,
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

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Changes with respect to the DoA
Delivery date was postponed from 31/07/2021 to April 2022 in agreement with the EC.
Dissemination and uptake **(Who will/could use this deliverable, within the project or outside the project?)**
The results are of interest to researchers using bookkeeping and dynamic global vegetation models, as this work highlights dominant components in their work which may be targeted to have the greatest possible impact on uncertainty reduction. It may also be relevant for inventory compilers as an indicator (complimentary to their own methods for identifying uncertainty).
Short Summary of results (<250 words)
We identified cropland and pastureland abandonment as important drivers for total land use change fluxes in Europe according to the bookkeeping model BLUE. We also used factorial simulations to identify carbon dioxide fertilization and nitrogen deposition as playing important roles in the net biome production reported by the DGVM ORCHIDEE. Taken together, these results point to areas in which uncertainty reduction would have the greatest overall impact of the total net carbon fluxes reported by these models. Such uncertainty reduction is essential to using independent research models in monitoring, reporting, and validation of official greenhouse gas inventories by member states to the UNFCCC.
Evidence of accomplishment **(report, manuscript, web-link, other)**
All the simulation results are accessible through the dedicated data THREDDS server: **https://verifydb.lsce.ipsl.fr/thredds/catalog/verify/WP3/catalog.html** **The results were given and explained in a 12 minute oral presentation during the Final VERIFY General Assembly from May 9-11, 2022, and the recorded talk is accessible from: https://verify.lsce.ipsl.fr/index.php/news/last-general-assembly-of-verify-final-meeting**

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Version	Date	Description	Author (Organisation)
V0	19/06/21	Creation/Writing	Matthew McGrath (CEA)
V0.1	11/05/22	Writing/Formatting of methods and results	Matthew McGrath (CEA)
V1	25/05/2022	Formatting/Delivery on the Participant Portal	Philippe Peylin (CEA) and Aurélie Paquirissamy (CEA)

1. Glossary

Abbreviation / Acronym	Description/meaning
BLUE	A bookkeeping model
DGVM	Dynamic global vegetation model
Harv	Harvest
LULUCF	Land use, land use change, and forestry
NBP	Net biome production, the overall carbon flux reported by ecosystem models including disturbances
ORCHIDEE	A dynamic global vegetation model
ORCHIDEEv2	A version of ORCHIDEE without a dynamic nitrogen cycle coupled to the carbon cycle
ORCHIDEEv3	A version of ORCHIDEE including a dynamic nitrogen cycle
PFT	Plant functional type
Photo	Photosynthesis
Resp	Respiration
TRENDY	A model intercomparison project using DGVMs to look the carbon cycle

2. Executive Summary

Carbon fluxes associated with land use, land use change, and forestry (LULUCF) are highly uncertain. In particular, different model classes have widely varying uncertainty ranges, even if the mean results agree reasonably well. Making the use of high-resolution simulations over Europe carried out in VERIFY, this deliverable looks at drivers behind these fluxes to determine which input data and components have the largest effect. In this way, researchers will be able to improve model responses to these drivers and consequently make significant advances in uncertainty reduction.

Two model classes are considered here: bookkeeping models and dynamic global vegetation models (DGVMs). Bookkeeping models keep track of the carbon stored in vegetation, soil, and wood products before and after land area has been converted from one class to another. Literature-based response curves describe decay and regrowth of carbon pools. These transitions (and the resulting emissions from decay of the dislocated carbon) are grouped here into four categories: cropland expansion, pastureland expansion, abandonment, and net fluxes from wood harvest. DGVMs, on the other hand, are process-based models which often operate at sub-daily timescales, incorporating information from meteorological data to predict how vegetation grows and dies. Basic information on human activities, including land use change, is often included. Bookkeeping models may differ from each other by using different plant functional types, land-use transition data, carbon densities, and response curves. DGVMs often differ from each other through different climate forcing, land use data, plant functional types, descriptions of the processes included (e.g., different equations or parameters to describe photosynthesis), and the exact processes included (e.g., fire, storms).

Using factorial simulations for the ORCHIDEE DGVM and examining the different components in the BLUE bookkeeping model, we found that, for the EU-27+UK, abandonment dominates the net carbon fluxes on most pixels across the continent. Abandonment results in an uptake of carbon dioxide from the atmosphere, but this does not mean that most pixels are carbon sinks as the combined effect of cropland expansion, pasture expansion, and wood harvest may be greater; this issue is elucidated in more detail by looking at annual time series for all four fluxes, which confirms that important role of abandonment. As for the DGVMs, one version of the ORCHIDEE model including a nitrogen cycle coupled to the carbon cycle simulates feedback of nutrient limitation on photosynthesis. This allowed examination of four different drivers: atmosphere carbon dioxide levels, climate change, land cover and land use change, and nitrogen deposition. We found that carbon dioxide fertilization was important across large parts of the continent, with nitrogen deposition playing a major role in the remaining regions. Together, this suggests that reducing the uncertainty on abandonment in bookkeeping models and reducing the uncertainty on carbon dioxide fertilization on nitrogen deposition in DGVMs will reduce the overall uncertainties in these methods in the European Union.

