NextGenCarbon

Monitoring Earth's Carbon Balance

Deliverable 7.1

Simulation protocols: protocols for the GCB-Trendy and the Near-Real-Time Land surface Model simulations to ensure a common set of forcings and outputs

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NextGenCarbon
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PU = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

History of changes

Version	Date	Beneficiary	Author	Description
V1	27 Sept 2025		Stephen Sitch	

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Abbreviations

BIM. Budget Imbalance
CRU. Climate Research Unit
ENSO. El Niño Southern Oscillation
ELUC. Emissions from Land-Use Change
ESA. European Space Agency
ESA CCI. European Space Agency Climate Change Initiative
FAO. Food and Agricultural Organisation
GCB. Global Carbon Budget
HYDE. History Database of the Global Environment agriculture dataset
LSM. Land Surface Model
LUH2. Land-Use-Harmonization-version 2 land use dataset
LULCC. Land Use and Land Cover Change
NBP. Net Biome Productivity
NGHGI. National Greenhouse Gas Inventory
NRT. Near Real Time
PFT. Plant Functional Type
SLAND. Natural Land Sink
UN. United Nations

1 Introduction

An international ensemble of Land Surface Models (LSMs), known as the 'Trends and drivers of the regional scale terrestrial sources and sinks of CO2' (TRENDY) project (Sitch et al., 2024), quantifies land biogeochemistry cycles to support the annual Global Carbon Budget (GCB) assessment (Friedlingstein et al., 2024). LSMs use a common protocol and set of driving datasets. A set of global factorial simulations allows attribution of spatio-temporal changes in land surface processes to three primary global change drivers: changes in atmospheric CO_2, climate change and variability, and Land Use and Land Cover Changes (LULCC). LSMs contribute carbon sink and source estimates to two of the five budget components, namely the natural land sink (SLAND) and the uncertainty range for the emissions from LULCC (ELUC), see Figure 1.

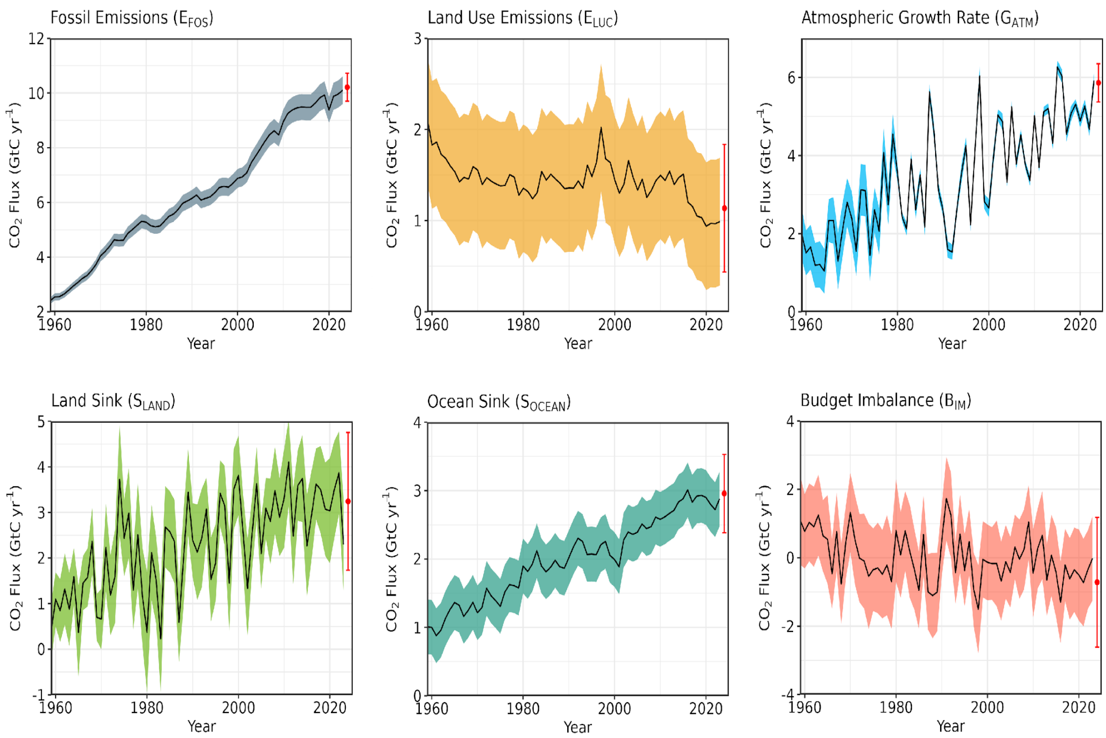

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Figure 1. The five components of the global carbon budget: Fossil emissions, Land Use Emissions, and their fate, atmospheric Growth Rate, the natural Land Sink and Ocean Sink. (Friedlingstein et al., 2025).

The budget imbalance (BIM) is the total emissions minus the estimated growth in the atmosphere, land and ocean sinks, and reflects the limits of our understanding in the global carbon cycle. This large and unexplained variability in the global carbon balance caused by uncertainty and understanding hinder independent verification of reported CO_2 emissions. The BIM has a *semi-decadal* to *interannual variability*, (Figure 1.) which is postulated to result from inadequate or a lack of representation of disturbance, its legacy, and recovery in LSMs, in response to climate variability and extreme events.

Extreme events can furthermore quickly derail the potential for land-based mitigation strategies, by inducing widespread and strong impacts on ecosystems. For example, the European drought of summer 2018 resulted in carbon losses from managed land of 0.2 Billion tons in Germany and Poland (Bastos et al., 2020), and turned managed forests in Czechia from a stable carbon sink to a strong carbon source from 2018-2022 (based on UNFCCC reports, available at https://di.unfccc.int/detailed_data_by_party), due to insect-driven tree mortality (Hlásny et al., 2021). The impacts of extreme events on GHG budgets need therefore to be assessed more rapidly than with current inventory systems to support responsive management to facilitate the recovery of carbon stocks and to improve the accounting of carbon losses in annual inventories. More recently, van der Woude et al., 2023 combined a fast-track modelling methodology with flux towers and Earth Observation to quantify the impact of the summer 2022 temperature extreme over Europe. Results suggest reduced carbon uptake by forests in Europe during this period (van der Woude et al., 2023).

Currently, TRENDY simulations performed for GCB are updated annually until December of the previous year (Sitch et al., 2024). This implies that climate events of interest, for example the impact of major droughts or of El Niño Southern Oscillation (ENSO) events, can only be analysed more than a year after they occur (Figure 2).

