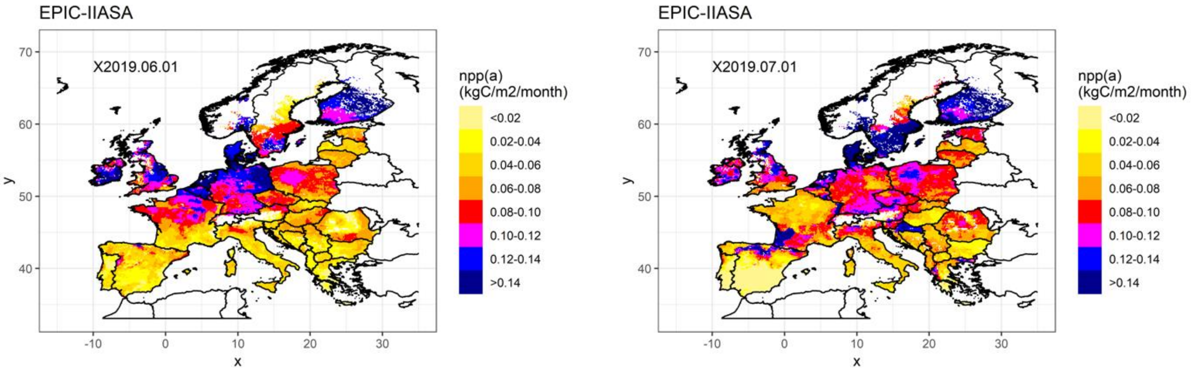


Figure 23: Mean above-ground NPP (npp(a), kg C m^{-2} month^{-1}, April to July 2019) calculated by EPIC-IIASA from crops grown in 2019 under the business-as-usual crop management (CRUHAR v. 3.1 meteorological forcing).