3. Introduction

Precise knowledge of the amount of carbon stored in ecosystems is essential for an accurate estimation of national greenhouse gas budgets, in addition to being necessary for carbon accounting in projects designed to offset unavoidable carbon dioxide emissions from other sources. While official estimates of carbon dioxide emissions from land use, land use change, and forestry (LULUCF) for the EU-27+UK show uncertainties on the order of 15% of the overall sink strength, the uncertainty from other model classes (as indicated by the spread of results for multiple models of similar types) remains high. Figure 1 shows annual LULUCF emissions for the past three decades from official reported values to the UNFCCC and two different model classes widely used in academic research: bookkeeping models and dynamic global vegetation models (DGVMs), the latter represented by the spread of an ensemble of more than ten different models submitted to the TRENDY intercomparison.

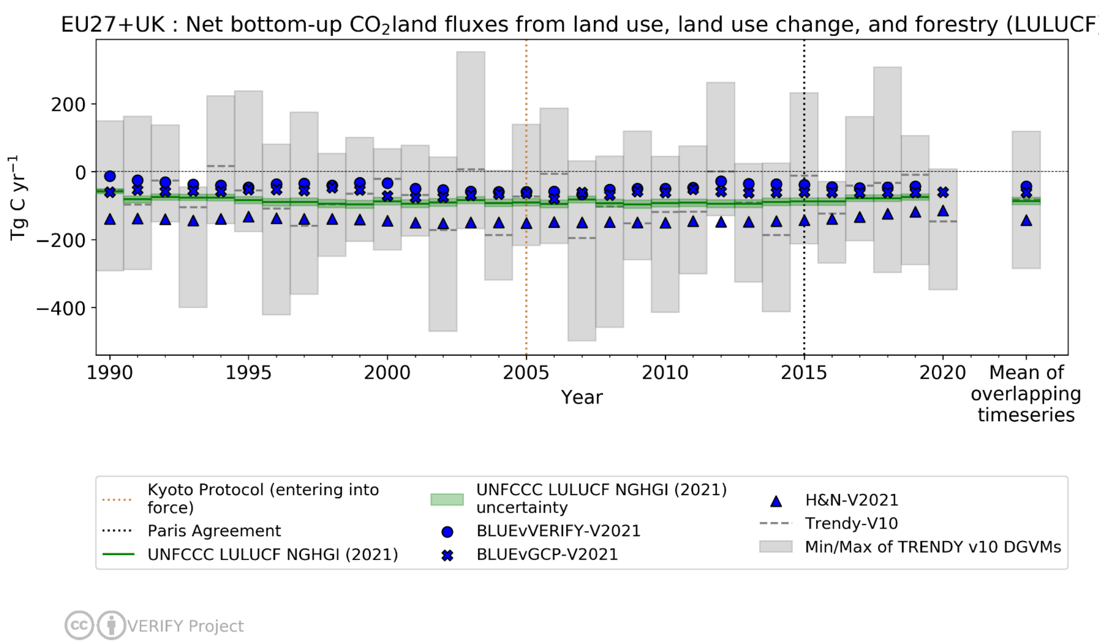

Figure 1: Emissions for the land use, land use change, and forestry (LULUCF) sector for the EU-27+UK for the years 1990-2020. Different classes of models are shown in different colors: UNFCCC inventory (green); bookkeeping models (blue); dynamic global vegetation models (TRENDYv10, gray). Negative values indicate a carbon sink in the land surface.

Figure 1 shows a clear difference in the uncertainty associated with each model class. The official reported inventory has a reported uncertainty of around 15%. Three different datasets for bookkeeping models (two different models, and two versions of one model run with different input data) show an increased spread of around 50% of the reported mean. The TRENDYv10 ensemble, comprising 15 different models with different model structure and parameters (although they are not completely independent) and harmonized input data, gives the widest range. Contrary to other emission sectors, LULUCF can be either a source or a sink of carbon and is often the residual of large fluxes. Therefore, small changes and uncertainties in the component fluxes can change the sign of the overall net biome production (NBP) from positive to negative, exaggerating the uncertainty. Understanding the source of this uncertainty is key to reducing it in process-based models.

