Project: **891**

Project title: **Forest management in the Earth system**

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Report period: **2022-11-01 to 2023-10-31**

The scientific work under bm0891 during the reporting period focused on a more profound understanding and better quantification of land-related carbon fluxes, applying process-based (JSBACH) and bookkeeping models (BLUE)and starting work on assessing Earth system consequences. We also developed a consolidated country mask to facilitate a clear aggregation of gridded data to country level.

TRENDYv12 and JSBACH development

For participation in the Global Carbon Budget 2023 (Friedlingstein et al., 2023), simulations with JSBACH3 were conducted following the TRENDY protocol. The TRENDY version of JSB3 (extended by PFT-level output), which had been established as a separate branch in the MPI-ESM git repository last year, was updated with changes from the latest version of the branch mpiesm-landveg (date July 2023) and pushed to a new branch on the remote repository. The specified a target accuracy of the equilibrium state was reached after 2000 years of model spin-up, spinning off from the TRENDYv11 equilibrium state. Preprocessing included, e.g. LUH2-like data and climate (CRUJRAv2.4, 2023). Population density preprocessing had to be adapted. Four experiments (4x221 years) were conducted branching off the spin-up. Post-processing included computation of monthly means, cmorizing, and extraction of zonal total carbon. Postprocessing of cover fractions in experiment S3 have been fixed. Jupyter-hub was used to monitor and visualize the progress of the model integrations and results (Fig. 1). Results were first submitted on July 25, and resubmitted on September 14 to due server issues at the hosting institute. There are ongoing spin-off studies on last year's cycle (v11) and incoming collaborations on publications regarding this year's results. In preparation for cycle v12, along with establishing version control (gitlab repositories at DKRZ) extensive documentation and a detailed tasklist were created to adhere to FAIR principles. Pre- and post-processing has been reassessed and made more time and computationally-efficient.

In ForestNavigator we plan to improve JSBACH4, making use of its capabilities of including forest age classes, by forestry. Due to delays in the hiring process and subsequently the initial phase of the project, no research activities have been carried out during the reporting period so far. We aim to get started with developments on the latest ICON-Land development branch regarding forest age classes and forest management in the remainder of this year's allocation period.

Applications and model improvements of BLUE

Several research activities were carried out with the Bookkeeping model BLUE (Hansis et al. 2015). BLUE simulations were used for multiple publications (see list of publications) and it can be anticipated that the BLUE data will also be in demand in the future.

Global Carbon Budget (GCB): We contributed simulations to the GCB2023. We provided a new split of land-use emissions into five categories: fluxes from deforestation, forest (re-)growth, wood harvest and other forest management, peat drainage and peat fires, and other transitions. Additionally, we provided estimates for CO2 emissions from permanent deforestation (excluding emissions from deforestation in shifting cultivation cycles) and estimates for CO2 removals from long-term af-/reforestation (excluding removals from regrowth in shifting cultivation cycles). These data will also be used in the upcoming 2nd version of the State of CDR Report (see Smith et al., 2022 for the 1st version).

Time-variant carbon densities: By default, inventory-based carbon densities (mostly based on Houghton et al., 1983), are used to estimate land-use change emissions. The model only captures the environmental state at the time of the C density inventory. We replaced those fixed carbon densities with time-variant carbon densities and integrated results from a DGVM ensemble (9 DGVMs). The implementation of time-variant C densities accounts for the ecosystems' response to changing environmental conditions and resolves the bookkeeping error (e.g., discussed in Friedlingstein et al. 2022). Due to environmental effects, such as CO2 fertilization, global emissions from land-use change increased by 16% in the period 2012-2021 compared to the original estimate with time-invariant C densities (Fig. 2). This increase can mostly be attributed to higher gross emissions from deforestation and wood harvest, which are not fully compensated by increased gross sinks through reforestation/afforestation and regrowth after wood harvest. As environmental conditions will diverge further from the state captured by inventory-based C densities, the gap between time-variant and fixed estimates is expected to further increase in future decades.

Spatially explicit carbon densities: By default, literature-based C density values at the level of Plant Functional Types (PFT) are used. To reflect the local and regional heterogenity of the C stored in vegetation and soils, we developed an approach to estimate carbon equilibria for nine different PFT classes, as well as for crop and pasture at a resolution of 1 km using Random Forest Regression models. To implement these maps, the model code had to be adjusted. First results of the analysis are promising and we plan to finalize the implementation in the first months of 2024.

PFTs: An exploratory analysis was carried out to investigate options for a revision of the PFTs. We compiled numerous datasets on climate, soil, geomorphology, land-cover, human influence on ecosystems and tested several machine learning algorithms to generate different scenarios of PFT information. Estimates based on these new PFT data vastly agree with the default. However, differences in the results of the different scenarios, as well as regional differences highlight that a revision of the PFT information improves estimates.