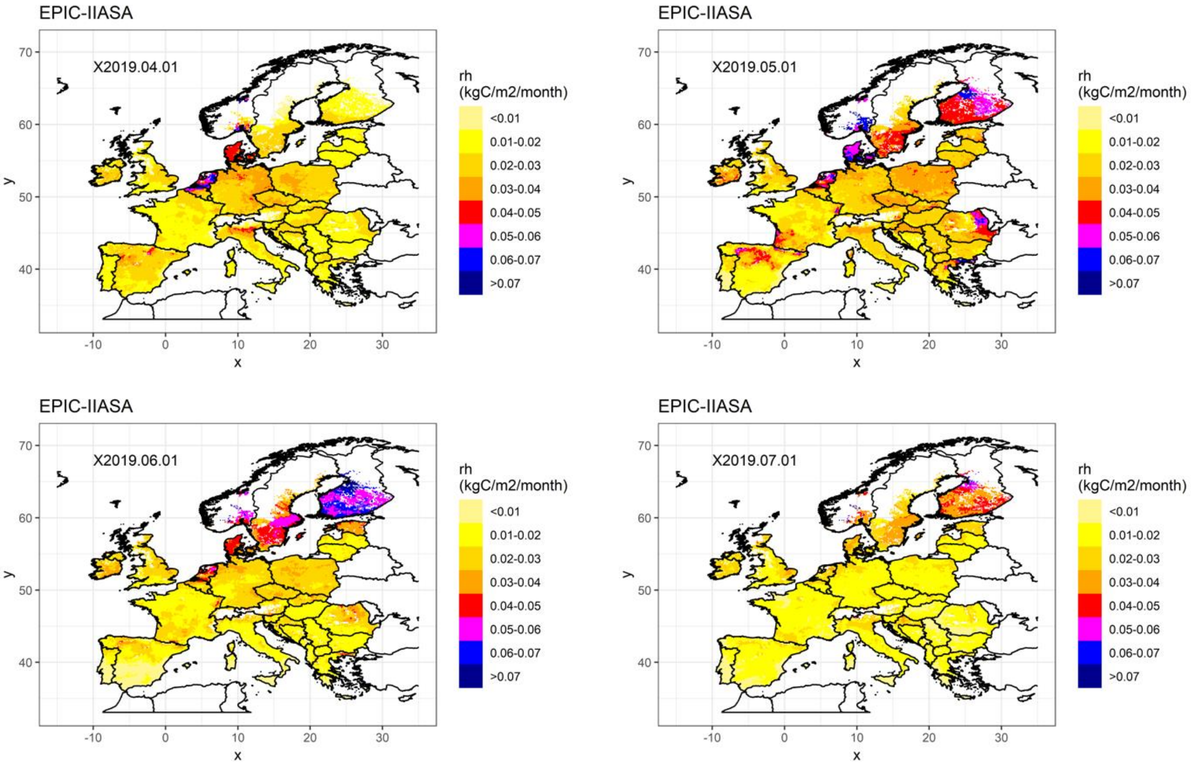


Figure 24: Mean heterotrophic respiration (rh, kg C m^{-2} month^{-1}, April to July 2019) calculated by EPIC-IIASA from crops grown in 2019 under the business-as-usual crop management (CRUHAR v. 3.1 meteorological forcing).

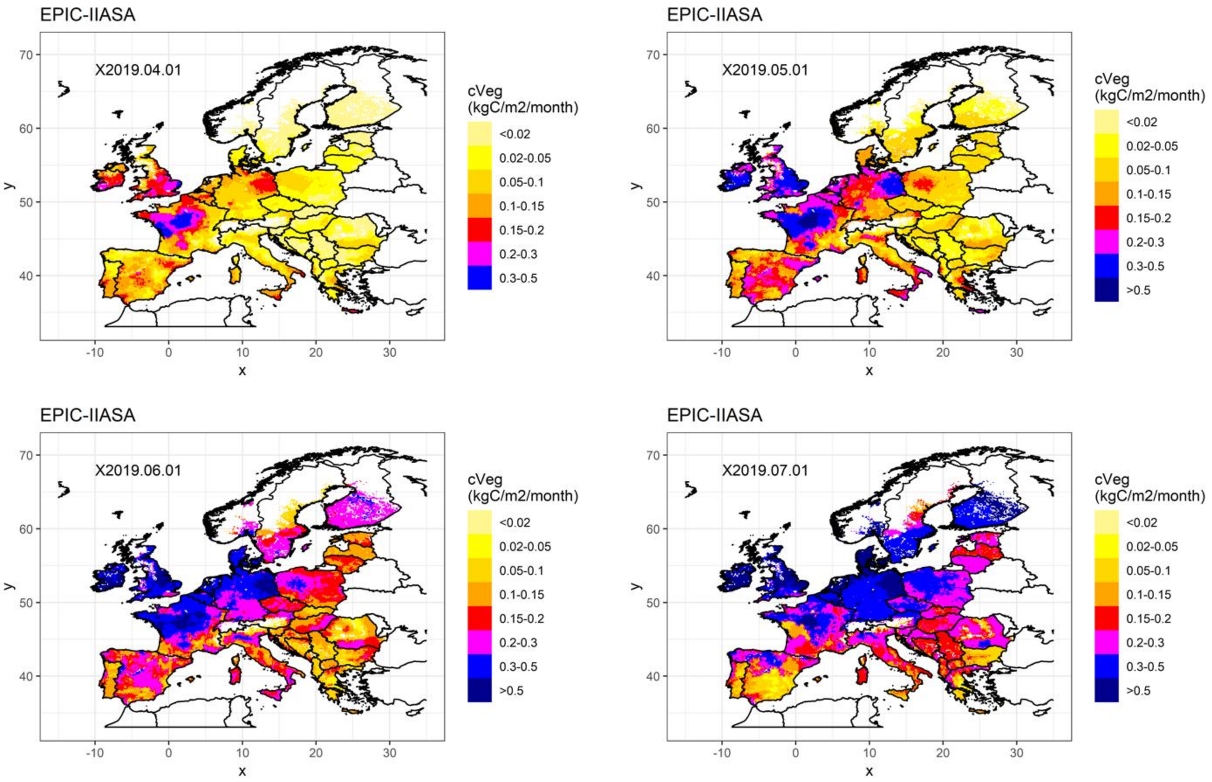


Figure 25: Mean carbon in vegetation (cVeg, kg C m^{-2} month^{-1}, April to July 2019) calculated by EPIC-IIASA from crops grown in 2019 under the business-as-usual crop management (CRUHAR v. 3.1 meteorological forcing).

5.7. G4M+FLAM

All inputs were re-gridded to 5 arc min resolution. G4M+FLAM only provides estimates for forest ecosystems.