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4. Methods

In order to understand where the uncertainty in the bookkeeping and DGVM models in Figure 1 comes from, we selected one representative of each model class to better examine the underlying drivers: BLUE and ORCHIDEE for bookkeeping models and DGVMs, respectively. The data for each model was taken from the VERIFY project. As the pre-operational nature of VERIFY generates results including the previous year by the end of summer of the current year, and as this deliverable is due before the summer of 2022, we used data from simulations submitted for V2021 (i.e., datasets end in the year 2020). BLUE and ORCHIDEE for V2021 are described in more detail in D3.6 (building on D3.4 and D3.5) and D3.9 (for BLUE), but key points are summarized below. Two main sets of analysis were carried out, one for ORCHIDEE and one for BLUE. In addition, a third analysis was done for ORCHIDEE based on a model version that does not include a nitrogen cycle.

Figure 2 gives a general idea of how the net biome production (NBP) is calculated in a generic DGVM.

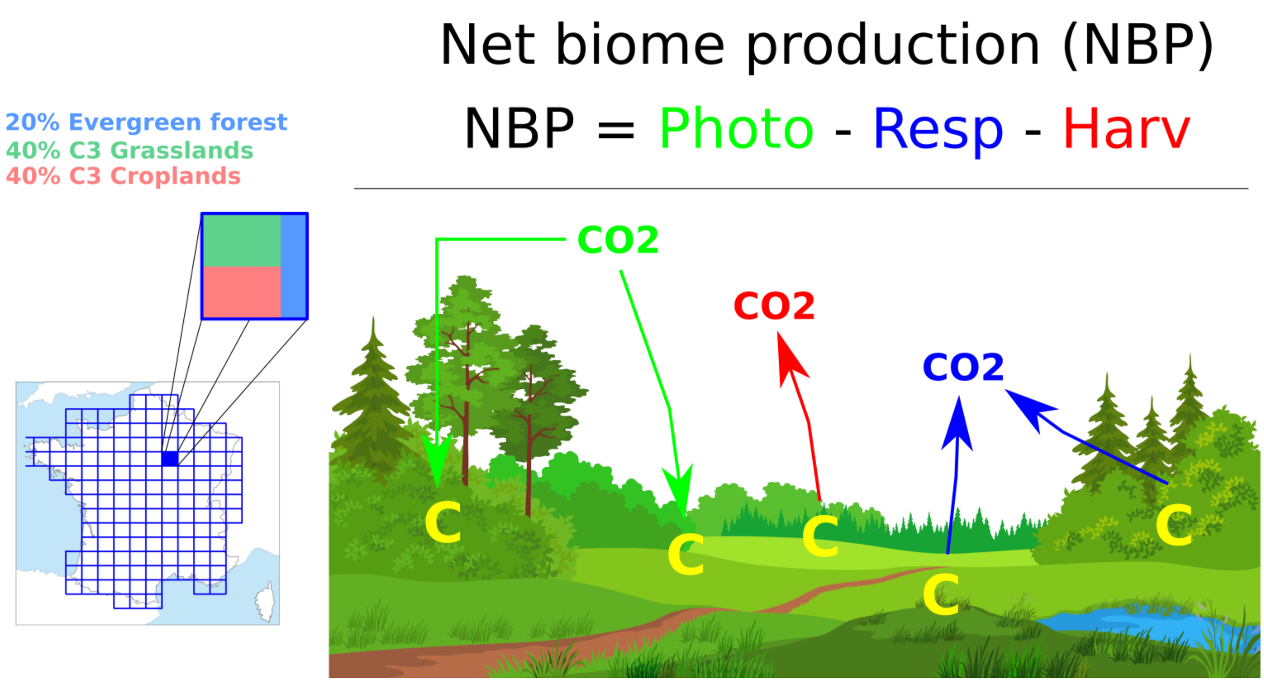

Figure 2: The calculation of the NBP in a generic DGVM. The NBP is a function of several fluxes, most notably the uptake of carbon dioxide by vegetation (photosynthesis); the return of carbon dioxide to the atmosphere (respiration); and human and natural disturbances. Most DGVMs have limited representation of disturbances, but harvest (of croplands and forests) and fire are common. The left side of the figure shows the spatially-explicit nature of the DGVMs and their dependence on plant functional types (PFTs) to represent large classes of vegetation.

ORCHIDEE is a DGVM originally designed to be coupled to an atmospheric model. The model includes complete descriptions of the energy, water, and carbon cycles, including the interactions between them. Two different versions of ORCHIDEE were used in VERIFY and this deliverable. The first version, labeled ORCHIDEEv2, is close to the version of ORCHIDEE used in the 6th cycle of the Coupled Model Intercomparison Project (CMIP6) that forms a basis of climate projections for the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). The second version, labeled alternatively ORCHIDEEv3 or ORCHIDEE-N, refers to a version developed from ORCHIDEEv2 including a nitrogen cycle coupled to the carbon cycle in order to better represent nutrient limitations on vegetation growth, and consequently impacts on the energy and water cycles. Both versions of ORCHIDEE use identical forcing data to the extent possible as described in D3.3 (namely Hilda+ for land cover and land use, and CRUERA for 3-hourly meteorological forcing).