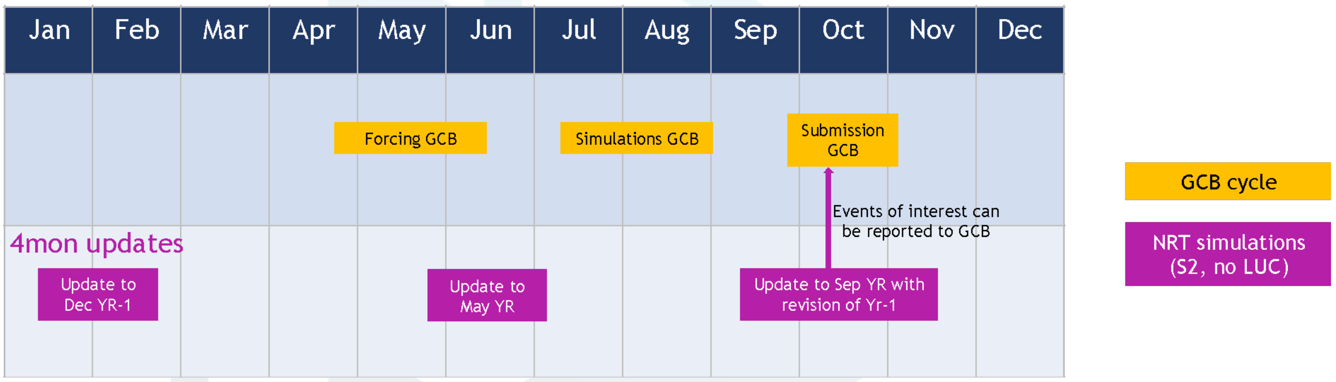

Figure 2. Idealised timeline for fast-track near-real-time carbon budgeting. Yellow is the approximate timeline for GCB, the purple the fast-track NRT timeline for assessments at multiple times in a year, and in response to regional climate extremes.

The main constraints towards faster updates of carbon fluxes by LSMs are the update cycles of the driving data, specifically CRU-JRA climate forcing, Land-Use-Harmonization-2/ History Database of the Global Environment (LUH2/HYDE) LULCC datasets, and global CO_2 data, which typically have a lag of several months. However, by applying alternative forcing datasets and simplifying the protocols these limitations can larger be overcome.

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In NextGenCarbon, new demography- and disturbance-enabled LSMs (improved LSMs) from WP5, constrained in WP6, will be applied ***regionally at a high resolution of 0.1 degrees*** in Task 6.3 and ***globally at 0.5-degree resolution*** in WP7 using the TRENDY protocol alongside the bookkeeping model BLUE (Hansis et al., 2015), (using the model developments of WP5), and contribute to the GCB annual assessments.

We will diagnose the BIM changes from our improved LSMs. The team will directly contribute to the data synthesis, preparation and publication of GCB annual assessments to be presented at annual UNFCCC COP events, connecting Task 7.1 results with Task 9.3.

In deliverable D7.1 we document a set of three experimental protocols: (1) Global Trendy for annual GCB (2) NRT global simulations at 0.5 Degrees (3) NRT simulations for Europe at high resolution (0.1 Degree). LSMs will be applied and deliver each year (yr 1-5) to Trendy-GCB. They will be further applied globally in NRT (2) during yr 1-3, to enable the team to proactively respond to any large global climate extreme. The improved LSMs will be applied in the second half of the project (yr 3-5) at high resolution (0.1 Degrees) over Europe. Here describe the three protocols in sequence.

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2 LSM simulation protocol for GCB

The aim of this set of LSM experiments is to provide the land components of the Global Carbon Budget, and an ensemble of land carbon cycle simulations to be used by the scientific community. Also, we aim for a better translation between our budgets and National Greenhouse Gas Inventories (NGHGIs); as such LSMs are reminded to provide Plant Functional Type (PFT) level output as requested where possible.

2.1 Model Simulations

Full transient simulations are needed from LSMs for the standard set of simulations (S0-S3) as climate and LULCC forcings typically change each retrospectively year (i.e. they are not just one year extension):

Climate dataset: We include the impact of historical changes in aerosols on radiation fields used to drive LSMs. We encourage models that can use fields of both radiation quantity and quality (diffuse radiation) to include them in simulations.

CO_2 file: The global CO_2 dataset is extended each year by one year.

Land use and Land cover changes: LUH2-GCB2025 will be based on the HYDE3.5 cropland/grazing/urban land dataset which is constrained by FAO country-level statistics and spatially based on multi-year satellite land cover maps from European Space Agency Climate Change Initiative Land Cover (ESA CCI LC). We replace the full FAO timeseries for Brazil and Indonesia with one based on mapbiomas (https://brasil.mapbiomas.org/en/) state-level area totals (1985-2023 for

Brazil, and 2000-2023 for Indonesia). For Indonesia, mapbiomas replace cropland only, which includes Palm Oil as does FAO, while grazing land is taken from FAO. We also replace the FAO timeseries for China, based on province-level totals from Yu et al., 2022 for the 1900-2019 period. For the pre-1985 period, the cropland area -per-capita was calculated for 1985 for each state of Brazil (based on MapBiomas), then these numbers (fixed) were used to multiply with the historical population numbers for each state of Brazil. We extend forward to 2025, using the trend. Using a similar methodology we adopt land cover change information from MapBiomas for Indonesia (2000-2023).

The complete LUH2-GCB2025 forcing timeseries has been updated to use the new HYDE3.5 data. LUH2-GCB2025 uses the 2025 FAO national wood harvest production data for years 1961-2023, along with new HYDE3.5 population data to reconstruct the historical wood harvest time-series.

To enable alignment with national inventories we need LSMs to output Net Biome Productivity (NBP) on a PFT basis where possible. This is needed to separate fluxes on managed versus unmanaged forested land and correct SLAND. This is essential moving forwards in future years in TRENDY-GCB.

We will also explore the option to include LSMs in the GCB ELUC term that are comprehensive with respect to land management practices and that are close to observed biomass in addition to the bookkeeping models.

Models can have static or dynamic natural vegetation, but all will use prescribed cropland and grazing land (=managed pasture+rangeland) distribution. The models will be forced over the 1700-2024 period with

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changing CO_2, climate and land use according to the following simulations.

GCB 2025 simulations are summarized below:

S0: Control. No forcing change (time-invariant “pre-industrial” CO_2, climate and land use mask). S0 is needed to diagnose any “cold start” issues or model drift

S1: CO_2 only (time-invariant “pre-industrial” climate and land use mask)

S2: CO_2 and climate only (time-invariant “pre-industrial” land use mask)

S3: CO_2, climate and land use (all forcing time-varying)

Models with N cycle should have time-varying N inputs for S1, S2 and S3 (see Appendix 1).

2.2 Criteria for budget inclusion

We apply three criteria for minimum model realism by including only those models with:

(1) steady state after spin-up. Diagnosed from S0 run. Steady-State defined as an offset < 0.10 GtC/yr, drift < 0.05 GtC/yr per century (i.e. first is the average over 1700-2025, second is the slope x 100).

(2) net annual land flux (SLAND-ELUC) is a carbon sink over the 1990s, 2000s and 2010s as constrained by global atmospheric and oceanic observations (Keeling and Manning 2014). Diagnosed from S3 run.

(3) global net annual land use flux (Eluc) is a carbon source over the 1990s. Diagnosed from S3-S2 runs.

LSM results will be evaluated in the ILAMB benchmarking system (Collier et al., 2018) and summary statistics will be given for each model (in summary table/figures) and included in the supplementary material of the GCB publication. This will enable us to document model improvement each year, and to identify possible issues / model deficiencies to aid model development. We do not envisage using the benchmarking results as criteria for budget inclusion now, but potentially in future years after further consultation among participating groups.

2.3 Datasets provided and data access

Forcing data will be available through University of Exeter and partners.

2.3.1 Climate Research Unit (CRU) Climate forcing

0.5 degree CRU monthly historical forcing over 1901-2024.

Monthly CRU data are provided by the University of East Anglia, 1901-2024 and available from the following website:

https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.09/

2.3.2 Merged CRU and JRA Climate forcing

0.5 degree CRU-JRA(3Q) 6-hourly historical forcing over 1901- 2024.