We used HARMONIE daily dataset: cruhar_v3_1 for all variables except for shortwave solar radiation (cruhar_v3_2) from 2002 until 2018; and ERA dataset (cruera_v1.1) for 2019. The model was calibrated using MODIS NPP: the time interval 2001-2013 was used for calibration and 2014-2015 for validation. To include information on burned areas we used the MODIS CCI dataset from 2001 to 2019. Annual land cover maps from HILDA+ were applied over period 2001-2015 to identify forest class based on ESA-CCI Land Cover. Validation of modeled NPP results showed the following scores: Root Mean Squared Error: 0.068 kg C m^{-2} yr^{-1}; R2 score: 91.21% in 2014, and Root Mean Squared Error: 0.081 kg C m^{-2} yr^{-1}, R2 score: 84.41% in 2015. We modeled NPP until 2019 using the VERIFY-supplied weather forcing and by keeping land cover as in HILDA+ in 2015. The forest NPP map modeled for 2019 is shown in Figure 26.

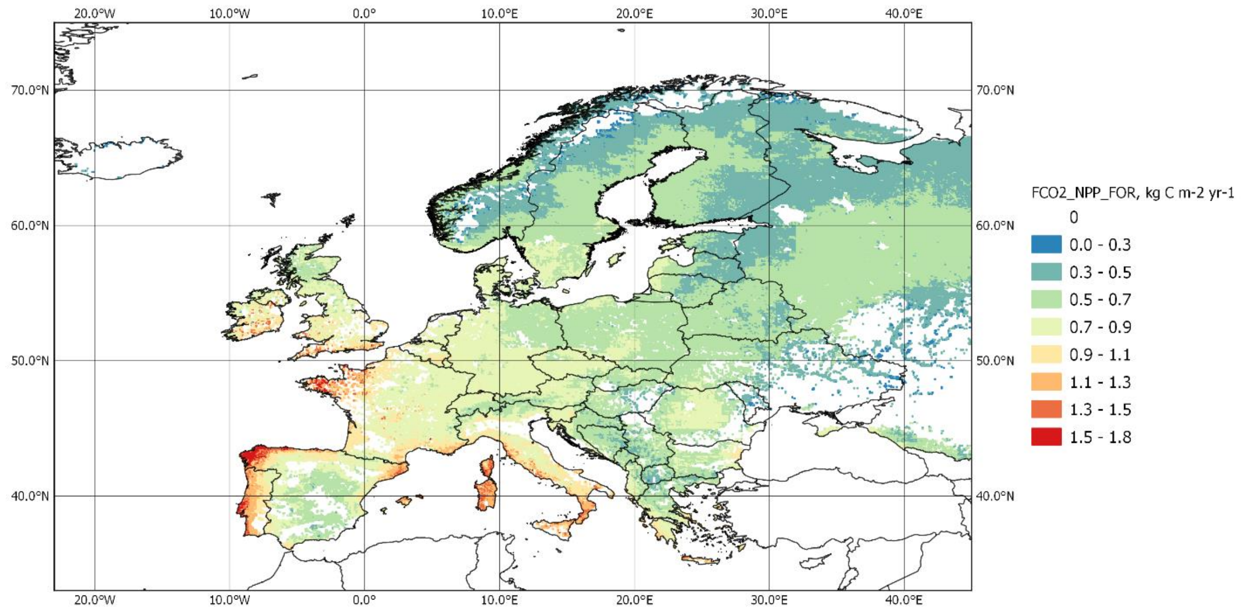


Figure 26: G4M+FLAM modeling results: forest NPP (kg C m^{-2} yr^{-1}) in 2019.

Figure 27 shows the above ground biomass map of forest ecosystems in 2019 calculated by the model. It was calibrated and validated using AGB maps from GlobBiomass project available for 2010 and 2017.