Potential carbon densities

We estimated the anthropogenic impact on carbon stocks of vegetation and soils, quantifying the "terrestrial carbon deficit" as a result of the carbon stocks as they occur today as opposed to their state in the potential absence of human interference. Using novel machine learning approaches, we provide a consistent approach to estimate the potential carbon stocks of aboveground vegetation, belowground vegetation, and soils. The estimates are based on the latest high-resolution carbon stock and numerous other state-of-the-art datasets from various fields, offering an unprecedented synthesis of the available evidence. A publication of this analysis is currently in review at Nature Geosciences.

Assessing the coupled Earth system response to land-use change

Research activities concerning coupled climate/carbon cycle assessments in the Horizon Europe project RESCUE were delayed owing to delays in the initial phases of the project and in the hiring process. We will allocate some of the remaining resources of this year to get started on model readiness, and also to conduct basic testing on the ability to initiate model runs using the first versions of the gridded datasets until 2100 of a single scenario provided by the IAMs.

Country mask

We developed a new country mask that can be used to attribute various quantities (e.g., land-use emissions, carbon stored in soils, vegetation,...) from gridded data to single countries. The country mask is based on a 1-km country mask from Eurostat. We adopted the Eurostat country definition (https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/countries) and grouped the countries a) into 199 countries that deliver reports to the UNFCCC and 2) into different regions defined by the IPCC (IPCC_Reg5, IPCC_Reg10, IPCC_Reg22). An additional advantage of the Eurostat mask is that it includes disputed territories, which we kept in our country mask. The country mask was regridded to various model resolutions (ranging from 0.1° to about 2° spatial resolution). Each grid cell of the regridded data contains information on the land fraction of the countries populating the grid cell and on the total land fraction in the grid cell. This makes it possible to attribute, e.g., land-use fluxes to all countries, even if they only cover a small fraction of a grid cell. The new country mask thus provides a fairer attribution of, e.g., land-use emissions to each country. The country mask was used to calculate each country's share of global land-use emissions from the bookkeeping model BLUE (see above) for GCB2023, and will in the future be used for additional analyses.

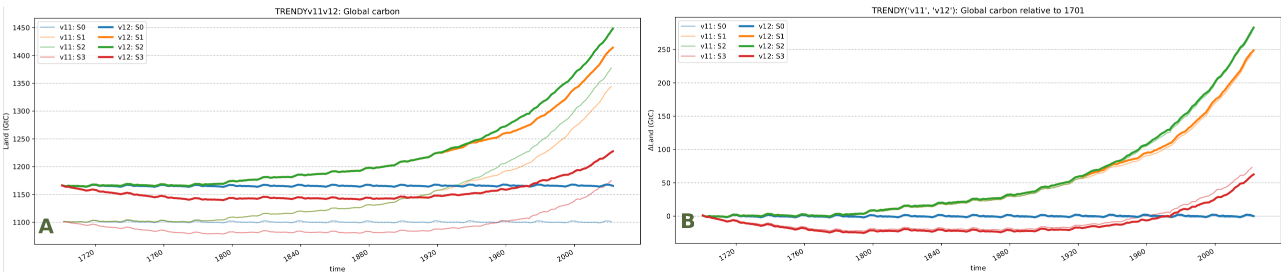

Figure 1: Comparison of results from TRENDY experiments S0-3 for both cycle v11 (GCB2022) and cycle v12 (GCB2023). (a) Absolute land carbon. (b) Land carbon relative to 1701.

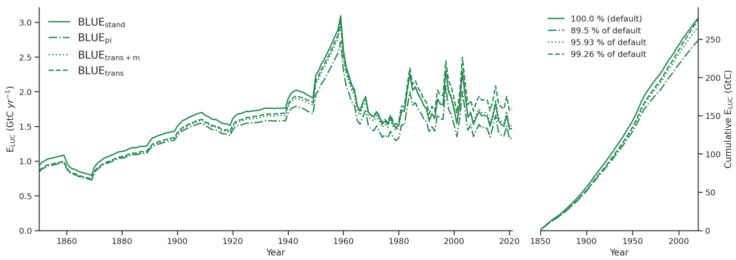

Figure 2: Global estimates of the net CO2 flux from land use change (ELUC) between 1850 and 2021 from four BLUE simulations. The left panel shows the annual emission estimates and the corresponding cumulative emissions are shown in the right panel. The fraction of cumulative values relative to BLUEstand as default are shown in %. Green solid line: BLUEstand with time-invariant carbon densities based on Houghton et al. (1983). Green dash-dotted line: BLUEpi with pre-industrial, time-invariant C densities. Green dashed line: BLUEtrans with time-variant C densities. Green dotted line: BLUEtrans+m with time-variant C densities and environmental changes after land-use change event.