6 hourly CRU-JRA(3Q) climatology provided by Ian Harris at UEA 1901-2024 and available through Exeter.

See Appendix two for more details on the merging methodology. See Figure 3. for a comparison of the new CRU-JRAQ3 climate variables against those used in GCB2024.

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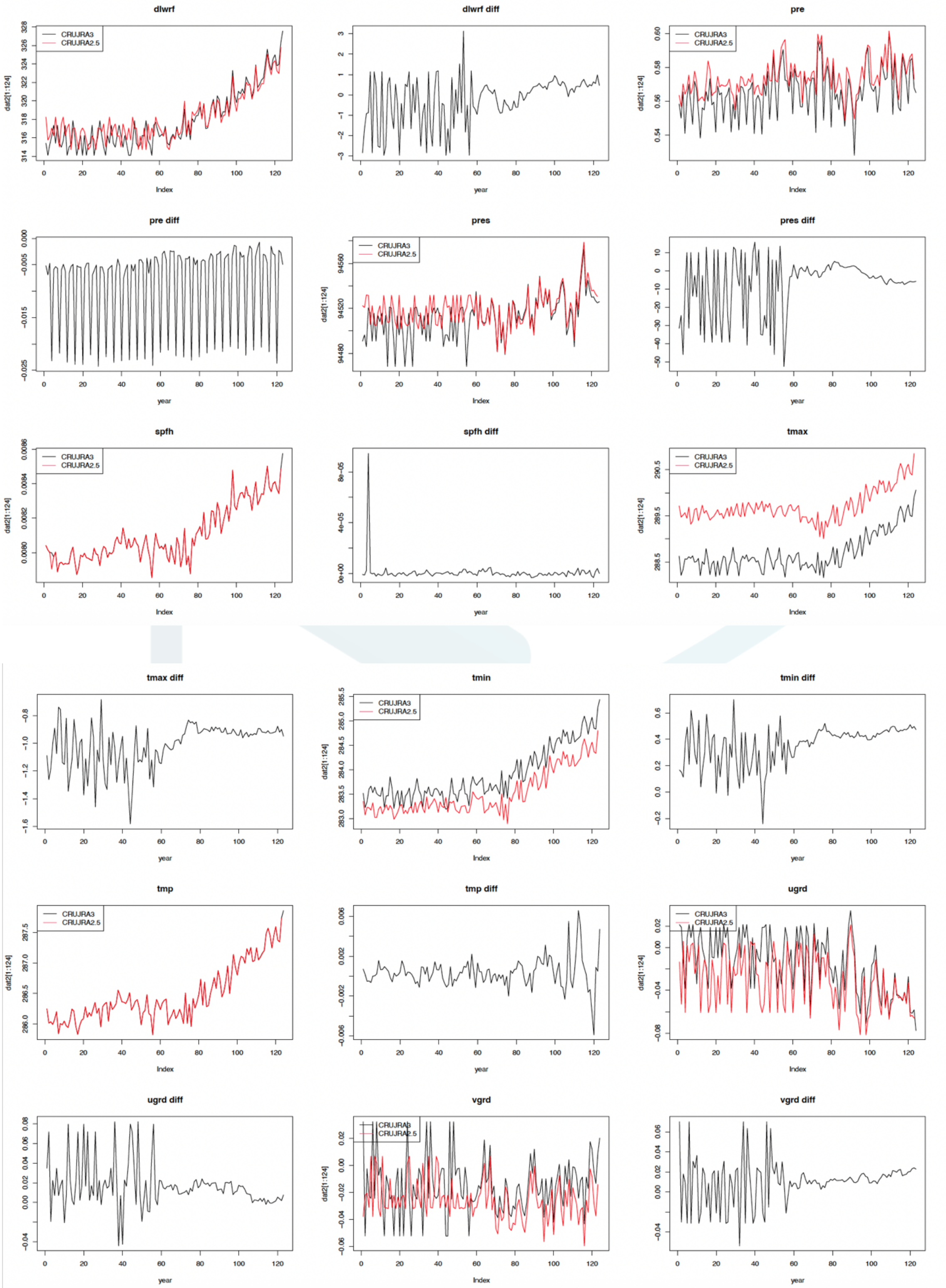

Figure 3. Comparison of GCB2024 (red) and the new GCB2025 CRUJRA3Q (black) climate forcing variables.

2.3.3 Revised Radiation fields

A diffuse fraction dataset offers 6-hourly distributions of the diffuse fraction of surface shortwave fluxes over the period 1901-2024, as described in O'Sullivan et al., 2021.

Two fields are distributed:

fd_gcb2025_year (diffuse fraction fields), tswrf_gcb2025_year (total downward shortwave radiation at the surface).

2.3.4 Global Atmospheric CO_2

The 1700-2024 annual time-series is derived from ice core CO_2 data and merged with NOAA annual resolution from 1958 onwards. It is prepared by Matthew Jones, UEA for the Global Carbon Project. This dataset is intended to be used as atmospheric forcing for modelling the evolution of carbon sinks.

Annual mean fields are generated from these monthly data. DGVMs may also wish to run directly with monthly CO2 fields.

CO2 data are available from Exeter.

2.3.5 Land Use Change

Land-use Harmonization (LUH) data for GCB 2025 is provided in 3 separate files, which can be downloaded directly from Zenodo (for the states, transitions, and management data layers respectively). We also have a DOI to enable citation for the dataset:

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Chini, L., & Hurtt, G. (2025). Land-Use Harmonization 2 for Global Carbon Budget 2025 (LUH2-GCB2025) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15557904

These files are based on HYDE3.5, as well as the 2025 FAO wood harvest data, for all years 850-2025. A summary of the methods we used are described in appendix two.