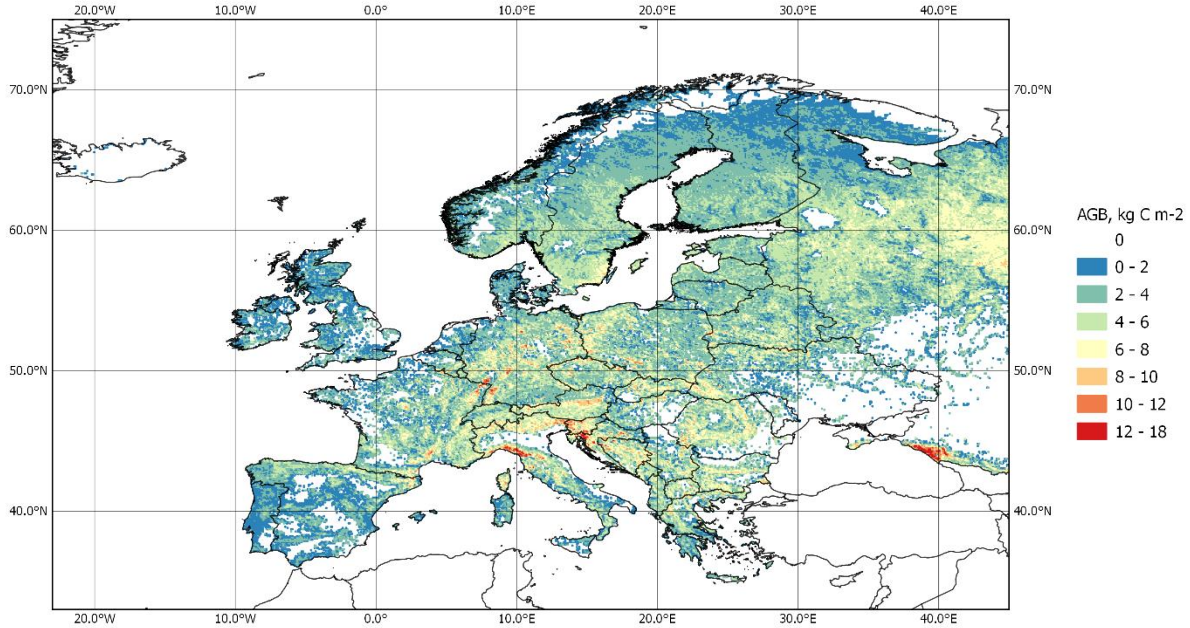


Figure 27: G4M+FLAM modeling results: forest AGB (kg C m^{-2}) in 2019.

5.8. ORCHIDEE

Figure 28 presents two examples of net ecosystem exchange fluxes (NEE) simulated in ORCHIDEE for all land ecosystems. The NEE is a measure of the amount of carbon flowing into or out of an ecosystem due to natural processes of uptake of carbon by vegetation and release of carbon by respiration from vegetation and from the soil. The sign convention is taken from the atmospheric perspective, where a negative value indicates that carbon is being absorbed into the land surface.

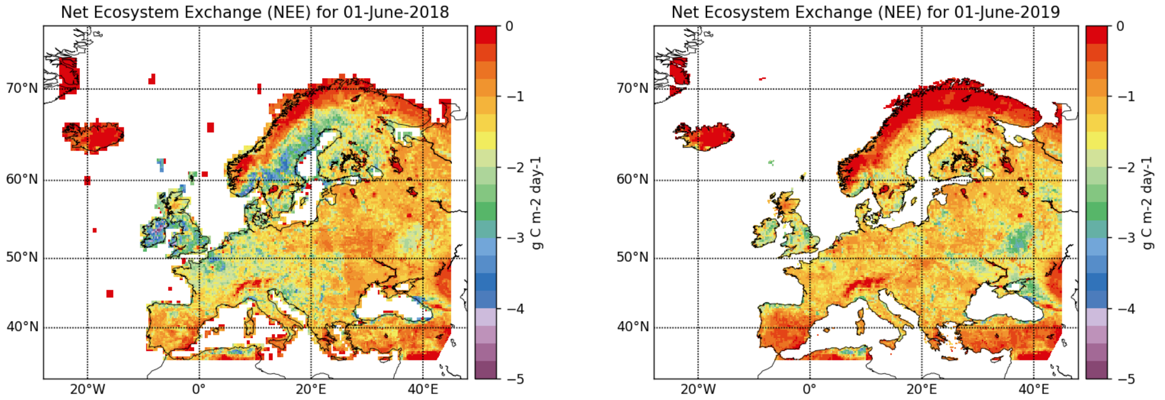


Figure 28 : Sample NEE fluxes from the ORCHIDEE model for a given day (3 hour block) in two different years.