In order to probe the drivers in a DGVM, we introduced a set of factorial experiments largely following the TRENDY protocol. Table 1 summarizes the different simulation experiments used. The drivers (CO2, climate, land cover/land use, and nitrogen deposition) refer to data used to force the model. As can be seen in the table, the only differences between the simulations is that some forcing data is held constant at the value for the initial year (in the case of climate data, which is available on a 3-hour timestep, the whole timeseries for the initial year is repeated to ensure an accurate seasonal cycle; similar consideration applies for nitrogen deposition, available at a monthly timescale). Consequently, if one takes the difference between the results for two simulations which only differ by a single forcing, one has the impact of this forcing on the overall simulation.

	S0	S1	S2	S3	*S4 (if app.)*
CO2	static	dynamic	dynamic	dynamic	*dynamic*
Climate	static	static	dynamic	dynamic	*dynamic*
Land cover/land use	static	static	static	dynamic	*dynamic*
Nitrogen deposition (if applicable)	*static*	*static*	*static*	*dynamic*	*static*

Figure 1: Explanation of the TRENDY-style factorial simulation experiments. CO2 refers to the atmospheric concentration of carbon dioxide; climate refers to the meteorological forcing; land cover/land use refers to the vegetation classes (PFTs); and nitrogen deposition refers to the amount of nitrogen input into the system from the atmosphere.

BLUE is a bookkeeping model. Bookkeeping models track emissions from land use transitions, such as those resulting from the conversion of natural vegetation to cropland, degradation of rangeland dynamics, and wood harvest. BLUE is spatially-explicit, like the DGVMs, and relies on various inputs (e.g., spatially explicit information on static plant functional types,

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literature-based carbon densities) on land use and land cover transition maps as external forcing data. The resolution of the output fluxes matches that of the land use transition maps. For VERIFY, the Hilda+ dataset was used, requiring modifications to the BLUE model to account for the high-resolution nature of the input. On each pixel and for every year, the amount of land making the transition from one land cover/land use to another serves as the basis for estimating the total amount of dislocated carbon. This carbon is placed in several pools and decays over time. All of these transitions and decays are tracked, and the output is the net carbon flux from land use change. Since HILDA+ does not provide information on wood harvest, spatially-explicit data of wood harvest was taken from LUH2 and adjusted to HILDA+ (D3.9). Figure 3 gives a general idea of the different transitions tracked in the model. The overall land use change fluxes are disaggregated into four main categories to examine the drivers: cropland expansion, pastureland expansion, wood harvest, and abandonment.

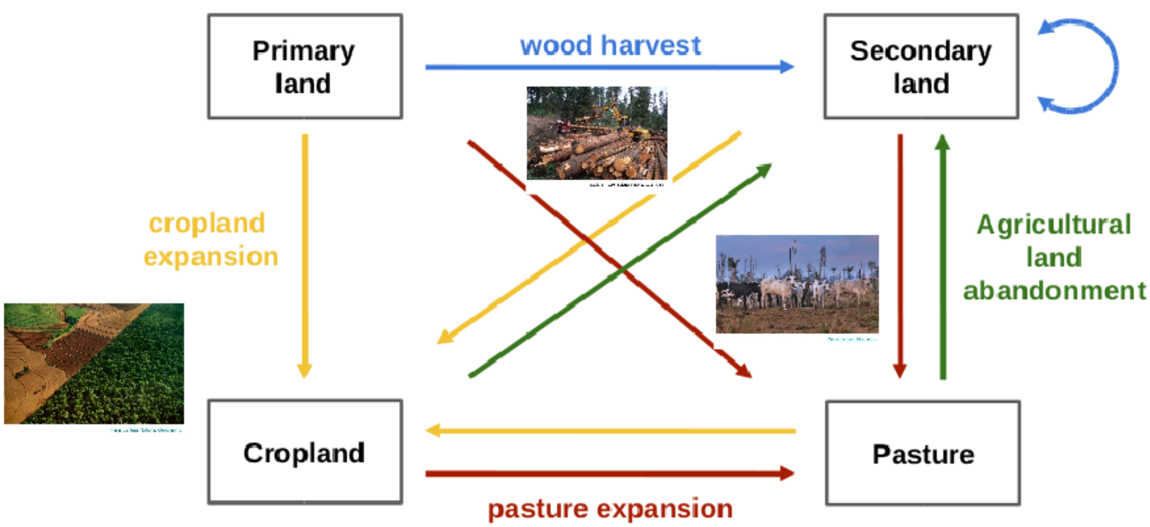

Figure 3: The different land use transitions considered in the BLUE model.