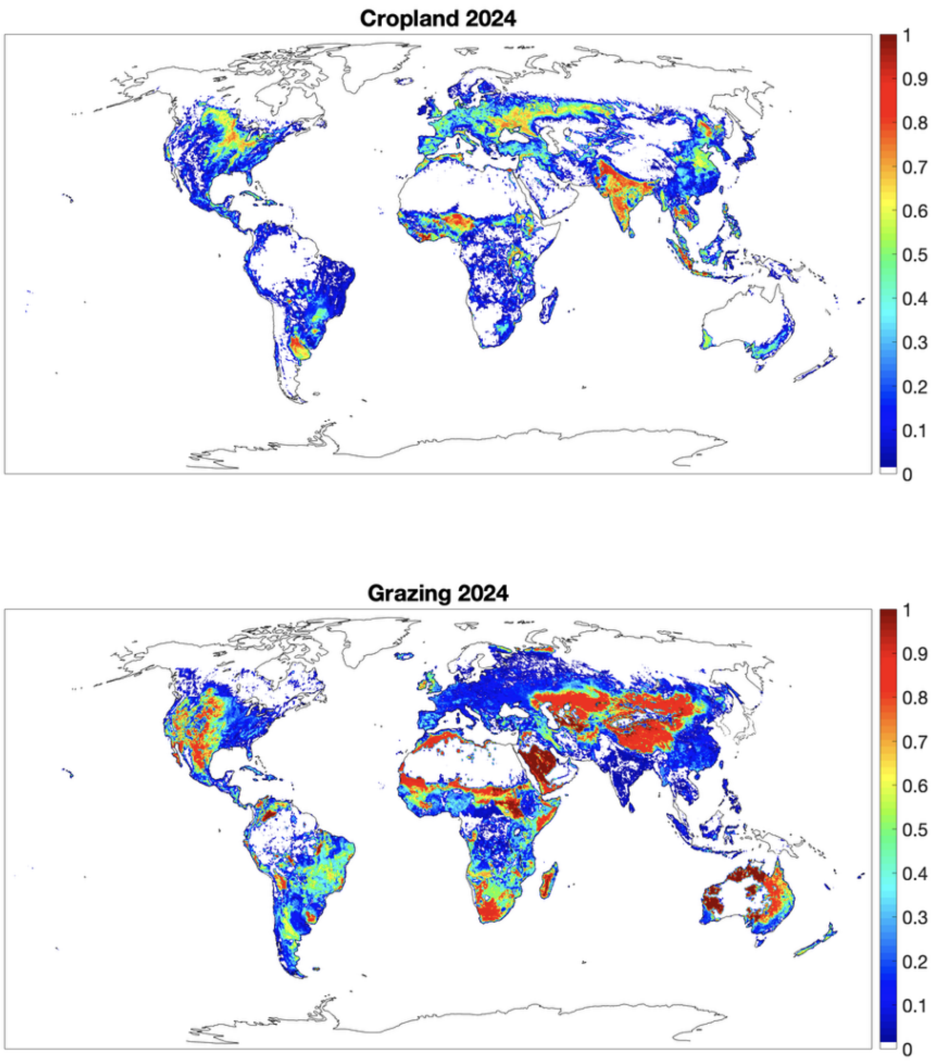

Figure 4. LUH2 Cropland and Grazing fraction in 2024 (Courtesy: Louise Chini)

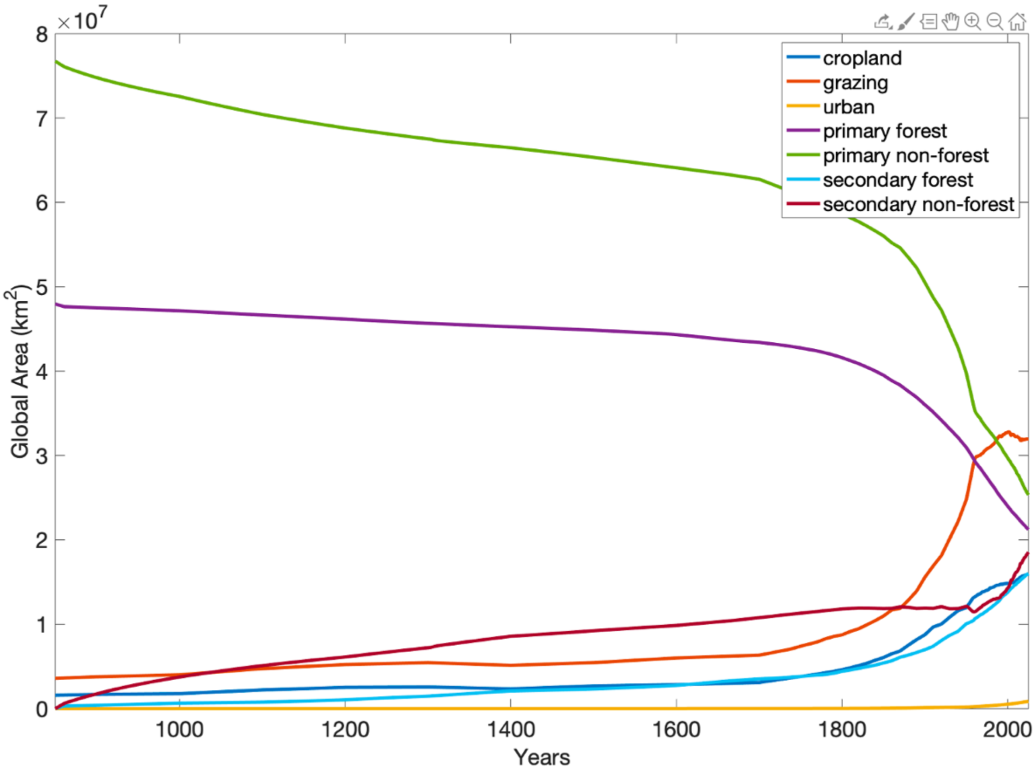

Figure 5. Historical LULCC from LUH2 (Courtesy: Louise Chini)

The data files are for the years 850-2025 (Figure 4, 5), which keeps the file format consistent with the LUH2 data produced for CMIP6, hence the start year of 850. The LUH2-GCB2025 data will be different from the LUH2 v2h data used for CMIP6 for all years, due to the use of the new HYDE3.5 crop/grazing/urban land dataset. LUH2-GCB2025 also differs from the new LUH3 dataset produced for CMIP7 as it uses newer HYDE data and retains the annual temporal resolution of that dataset.

2.3.6 Miscellaneous Datasets

Each group will use its own data source for soil properties etc (see Appendix 4 on lightening ignition and population density information).

2.4 Experimental Protocol

Note: the core set of simulations is the same as in GCB2024, but with a slightly revised 1700 CO_2 concentration (277.57 ppm).

Model spin up:

  - 1700 CO_2 concentration (277.57 ppm).
  - recycling climate mean and variability from the early decades of the 20th century (i.e. 1901-1920).
  - constant 1700 LULCC (crops and pasture distribution).

- 1701-1900 transient simulation:
  - varying CO_2 (S1, S2, S3). 1700 CO_2 (S0)
  - continue recycling spin up climate (all simulations)
  - varying LULCC (S3). 1700 LUC, as in spin-up (S0, S1, S2)
- 1901-2024 transient simulation:
  - varying CO_2 (S1, S2, S3). 1700 CO_2 (S0).
  - varying climate (S2, S3). Continue recycling spin up climate (1901-1920: S0, S1)
  - varying LULCC (S3). 1700 LUC, as in spin-up (S0, S1, S2)

Models having a nitrogen cycle should use time varying Nitrogen inputs (see Appendix 1).

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2.5 Required Outputs

- For all simulations (S0 to S3): Ascii file with five columns: year, annual global NBP, annual northern extra tropics NBP, annual tropical NBP, annual southern extra-tropics NBP (see excel file for definition and sign convention); one row per year, 1700-2024. Name convention: Model_zonalNBP.txt, e.g. JULES_zonalNBP.txt. Units are $PgCyr^{-1}$. One dataset per simulation S0-S3, four in total. First row use the following column headings and order: "Year, Global, North, Tropics, South". Row 2 values for the year 1701, Row 3 for year 1702 … North = north of 30oN; Tropics = 30oN to 30oS; South = south of 30oS.
- List of gridded output variables: See Table 1.
    - Level 1 variables: essential
    - Level 2 variables: desirable for additional analysis/studies
    - Additional N-cycle variables where applicable (see end of excel file)
- Time period: 1701-2024
- Time resolution: as specified in the file
- Spatial resolution: 0.5x0.5 (or at a coarser resolution if necessary; ideally at 0.5 or 1 degree)
- Format netcdf . See Appendix 5 for netcdf formats developed with input from ILAMB team.
- Please define PFTs in the header of Vegtype level netcdf files, e.g. PFT 1 = broadleaf tree, PFT2 = … Groups are requested to supply

Fractional Land Cover [0-1] of PFT for each simulation as requested (1=total land). If Dynamic Vegetation is not enabled in your LSM (i.e. changing natural PFT fraction in response to climate) please indicate (e.g. include information in an associated README file). Note the ocean fraction of any given gridcell may not be zero (e.g. at coastal gridcells). Please provide your gridbox fluxes in units per m2 of land fraction, PFT fluxes should be per m2 of PFT, and the PFT land cover fraction should be provided. Please upload the land-sea mask that you are applying.