Two features stand out from Figure 28. The first is that interannual variability is clearly seen, with June 1 in 2018 uptaking more carbon than the corresponding day in the following year. Despite that 2018 was a year of extreme drought across much of the continent, such a pattern is not seen for this specific three-hour block in late spring. The second obvious feature is the map themselves, and how more pixels are visible in 2018. This is a result of the meteorological data as described in D3.2, and represents one of the challenges of this year in the project. The meteorological data used last year (HARMONIE re-aligned to the CRU observational monthly means) used a different land-sea mask. The switch to ERA5-Land for 2019, due to the end of the UERRA project which produced the HARMONIE product, results in a different land mask, which has fewer land pixels (approximately 13% fewer). As can be seen from Figure 28, most of these are islands and northern coastlines, areas which are unlikely to contribute significantly to country-level carbon fluxes, and therefore the impact is not expected to be great. This issue is expected to be resolved by a full transition to ERA5-Land next year.

5.9. Statistical upscaling of eddy covariance fluxes (Fluxcom)

The resulting carbon fluxes (GPP, NEE) were delivered across Europe for simulation conditions described in Section 4.9: “RS only” and “RS + meteo”. The RSMeteo data cover 2001-2019 at 0.5 deg spatial and monthly temporal resolutions (aggregated from hourly). The Rsonly data cover the same years at 0.25 deg spatial and monthly temporal resolutions (aggregated from eight days and 1/12 deg). Examples of plots of the data are shown in Figures 29 and 30.

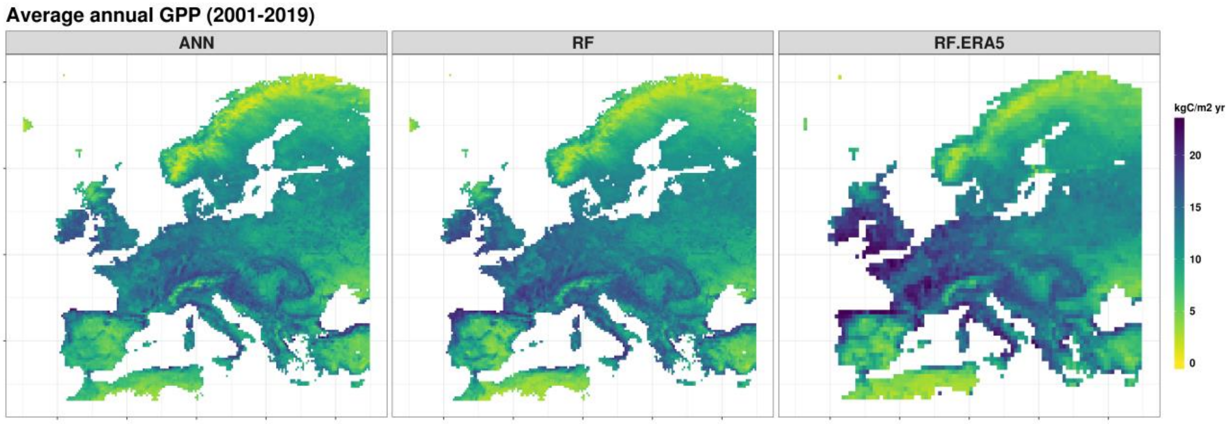


Figure 29: Average annual GPP for the ‘RS+meteo’ setup using ERA5 meteorology as well as the ‘RS only’ setup for two different machine learning methods (random forest and neural networks) for the years 2001-2019.