5. Results

In order to explore the drivers for both BLUE and ORCHIDEE, we ran a similar analysis using the different datasets:

1) Create a map showing the dominant driver on each pixel (where “dominant” is defined as the component with the maximum of the absolute value, to account for the fact that fluxes may be positive or negative in accordance with our sign convention of negative fluxes as a carbon sink in the land surface). A filter is applied to “gray-out” pixels with weak net fluxes relative to the rest of the region.
2) Aggregate the results of the component fluxes to an annual timeseries for the EU-27+UK

Step (2) above is made possible through the VERIFY machinery outlined in other deliverables (such as D8.7), in which the data products are harmonized as much as possible (metadata and format) before being placed on the database. Country masks for all countries in Europe and numerous regions (including the EU-27+UK) are then applied as the data is aggregated both spatially and temporally. Step (2) enables us to provide additional verification of the conclusions drawn in step (1).

The results for the BLUE model are shown in Figures 4 and 5. The colors in both figures have been selected to be the same to aid understanding. The spatial patterns of the fluxes indicate that abandonment drives the land use flux across the whole continent, although wood harvest becomes very important in the northern countries. Cropland and pastureland expansion appear to play more minor roles on the continental scale though dominant some regional fluxes (Spain, United Kingdom). Figure 4 may give the impression that most pixels in Europe are sinks. This is not necessarily the case, as the sum of the other fluxes can outweigh the sole negative flux (abandonment). However, the intention of this plot is to simply identify a single component where work may be focused to have the greatest impact on uncertainty reduction.

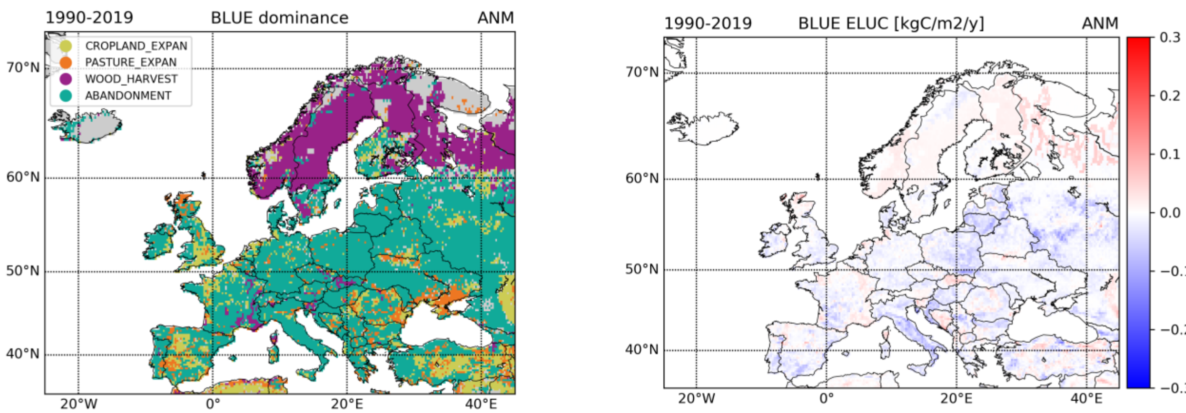

Figure 4: A map of the dominant fluxes on each pixel for the BLUE model over the past three decades (left) as well as the net flux from land use change for each pixel (right). The gray pixels on the left indicate where the absolute value of the net LUC flux on a pixel is in the lowest 10% for the region shown in the map.

The results for the annual timeseries of the same fluxes aggregated over the EU-27+UK support the picture of dominant fluxes created by the spatial maps. It's clear from Figure 5 that abandonment dominates the land use change flux in the EU-27+UK. Notice that abandonment is the only flux in BLUE that is a sink of carbon from the atmosphere into the land surface. As Figure 1 indicates that all models predict a general sink of the LULUCF sector in the EU-27+UK, it's unsurprising that the sole negative flux is the one which dominates.

Wood harvest is the net flux of gross emissions (from decay of the products) and gross removals (from regrowth of the trees). The relatively small contribution of the wood harvest (purple) to the overall LULUCF flux reported in Figure 5 may come as a little more of a surprise given the dominance of purple in the northern countries in Figure 4. However, this also has

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several possible explanations. The wood harvest emissions may not generally be as high of magnitude as the sink resulting from new forest growth on abandoned agricultural land, in particular in southern pixels with optimal growing conditions, assuming that wood harvest includes forest thinning and not simply full clearcut operations. It's also clear from the right panel in Figure 4 that the areas of largest net flux are found on pixels where abandonment dominates, and thus this pixels will contribute most heavily to the overall picture.