- Note- in previous years we have received identical outputs for different experiments (e.g., same S1 and S2 outputs), different units for different experiments – groups should double check before submission.
- Note- in previous years there has been an order of magnitude size difference in the same output from different LSMs, e.g. PFT level LAI ranges from ~ 6 to 60 GB – this is likely due nc version (it makes a massive difference). Groups generating massive nc files should consider changing nc version.

2.6 Output Filename Convention

One file per variable, entire time-series

Model_Simulation_variable.nc (e.g. JULES_S1_mrso.nc)

Please see Annex 5 for an example netcdf header for variable nomenclature.

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3 LSM simulation protocol for Near-Real-Time climate extremes

Two Near Real Time simulations are envisaged in NextGenCarbon. In the first the LSMs are applied globally at 0.5-degree resolution. The second will be using the improved LSMs and applied at high resolution (0.1 Degrees) over the European domain.

3.1 Global NRT simulations

These will run using a TRENDY S2-style simulation (CO_2+climate) (see section 2.1). LSMs can be forced by climate fields from ERA5 instead of CRU-JRA, which have higher frequency (hourly) and are more frequently updated (daily updates) with lower latency (ca. 5 days) and by projected CO_2 concentration. The S2 simulation (LULCC fixed) further allows to overcome the need to re-do the time-consuming spin-up, which is typically needed due to annual retrospective updates in LUC fields. In case NOAA global CO_2 concentration values are not yet available at a given point in time, the projected CO_2 increases from the GCB in the previous year can be used (Friedlingstein et al., 2022). This is needed as LSMs are applied with annual mean atmospheric CO_2 concentration. This would allow to provide fast-track estimates of major anomalies in carbon sources and sinks due to climate events of interest. This was applied in recent NRT publications for 2023 and 2024, e.g. Piyu et al., 2024, Piyu et al., in review.

To test the capacity of this new approach to estimate the impacts of specific extreme events on the carbon cycle we developed a pipeline where simulations can be frequently updated (about every 4 months or on-demand) with a latency of ca. 1-2 months. ERA5 data are revised and

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sometimes corrected for the 3 months prior to the most up-to-date date. NOAA global CO_2 growth rate for the previous year typically becomes available in summer. Therefore, the last simulation of each year will revise the previous year and update runs until the latest data of the given year. In order for outputs to reflect the response of present-day vegetation to climate anomalies, the simulation S2 should be forced with present land-cover distribution, proposed here to be 2020. This represents an update on the approach used in Ke et al., 2024, 2025, which adopted fixed land use for year 2010.

3.1.1 Simulation protocol

Workflow of simulations

Contact point: Ana Bastos (ana.bastos@uni-leipzig.de), Stephen Sitch (s.a.sitch@exeter.ac.uk)

(1) Update and quality checks of forcing data in mid- January, June and September every year: UL, UNEXE.
(2) Teams run model simulations starting from the last full year of simulations: UL/UNEXE/LSCE
(3) Model outputs in TRENDY format after 1-2 weeks

Note, we are currently in discussions with regards a central SLU data storage and exchange under NextGenCarbon.

Global Simulations (yr 1-3), 0.5-degree resolution

Model spin up:

- 1850 CO_2 concentration (287.43 ppm).

- recycling climate mean and variability from 1960-1970.
- constant 2020 LULCC (crops and pasture distribution).

- 1851-1960 transient simulation:
  - varying CO_2.
  - continue recycling spin up climate (1960-1970)
  - constant 2020 LULCC (crops and pasture distribution).
- 1961-2025 transient simulation:
  - varying CO_2.
  - varying climate (1961-2025)
  - constant 2020 LULCC (crops and pasture distribution).
  - *Optional extra simulation*: diagnostic fire run (FireCCI burned area product updated to 2024)
  - *Optional extra simulation 2: inclusion of HILDA+ LULCC at global scale from 1900.*

3.2 Regional Europe Simulations at high-resolution

These simulations will be conducted with the NGC-advanced demography-enabled LSMs. They will be applied at high resolution (ca. 9km) ERA5-Land climate forcing and time varying LULCC over the European domain.

Model spin up:

- 1850 CO_2 concentration (287.43 ppm).

  - recycling climate mean and variability from 1960-1970.
  - 1900 HILDA+ LULCC (crops and pasture distribution).
- 1851-1960 transient simulation:
  - varying CO_2.
  - continue recycling spin up climate (1960-1970)
  - time varying HILDA+ LULCC from 1901-1960 (crops and pasture distribution), 1851-1859 uses 1900 HILDA+
- 1961-2025 transient simulation:
  - varying CO_2.
  - varying climate (1961-2025)
  - time-varying HILDA+ LULCC (crops and pasture distribution). Currently FAO is available to 2023. HILDA+ will be held constant in 2024-2025 at their 2023 values.

Data output will be as described in the LSM simulations for global GCB. (section 2).

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Appendices

Appendix 1. Nitrogen Cycle

Models having a nitrogen cycle should use time varying Nitrogen inputs as follows:

S0 none (PI CO_2, PI climate, PI LUC, PI Ndep, PI Nfert)

S1 CO_2 + Ndep (PI Nfert)

S2 CO_2 + climate + Ndep (PI Nfert)

S3 CO_2 + climate + LUC + Nfert + Ndep

Note: PI = 1700 for LUC, PI = 1850 for Nfert, PI= 1850 Ndep.

Nitrogen fertiliser input datasets are available via the NMIP2 project (Tian et al. 2022).
Note, N fertiliser data is available until 2022 from NMIP2. As NMIP2 assume these N input data remain unchanged in year 2023-2024. N fertiliser is available only from 1910, please assume N Fertiliser at the 1910 value for years 1700-1860.

Manure is an organic fertiliser (animal waste put on fields). It's important from the N cycle perspective, because it's one of the important pre-artificial fertiliser sources. However, as it's based on organic N, it causes a problem with the model mass balance (groups will need to take the C and N from land, respire some of the C, and then add the remaining C:N onto the cropland). Doing this wrongly will influence the C cycle simulation. For TRENDY, we recommend to not include it (however if you use it, you must tell us where you take the C and N from). Note: If models choose to include manure, against our recommendation, then we need a manure application rate for S0-S3 Nfert.

In terms of artificial fertiliser, it's safe to assume that the per area rates haven't changed much between 1700 and 1850. For manure, this would not be so easy.

N deposition (search for “N deposition” from):

https://esgf-node.llnl.gov/search/input4mips/

Please use the historical N-deposition database (1850-2014) then transition onto the Future RCP8.5 N-deposition databases (2015-2100) for years 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023 and 2024. Note, this is the same as applied in NMIP.

N deposition is available only from 1850, please assume N deposition at the 1850 value for years 1700-1850.

Appendix 2. Description of CRU-JRA(3Q)

The revised reanalysis from JRA-3Q (Japanese 3-quarter century Reanalysis) was merged with the CRU TS dataset.

1. All JRA-3Q data are regridded to the CRU 0.5° grid using appropriate NCL routines and masked to give a land-only (excluding Antarctica) dataset.