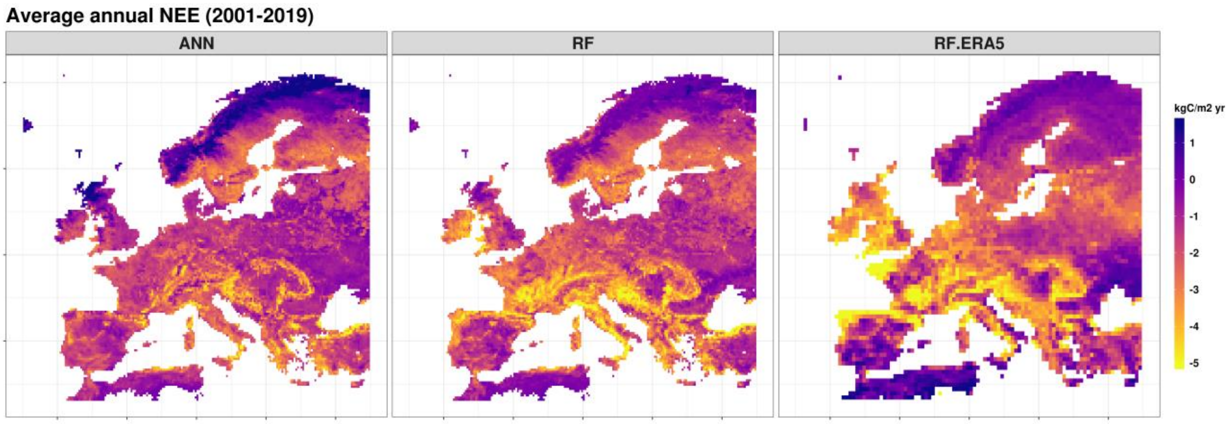


Figure 30: Average annual NEE for the ‘RS+meteo’ setup using ERA5 meteorology as well as the ‘RS only’ setup for two different machine learning methods (random forest and neural networks) for the years 2001-2019.

5.10. CCDAS-SDBM3

We expect first global results to be available early next year. Due to personnel changes, focus of our group has been on completing top-down inversions for VERIFY, which are less-well represented than bottom-up models in WP3.

6. Conclusions

The bottom-up simulations were designed to provide estimates of terrestrial carbon dioxide fluxes from natural and human-influenced ecosystems, including croplands, grasslands, and forests. For this period we have the simulations for sectorial and global models:

- Forest only: EFISCEM-SPACE, CBM-CFS3 and G4M/FLAM
- Crop only: ECOSSE and EPIC-IIASA
- Grass only: ECOSSE
- All ecosystems: ORCHIDEE, FLUXCOM and BLUE (only for land-use land-cover changes)

Major advances in model refinements this year included: ECOSSE upgrading to output a comparable carbon flux to the other models and national inventories, thus permitting additional comparisons for grasslands and croplands; G4M+FLAM adding results for the net primary production of forest ecosystems, complementing another forestry model, EFISCEN, which has expanded spatial coverage of its results to sixteen countries; and EPIC using a new parameterization of the soil organic carbon routine for calculating cropland fluxes.

Technical work remains to harmonize more of the forcing data used in the models. While land cover/land use data (Hilda+ dataset) and meteorological forcing products have been provided by VERIFY partners and are being used by several of the models, some additional work is still needed to ensure the widest-possible use of these data. In addition, several of the models simulate processes around the nitrogen cycle. Work has been carried out in 2020 to provide a harmonized nitrogen dataset to be used as forcing for the models through VERIFY partners at the JRC, but that work is not yet completed. The meteorological forcing will also have to be almost entirely redone in 2021. This year represented a “stop-gap” year between two meteorological forcing projects, UERRA (which provided the HARMONIE dataset used in the first year of VERIFY, and stopped production in August of 2019) and ERA5-Land (which will only have sufficient data available to force all the WP3 models sometime in 2021). ECMWF, who produces ERA5-Land, has reported delays to the creation of EAR5-Land due to the Covid19 pandemic; originally scheduled to be complete at the end of 2020, completion is now projected by mid-2021. The years 1981-2019 are currently available. We are looking at alternative solutions should the entire dataset not be ready by the time VERIFY’s 2021 simulations are set to launch.

Next year will bring more models into the simulation exercise as we are looking into the possibility of providing harmonized forcing data to the dynamic global vegetation models which participate in the TRENDY project. These models belong to the same class of models as ORCHIDEE in WP3. Models like ORCHIDEE are too expensive to permit a full uncertainty analysis comprising input data, parameters, and model structure. Such an exercise requires tens of thousands of simulations, and a single simulation of ORCHIDEE for VERIFY takes more than 1,000 computer hours. The use of a group of similar models running harmonized forcing data, called and “ensemble”, allows a realistic estimation of the uncertainty due to model structure, which will be invaluable to the synthesis efforts in WP5 and the comparison with the national greenhouse gas inventories.