It's important to discuss legacy effects here. As mentioned above, disturbances result in dislocated carbon, which then decays over long periods of time into the atmosphere. We have chosen to calculate a mean flux over years 1990-2019 for BLUE in Figure 4. However, due to legacy effects, these abandonment effects have taken place before 1990 (e.g., in the 1970s or 1980s). One should thus be careful interpreting this graph as evidence of significant abandonment in recent decades.

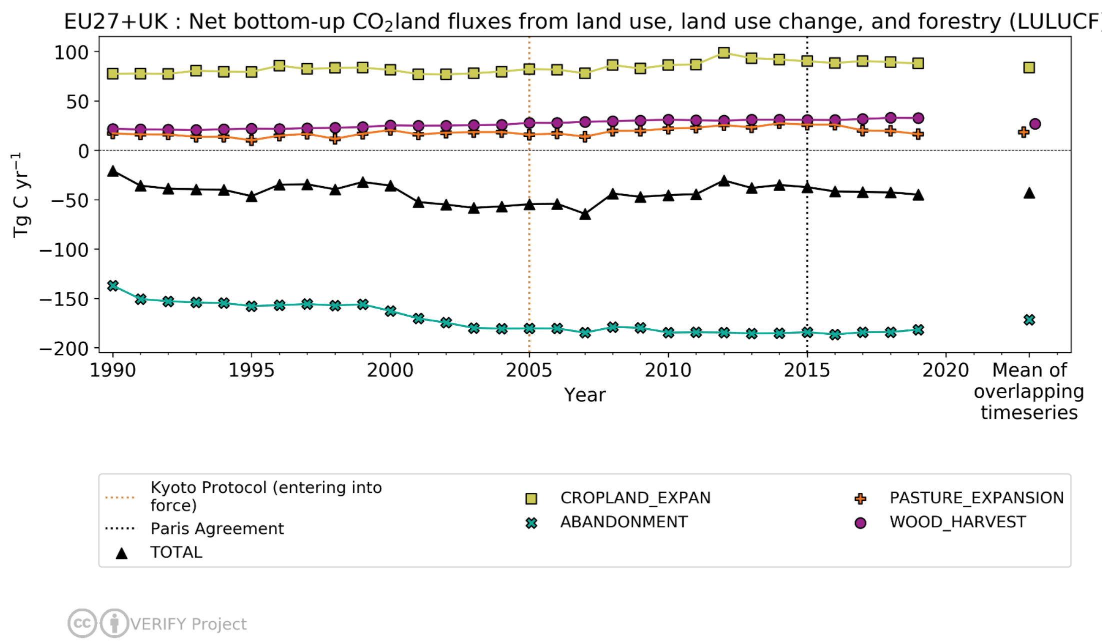

Figure 5: Annual timeseries of the component fluxes of the BLUE model from 1990-2019 for the EU-27+UK. The colors and fluxes are identical as to Figure 4.

Similar maps and timeseries are shown in Figures 6, 7, 8, and 9 for the two different versions of ORCHIDEE explored in this work. The maps show many similarities, apart from the obvious difference due to the fourth driver (nitrogen, shown in yellow). Blue (CO2) dominates both maps across Eastern Europe, and the green areas in the north from land use change also appear to be fairly similar. Two striking differences are the prevalence of yellow across Western Europe in ORCHIDEEv3, indicating that nitrogen deposition is the dominating flux in that region controlling the NBP. The absence of a nitrogen cycle results in this region being controlled by CO2 in ORCHIDEEv2. A second unexpected feature is the disappearance of the climate-dominated regions in the north in the ORCHIDEEv3 analysis, which are instead replaced by blue (CO2) and some green (LUC). This suggests that the nitrogen cycle in ORCHIDEEv3 can change the controlling variables even in regions where nitrogen does not dominate. Such a result is worthy of further study.

The timeseries plots in Figures 7 and 9 are also very illuminating, in that they propose an answer as to why the influence of climate is not seen more widely in the maps: the mean influence due to climate is close to zero across the 30-year timespan, despite the possibility of a high value in any given year. Our analysis is based on the mean value across the whole timeseries. Additional analysis should look into the impact of interannual variability, as such an analysis may reveal a stronger role for climate. This effect appears most problematic in the ORCHIDEEv2 simulations without the nitrogen cycle. Figure 9 shows that the annual timeseries of the influence of LUC and CO2 are very steady, while that of CLIM varies wildly from year-to-year., and indeed drives all of the interannual variability in the overall NBP. Despite this, almost no red shows up on the map in Figure 8.