2. For the four variables tmp, dswrf, shum and pre, JRA-55 is aligned to CRU TS (v4.09) tmp, cld, vap and pre (also wet) respectively over land, using the same transformations as previously. The other four variables (pres, ugrd, vgrd, dlwrf) pass through without further modification.

3. For years between 1948 and 2023, JRA-3Q is used. Alignment to CRU TS occurs where appropriate.

4. For years between 1901 and 1947, random (but fixed) years from JRA-3Q for 1948-1957 are used to fill. Alignment to CRU TS applies separately to each instance, as appropriate (ie, using the appropriate CRU TS year).

The resolution of JRA is 0.5 degree. This means that now resolution of reanalysis is compatible with resolution of the CRU dataset. This will not change the monthly fields that are still aligned to CRU TS but obviously it will change the spatial and high frequency temporal variability of the fields.

Appendix 3. LULCC forcing

Land-use states for all years 850-2025.

Land-use states are based on updated HYDE3.5 land use and population data and FAO wood harvest data. In addition, the time series has been extended to include land-use states in the year 2025 (and land-use transitions during the year 2024). LUH2 algorithms and methodology remains the same, and other inputs to the LUH2 model also remain the same.

HYDE inputs: Data from HYDE3.5, prepared for GCB 2025, is based on a FAO release (bulk download Feb 2025), which includes yearly data from 1961 up to and including the year 2022. After the year 2022 HYDE extrapolates the cropland, pasture, and urban data, based on the trend over the previous 5 years, to generate data until the year 2025. HYDE also uses satellite imagery from ESA-CCI from 1992 – 2018 for more detailed yearly allocation of cropland and grazing land. The 2018 map is also used for the 2019-2024 period. The original 300-meter resolution data from ESA was aggregated to a 5-arc minute resolution according to the classification scheme as described in Klein Goldewijk et al (2017). For Brazil we replace FAO state-level data for cropland and grazing land by those from in-country land cover dataset MapBiomas for 1985-2023. ESA-CCI is used to spatially disaggregate as described above. Similarly, an estimate for years 2024-25 is based on the MapBiomas trend 2018-2023. The pre-1985 period is scaled with the per capita numbers from 1985 from MapBiomas, so this transition is smooth. Similar for Indonesia for the 2000-2019 period, where the pre-2000 period is scaled with the per-capita numbers from MapBiomas. As in GCB2024 we replace the FAO timeseries for China, based on province-level totals from Yu et al., 2022 for the 1900-2019 period. FAO has retrospectively updated their data for DRC – this modification is in response to a query regarding a large LU change in 2011 identified in GCB2021/Trendy-v10 and has also been accounted for in the GCB 2022 update.

Wood harvest inputs: The version of wood harvest data used for LUH2 v2h was based on a previous FAO release that included data up to and including the year 2014 – those inputs have been updated for this GCB dataset to use the 2025 FAO wood harvest dataset for all years from 1961 to 2023. After the year 2023 we extrapolated the wood harvest data until the year 2025. The HYDE3.5 population data is also used to extend the wood harvest time series back in time. Other wood harvest inputs (for years prior to 1961) remain the same in LUH2.

Conversion to pasture/rangeland

The LUH2 methodology uses the cropland, urban, managed pasture, and rangeland layers from HYDE. DGVM groups in the past have requested more information on whether natural vegetation is lost in conversion to pasture and rangeland.

Following LUH2 simple guidelines (on their website): "all natural vegetation should be cleared for managed pasture, and only cleared for rangeland if it is forested".

Using this rule/guideline gives maps of forest area, carbon density, and carbon emissions that are consistent with other published maps.

The "staticData_quarterdeg.nc" file on the LUH2 website contains a layer named fstnf which is 1 when the potential vegetation is forested, and 0 when it is not. This layer can be used to designate whether any rangeland increases should imply clearing of natural vegetation (yes, if fstnf is 1 and no if fstnf is 0).

Users can download this file from here:
https://luh.umd.edu/LUH2/LUH2_v2h/staticData_quarterdeg.nc

Appendix 4. Lightening ignition and population density

Given uncertainties around lightning datasets, scaling factors, and potential need for model recalibration, and the fact in TRENDY we want models to supply their best C-cycle representation, groups are free to choose the lightning dataset they use.

Gridded population data based on HYDE3.4 is available. This is total population per grid cell. Each modelling group needs to convert this to pop/area, depending on their own land/sea/water masks.

For fire-enabled LSMs please use varying population density in simulations S1-S3. Our simplified logic is there is LUC and its direct consequences (Nfert) that go together in Eluc, and all other environmental changes (Ndep, population, climate, CO_2) in SLAND.

Appendix 5. Output netcdf formats

The aim is to be more consistent with CMIP, LUMIP, LS3MIP in our format/variable requests to aid analysis:

1. Please follow the protocol (or explicitly state why not).
2. All modelling teams provide a methodology (in a README file) of how to calculate global annual nbp from gridded

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monthly files (grid and pft level). This will avoid confusion of whether to use landmasks/landcover/gridareas/etc.

3. In the past "lai" has not been consistent between models. We have changed "lai" to gridcell mean lai and include new variable laipft for the pft level.
4. Order of dimensions should be consistent. Eg [lon,lat,PFT,time]. When using ncdump this reads as [time,PFT,lat,lon].
5. Please provide a list of variables that are not applicable for your model. E.g. cSoilpft might not exist. This gives us an idea of what variables we can request/expect.
6. Please include the forcing/driving data (precipitation and surface air temperature) as output by your model on the grid that you use. This is used by ILAMB to estimate relationships with other variables.
7. Using cf-complient units. Remove "C" for carbon and "N" for nitrogen from the units and don't measure time in years or months, e.g. All CO2 stocks and fluxes were previously requested in units kgC m-2, and kgC m-2 s-1, respectively, please remove the letter C to be cf-complient in the netcdf files.
8. Gridbox fluxes should be per m2 of land
9. PFT fluxes should be per m2 of PFT
10. Pools, coverages, LAI etc should be per m2 of land
11. All models to provide a land fraction file if using regular lat-lon grids, or a land fraction and grid area if using non regular grids.
12. All models should use a consistent file naming (e.g. JULES_S1_mrso.nc). Eg. do not include annual/monthly/perpft tag.

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13. Following this, PFT labels are different among DGVMs (pft, PFT, vegtype…). Please all use nomenclature, PFT.
14. Consistent latitude/longitude use (e.g. do not use lat/lon)
15. Consistent fill value of -99999 to be used (e.g. not -9999)
16. All data from -180 -> 180 and -90 -> 90.
17. All models output over the same time period, 1700-2024, e.g. until now some supply from 1700, others 1840, 1850, 1900, 1901.

To ensure accessibility by broad users, avoid to format netcdf files with netcdf library 4.4.0 or earlier, combined with libhdf5 1.10.0 or greater. There is a known issue with netcdf formatted by this set of libraries.

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Table 1. Output Variables.

priority	long name	units	comment	output variable name	CMOR dimensions	missing v:	frequency
	FIRST PRIORITY						
	Physical variables						
1	Near-Surface Air Temperature	K	near-surface (usually, 2 meter) air temperature.	tas	longitude latitude time	-99999	monthly
1	Precipitation	kg m^{-2} s^{-1}	at surface; includes both liquid and solid phases from all types of clouds (both large-scale and convective)	pr	longitude latitude time	-99999	monthly
1	Surface Downwelling Shortwave Radiation	W m^{-2}	surface_downwelling_shortwave_flux_in_air	rsds	longitude latitude time	-99999	monthly
1	Total Soil Moisture Content	kg m^{-2}	Compute the mass per unit area (summed over all soil layers) of water in all phases.	mrso	longitude latitude time	-99999	monthly
1	Total Runoff	kg m^{-2} s^{-1}	compute the total runoff (including "drainage" through the base of the soil model) leaving the land portion of the grid cell.	mrro	longitude latitude time	-99999	monthly
1	Total Evapo-Transpiration	kg m^{-2} s^{-1}		evapotrans	longitude latitude time	-99999	monthly
	The following variables at the level of each vegtype		All the following biophysical/biogeochemical variables listed in the files should be reported per PFT/Veg type. Average pixel values are not very useful if not for the few "pure" pixel where we can attibute a specific flux to a given PFT/Veg Type				
1	Vegtype level evapotranspiration	W m^{-2}	If possible we would prefer to have two separated fluxes for tree transpiration and ecosystem evaporation. The sum of the two is the total evapotranspiration. We would prefer water fluxes expressed in energy terms (W/m2), see next two items	evapotranspft	longitude latitude pft time	-99999	monthly
1	Vegtype level transpiration	W m^{-2}		transpft	longitude latitude pft time	-99999	monthly
1	Vegtype level Soil evaporation	W m^{-2}		evapo	longitude latitude pft time	-99999	monthly
1	Vegtype level Broadband Albedo	fraction	if available provide black and white sky albedo. If only blue sky albedo is available than we need the fraction of incoming diffuse shortwave	albedopft	longitude latitude pft time	-99999	monthly
1	Vegtype level snow depth or snow water equivalent	m m^{-2}		snow_depthpft	longitude latitude pft time	-99999	monthly
1	Vegtype level sensible heat flux	W m^{-2}	required only for models that solve the energy/water balance at the vegtype level	shflxpft	longitude latitude pft time	-99999	monthly
1	Vegtype level net radiation	W m^{-2}	required only for models that solve the energy/water balance at the vegtype level	rnpft	longitude latitude pft time	-99999	monthly
	Land Carbon variables						
	Pools						
1	Carbon in Vegetation	kg m^{-2}	Previously reported in units, kgC m-2. Please remove the letter C in output files.	cVeg	longitude latitude time	-99999	annual
1	Carbon in Above-ground Litter Pool	kg m^{-2}	Previously reported in units, kgC m-2. Please remove the letter C in output files.	cLitter	longitude latitude time	-99999	annual
1	Carbon in Soil (including below-ground litter)	kg m^{-2}	Previously reported in units, kgC m-2. Please remove the lett	cSoil	longitude latitude time	-99999	annual

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1	Carbon in Products of Land Use Change	kg m^{-2}	Previously reported in units, kgC m-2. Please remove the letter C in output files.	cProduct	longitude latitude time	-99999	annual
1	Vegtype level Carbon in Vegetation	kg m^{-2}	Previously reported in units, kgC m-2. Please remove the letter C in output files.	cVegpft	longitude latitude pft time	-99999	annual
2	Vegtype level Carbon in Soil	kg m^{-2}	Previously reported in units, kgC m-2. Please remove the letter C in output files.	cSoilpft	longitude latitude pft time	-99999	annual
	Fluxes					-99999	
1	Gross Primary Production	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	gpp	longitude latitude time	-99999	monthly
1	Autotrophic (Plant) Respiration	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	ra	longitude latitude time	-99999	monthly
1	Net Primary Production	kg m^{-2} s^{-1}	needed for models that do not compute GPP (if any). Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	npp	longitude latitude time	-99999	monthly
1	Heterotrophic Respiration	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	rh	longitude latitude time	-99999	monthly
1	CO2 Emission from Fire	kg m^{-2} s^{-1}	CO2 emissions from natural fires + human ignition fires as calculated by the fire module of the DGVM, but excluding any CO2 flux from fire reported under variable "CO2 Flux to Atmosphere from Land Use Change". Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	fFire	longitude latitude time	-99999	monthly
1	CO2 Flux to Atmosphere from Land Use Change	kg m^{-2} s^{-1}	human changes to land accounting possibly for different time-scales related to fate of the wood, for example. Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	fLuc	longitude latitude time	-99999	monthly
1	Soil Respiration	kg m^{-2} s^{-1}	root + microbial CO2 efflux	soilr	longitude latitude time	-99999	monthly
1	Net Biospheric Production	kg m^{-2} s^{-1}	This is the net flux between land and atmosphere defined as photosynthesis MINUS the sum of plant and soil respiration, carbonfluxes from fire, harvest, grazing, land use change and any other C flux in/out of the ecosystem (eg DIC, DOC, VOCs,...). Positive flux is into the land. NBP SHOULD be equal to changes in total carbon reservoirs. Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	nbp	longitude latitude time	-99999	monthly
1	Vegtype level GPP	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	gpppft	longitude latitude pft time	-99999	monthly
1	Vegtype level NPP	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	npppft	longitude latitude pft time	-99999	monthly
1	Vegtype level Rh	kg m-2 s-1	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	rhpft	longitude latitude pft time	-99999	monthly
1	Vegtype level NBP	kg m^{-2} s^{-1}	If soils are associated with PFT fraction	nbppft	longitude latitude pft time	-99999	monthly
	Structure						

1	Fractional Land Cover of PFT		using each individual ESM PFT definition. This includes natural PFTs, anthropogenic PFTs, bare soil, lakes, urban areas, etc. **Sum of all should equal the fraction of the grid-cell that is land.** Note that for degraded resolution simulation, ocean fraction of grid cell may not be zero.	landCoverFrac	longitude latitude pft time	-99999	annual (if dyanamic veg) or once (if static veg)
1	Fractional Ocean Cover		ocean fraction of grid cell may not be zero.	oceanCoverFrac	longitude latitude time	-99999	once
1	Burnt Area Fraction	fraction	fraction of entire grid cell that is covered by burnt vegetation.	burntArea	longitude latitude time	-99999	monthly
1	Leaf Area Index		projected leaf area	lai	longitude latitude time	-99999	monthly
1	Vegtype level Leaf Area Index		projected leaf area per PFT	laipft	longitude latitude PFT time	-99999	monthly
	Internal processes						
1	Carbon in Leaves	kg m^{-2}	Previously reported in units, kgC m-2. Please remove the letter C in output files.	cLeaf	longitude latitude time	-99999	annual
1	Carbon in Wood	kg m^{-2}	including sapwood and hardwood. Previously reported in units, kgC m-2. Please remove the letter C in output files.	cWood	longitude latitude time	-99999	annual
1	Carbon in Roots	kg m^{-2}	including fine and coarse roots. Previously reported in units, kgC m-2. Please remove the letter C in output files.	cRoot	longitude latitude time	-99999	annual
1	Carbon in Coarse Woody Debris	kg m^{-2}	Previously reported in units, kgC m-2. Please remove the letter C in output files.	cCwd	longitude latitude time	-99999	annual
1	Carbon in individual soil pools	kg m-2		cSoilPools	longitude latitude pool time	-99999	annual
1	Total Carbon Flux from Vegetation to Litter	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	fVegLitter	longitude latitude time	-99999	monthly
1	Carbon Flux from Leaves to Litter	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	fLeafLitter	longitude latitude time	-99999	monthly
1	Carbon Flux from Wood to Litter	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	fWoodLitter	longitude latitude time	-99999	monthly
1	Carbon Flux from Roots to Litter	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	fRootLitter	longitude latitude time	-99999	monthly
1	Total Carbon Flux from Litter to Soil	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	fLitterSoil	longitude latitude time	-99999	monthly
1	Total Carbon Flux from Vegetation Directly to Soil	kg m^{-2} s^{-1}	In some models part of carbon (e.g., root exudate) can go directly into the soil pool without entering litter. Previously reported in units, kgC m-2 s-1. Please remove the letter C in	fVegSoil	longitude latitude time	-99999	monthly
1	Carbon Flux from individual soil pools	kg m-2 s-1	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	rhPools	longitude latitude pool time	-99999	monthly
1	Vegtype NPP allocation to leaves	kg m^{-2} s^{-1}		fAllocLeaf	longitude latitude pft time	-99999	monthly