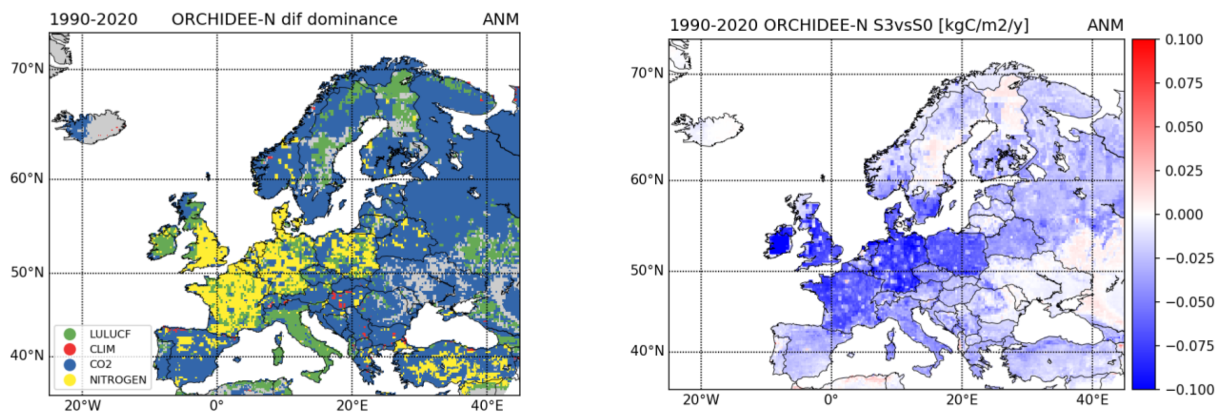

Figure 6: A map of the dominant fluxes on each pixel from the set of TRENDY-style factorial experiments for ORCHIDEEv3, which includes the nitrogen cycle, over the past three decades (left) as well as the net flux from the S3-S0 simulations for each pixel showing the combined effect of all drivers (right). The gray pixels on the left indicate where the absolute value of the net LUC flux on a pixel is in the lowest 10% for the region shown in the map.

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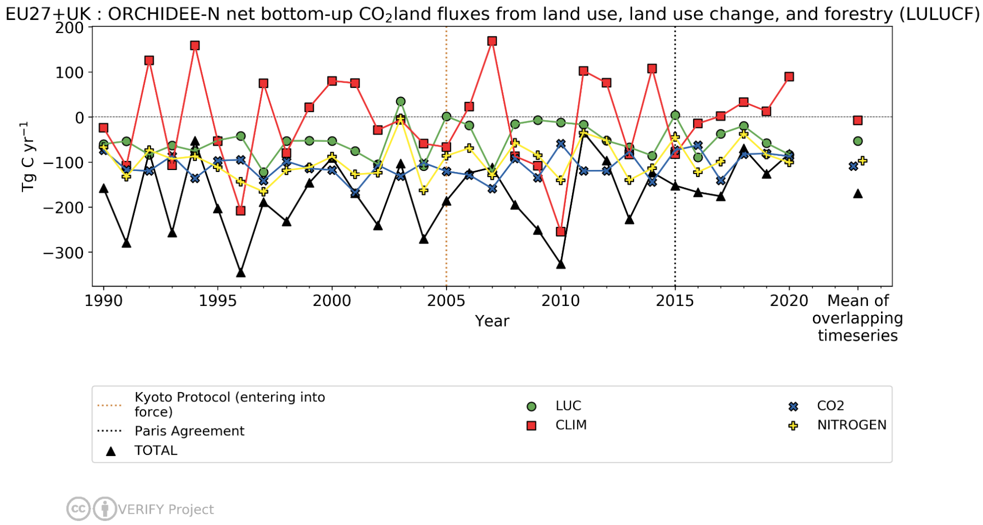

Figure 7: the annual timeseries of the influence of different drivers on the total LULUCF flux from the ORCHIDEE model which includes a nitrogen cycle for the EU-27+UK. The mean of the timeseries is shown on the far right.