1	Vegtype NPP allocation to Wood	kg m^{-2} s^{-1}		fAllocWood	longitude latitude pft time	-99999	monthly
1	Vegtype NPP allocation to Root	kg m^{-2} s^{-1}		fAllocRoot	longitude latitude pft time	-99999	monthly
1	CO2 Emission from Cveg due to Fire	kg m^{-2} s^{-1}	contribution of combustion of live biomass to total CO2 emissions from fire	fFireCveg	longitude latitude time	-99999	monthly
1	CO2 Emission from Litter due to Fire	kg m^{-2} s^{-1}	contribution of combustion of above ground necromass/litter to total CO2 emissions from fire	fFireLitter	longitude latitude time	-99999	monthly
1	CO2 Emission from Csoil due to Fire	kg m^{-2} s^{-1}	contribution of combustion of Csoil to total CO2 emissions from fire	fFireCsoil	longitude latitude time	-99999	monthly
	SECOND PRIORITY **Physical variables**						
2	Temperature of Soil	K	Temperature of each soil layer.	tsl	longitude latitude stlayer time	-99999	monthly
2	Moisture of Soil	kg m^{-2}	Compute the mass of water in all phases in each soil layer	msl	longitude latitude smlayer time	-99999	monthly
2	Evaporation from Canopy	kg m^{-2} s^{-1}	Report the canopy evaporation+sublimation (if present in model).	evspsblveg	longitude latitude time	-99999	monthly
2	Water Evaporation from Soil	kg m^{-2} s^{-1}	includes sublimation.	evspsblsoi	longitude latitude time	-99999	monthly
2	Transpiration	kg m^{-2} s^{-1}		tran	longitude latitude time	-99999	monthly
2	Vegtype level Skin temperature	K	(min/max or day/night separated) of outgoing longwave	tskinpft	longitude latitude pft time	-99999	monthly
2	Vegtype level soil moisture	kg m^{-2}	required only for models that solve the energy/water balance at the vegtype level. Most model shares soils between pfts. This is a very crude assumption and we invite modelers to simulate PFT specific soils, e.g. for CLM this is actually possible by defining a different soil column for each PFT. We know that some of the interaction between vegetation type and climate is mediated by soil water content (see work of Sonia S.) in particular during extreme events as droughts and heatwaves	mslpft	longitude latitude pft time		monthly
						-99999	
2	Vegtype level tree heights	m		theightpft	longitude latitude pft time	-99999	annual
	Land Carbon & Biogeochemistry					-99999	
2	CO2 Flux to Atmosphere from Grazing	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	fGrazing	longitude latitude time	-99999	monthly
2	CO2 Flux to Atmosphere from Crop Harvesting	kg m^{-2} s^{-1}	Previously reported in units, kgC m-2 s-1. Please remove the letter C in output files.	fHarvest	longitude latitude time	-99999	monthly
						-99999	
2	Leaf Area Index Daily		projected leaf area per PFT, from 1980 onwards	dlai	longitude latitude time	-99999	daily
2	Vegtype level irrigation	kg m^{-2} s^{-1}		irripft	longitude latitude pft time	-99999	monthly

	Additional N-cycle Variables						
	Land Nitogen Cycle					-99999	
	Pools						
2	Nitrogen in Vegetation	kg m^{-2}	Previously reported in units, kgN m-2. Please remove the letter N in output files.	nVeg	longitude latitude time	-99999	annual
2	Nitrogen in Leaves	kg m^{-2}	Previously reported in units, kgN m-2. Please remove the letter N in output files.	nLeaf	longitude latitude time	-99999	annual
2	Nitrogen in Wood	kg m^{-2}	including sapwood and hardwood. Previously reported in units, kgN m-2. Please remove the letter N in output files.	nWood	longitude latitude time	-99999	annual
2	Nitrogen in Roots	kg m^{-2}	including fine and coarse roots. Previously reported in units, kgN m-2. Please remove the letter N in output files.	nRoot	longitude latitude time	-99999	annual
2	Nitrogen in Above-ground Litter Pool	kg m^{-2}	Previously reported in units, kgN m-2. Please remove the letter N in output files.	nLitter	longitude latitude time	-99999	annual
2	Nitrogen in Soil (including below-ground litter)	kg m^{-2}	Previously reported in units, kgN m-2. Please remove the letter N in output files.	nSoil	longitude latitude time	-99999	annual
2	Nitrogen Organic in Soil (including below-ground litter)	kg m^{-2}	Previously reported in units, kgN m-2. Please remove the letter N in output files.	nOrgSoil	longitude latitude time	-99999	annual
2	Nitrogen Inorganic (NH4+ and NO3-) in Soil (including below-ground litter)	kg m^{-2}	Previously reported in units, kgN m-2. Please remove the letter N in output files.	nInorgSoil	longitude latitude time	-99999	annual
2	Nitrogen in Products of Land Use Change	kg m^{-2}	Previously reported in units, kgN m-2. Please remove the letter N in output files.	nProduct	longitude latitude time	-99999	annual
	Fluxes					-99999	
2	Nitrogen deposition	kg m^{-2} s^{-1}	dry and wet deposition of reactive nitrogen onto land. Previously reported in units, kgN m-2 s-1. Please remove the letter N in output files.	fNdep	longitude latitude time	-99999	monthly
2	Biological N fixation	kg m^{-2} s^{-1}	biological nitrogen fixation. Previously reported in units, kgN m-2 s-1. Please remove the letter N in output files.	fBNF	longitude latitude time	-99999	monthly
2	Nitrogen uptake of Vegetation	kg m^{-2} s^{-1}	total plant nitrogen uptake (sum of ammonium and nitrate), irrespective of the source of nitrogen. Previously reported in units, kgN m-2 s-1. Please remove the letter N in output files.	fNup	longitude latitude time	-99999	monthly
2	net Nitrogen mineralisation	kg m^{-2} s^{-1}	Net nitrogen release from soil and litter as the outcome of nitrogen immobilisation and gross mineralisation. Previously reported in units, kgN m-2 s-1. Please remove the letter N in output files.	fNnetmin	longitude latitude time	-99999	monthly
2	total ecosystem nitrogen loss	kg m^{-2} s^{-1}	Total N lost to groundwater, rivers or atmosphere (including NHx, NOx, N2O, N2 and leaching). Previously reported in units, kgN m-2 s-1. Please remove the letter N in output files.	fNloss	longitude latitude time	-99999	monthly
2	N2O flux	kg m^{-2} s^{-1}	Total land N2O flux. Previously reported in units, kgN m-2 s-1. Please remove the letter N in output files.	fN2O	longitude latitude time	-99999	monthly