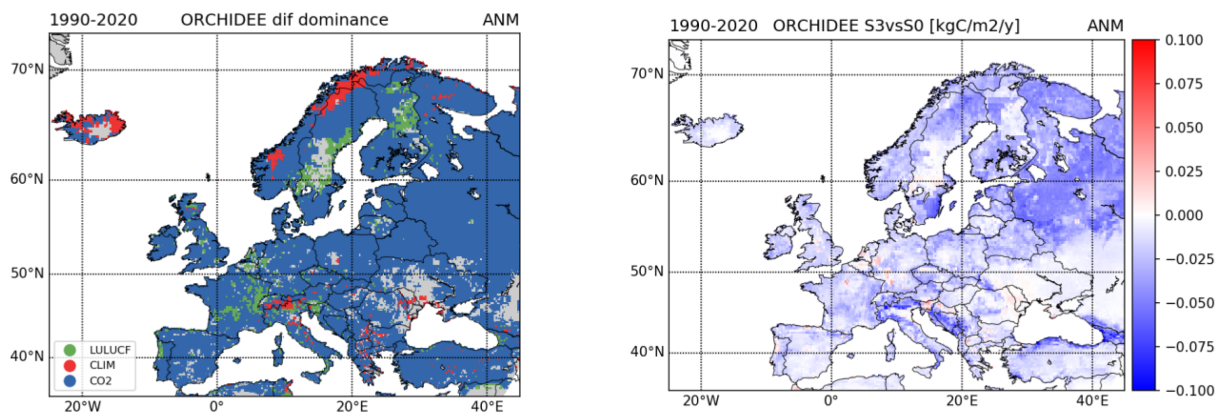

Figure 8: A map of the dominant fluxes on each pixel from the set of TRENDY-style factorial experiments for ORCHIDEEv2 over the past three decades (left) as well as the net flux from the S3-S0 simulations for each pixel showing the combined effect of all drivers (right). The gray pixels on the left indicate where the absolute value of the net LUC flux on a pixel is in the lowest 10% for the region shown in the map.

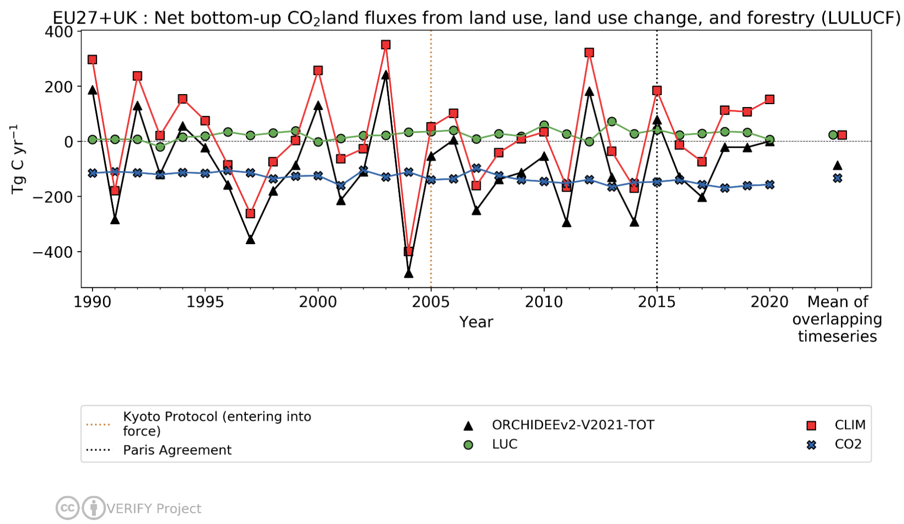

Figure 9: the annual timeseries of the influence of different drivers on the total LULUCF flux from the ORCHIDEE model which lacks a nitrogen cycle for the EU-27+UK. The mean of the timeseries is shown on the far right.

6. Conclusions

We presented here an analysis of the drivers of net carbon fluxes across the EU-27+UK for representatives of bookkeeping models (BLUE) and dynamic general vegetation models (ORCHIDEE). For ORCHIDEE, the influences were generated by a series of factorial simulation experiments holding various forcing data (CO2 concentration, meteorological forcing, land use and land cover information, and nitrogen deposition) fixed at the initial year or allowing it to vary throughout the course of the entire simulation. The influences from the BLUE model, on the other hand, are reported as the individual components which when summed together produced the total carbon flux from land use change activities (wood harvest, cropland expansion, pasture expansion, and abandonment).

We found that abandonment of cropland and pastureland dominates the overall land use change flux in the bookkeeping model. This conclusion is supported both by visual examination of the dominant flux in each pixel as well as the annual timeseries of the values for the EU-27+UK. Caution must be taken in inferring that all of these pixels are a sink of carbon, as the positive emissions from the other three drivers may outweigh the negative emissions from abandonment.

For ORCHIDEEv2 and ORCHIDEEv3 (which differ primarily by the inclusion of a dynamic nitrogen cycle), the factorial simulations revealed that carbon dioxide fertilization accounts for more of the NBP than nitrogen deposition, climate change, or land use/land cover change, at least when averaged over several decades. Annual timeseries show that the interannual variability, on the other hand, is largely driven by the meteorological forcing. The net effect of this forcing appears to approach zero when averaged out across decades. For ORCHIDEEv3, nitrogen deposition also played an important role in certain countries (e.g., UK, France, Germany, Denmark).

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Based on these results, developers of DGVMs who are looking to reduce model uncertainty across Europe would be encouraged to look into process and data driving carbon dioxide fertilization and nitrogen deposition, while developers of bookkeeping models would be advised to look into data on abandonment.

7. References

None. More detailed information, including references, are given in deliverables D3.3, D3.6, and D3.9.

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