

# Modelled land use and land cover change emissions - A spatio-temporal comparison of different approaches

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**Abstract.** Quantifying the net carbon flux from land use and land cover changes ( $f_{LULCC}$ ) is critical for understanding the global carbon cycle, and hence, to support climate change mitigation. However, large-scale  $f_{LULCC}$  is not directly measurable ~~-,but~~ and has to be inferred from models instead, such as semi-empirical bookkeeping models ~~-,and~~ and process-based dynamic global vegetation models (DGVMs). By definition,  $f_{LULCC}$  estimates are not directly comparable between these two different model types. As an important example, DGVM-based  $f_{LULCC}$  in the annual global carbon budgets is estimated under transient environmental forcing and includes the so-called Loss of Additional Sink Capacity (LASC). The LASC ~~accounts for results from~~ the impact of environmental changes on land carbon storage potential of managed land compared to potential vegetation, and accumulates over time, which is not ~~represented~~ captured in bookkeeping models. ~~In addition,-~~  $f_{LULCC}$  from transient DGVM simulations ~~differs depending on the arbitrary chosen simulation time period and the historical-, thus, strongly depends on the~~ timing of land use and land cover changes ~~(including different accumulation periods for legacy effects). An approximation of~~ mainly because LASC accumulation is cut off at the end of the simulated period. To estimate the LASC,  $f_{LULCC}$  by DGVMs

that from pre-industrial DGVM simulations, which is independent of the timing of land use and land cover changes and their legacy effects requires simulations assuming constant pre-industrial or changing environmental conditions, can be used. Additionally, DGVMs using constant present-day environmental forcings enable an approximation of bookkeeping estimates. Here, we analyze these three DGVM-derived  $f_{LULCC}$  estimations (under transient, pre-industrial, and present-day forcing) for twelve models within 18 regions and quantify their differences as well as climate- and CO<sub>2</sub>-induced components. The three estimations stem from the commonly performed simulation with transiently changing environmental conditions and two simulations that keep environmental conditions fixed, at pre-industrial and present-day conditions compare them to bookkeeping estimates. Averaged across the models, we find a global  $f_{LULCC}$  (under transient conditions) of  $2.0 \pm 0.6$  PgC yr<sup>-1</sup> for 2009–2018, of which ~40% are attributable to the LASC ( $0.8 \pm 0.3$  PgC yr<sup>-1</sup>). From 1850 onward,  $f_{LULCC}$  accumulated to  $189 \pm 56$  PgC with  $40 \pm 15$  PgC from the LASC. Around 1960, the accumulating nature of the LASC causes global transient  $f_{LULCC}$  estimates to exceed estimates under present-day conditions, despite generally increased carbon stocks in the latter. Regional hotspots of high cumulative and annual LASC values are found in the USA, China, Brazil, Equatorial Africa and Southeast Asia, mainly due to deforestation for cropland. Distinct negative LASC estimates, in Europe (early reforestation) and from 2000 onward in the Ukraine (recultivation of post-Soviet abandoned agricultural land), indicate that  $f_{LULCC}$  estimates in these regions are lower in transient DGVM- compared to bookkeeping-approaches. By unraveling spatio-temporal variability in three alternative DGVM-derived Our study unravels the strong dependence of  $f_{LULCC}$  estimates, our results call for a harmonized attribution of model-derived  $f_{LULCC}$ . We propose on the time a certain land use and land cover change event happened to occur, and on the chosen time period for the forcing of environmental conditions in the underlying simulations. We argue for an approach that bridges bookkeeping and DGVM approaches for provides an accounting of  $f_{LULCC}$  estimation by adopting that is more robust against these choices, for example by estimating a mean DGVM-ensemble  $f_{LULCC}$  and LASC for a defined reference period and homogeneous environmental changes (CO<sub>2</sub>-only).

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## 1 Introduction

Terrestrial ecosystems play an important role for the global carbon cycle as they act as substantial sinks and sources of carbon (C) (Keenan and Williams, 2018). In both directions, fluxes in the land carbon cycle have significantly been altered in previous centuries due to anthropogenic land use and land cover changes (LULCCs), in particular by deforestation e.g. through deforestation driven by early agricultural expansion in high-latitudes and more mid-latitudes, recent tropical deforestation or recent regional reforestation and afforestation (denoted reforestation in the following) in, and recent forest expansion in mid- and high-latitudes (Klein Goldewijk et al., 2011). Since 1850, the accumulated global net flux from LULCC ( $f_{LULCC}$ ) contributed approximately by a third to one-third of global anthropogenic CO<sub>2</sub> emissions and was the dominant source until the 1950s, when fossil fuel emissions drastically increased (Friedlingstein et al., 2019). Despite its decreasing relative contribution,

$f_{LULCC}$  comprises an important share of the global carbon budget (GCB) and might again account for the bulk of anthropogenic C emissions in future, if fossil emissions can be drastically reduced as described in some socio-economic pathways (Popp et al., 2017; Krause et al., 2018). ~~In line,~~  $f_{LULCC}$  may also gain an important role in the quest for negative CO<sub>2</sub> emissions technologies, with LULCCs such as reforestation and afforestation (denoted reforestation in the following) bearing significant potential to sequester atmospheric CO<sub>2</sub> (Griscom et al., 2017; Fuss et al., 2018; Sonntag et al., 2016; Arneth et al., 2017). Accordingly,  $f_{LULCC}$  quantification is essential to better understand global carbon cycle dynamics, to estimate future climate change, and to support the assessment of greenhouse gas reduction efforts (Friedlingstein et al., 2019).

~~Irrespective of the  $f_{LULCC}$  importance, there~~ There is so far no general agreement on a single valid definition and approach to assess ~~it~~  $f_{LULCC}$ . This is because  $f_{LULCC}$  cannot be directly measured on global scale due to the co-occurrence with natural C sinks and sources. For example, in managed forests, C fluxes result from logging and subsequent regrowth, which is part of  $f_{LULCC}$ , but also change in response to interannual variability or long-term trends in environmental conditions (Friedlingstein et al., 2019). Inventories or satellite-based measurements cannot distinguish C fluxes induced by LULCC from those induced by environmental changes. To separate these terms, models are applied. Here, various approaches exist. In the 2019 GCB of the Global Carbon Project (named GCB2019 in the following; Friedlingstein et al. 2019), two bookkeeping models are used, ‘Bookkeeping of Land Use Emissions’ (hereafter BLUE; Hansis et al. 2015) and ‘Houghton and Nassikas 2017’ (hereafter H&N2017; Houghton and Nassikas 2017). The bookkeeping mean  $f_{LULCC}$  in the GCB2019 is combined with the uncertainty derived from process-based dynamic global vegetation models (DGVMs). DGVMs exist in much larger numbers and their process-based methods to calculate C fluxes allow to account for the interplay of multiple drivers on C fluxes which bookkeeping models cannot.

However, estimates from bookkeeping models and DGVMs are not directly comparable due to underlying assumptions on C stocks (Pongratz et al., 2014). Bookkeeping models are semi-empirical models that combine observation-based C densities with information on areas affected by different types of LULCCs and response curves characterizing the speed of C uptake and release after specific LULCCs to calculate  $f_{LULCC}$ . In contrast, to isolate the LULCC effects from those of environmental changes, DGVM-based  $f_{LULCC}$  is generally estimated as the difference of net land C uptake from net biome productivity (NBP) between simulations with and without LULCC. Within the GCB2019, these simulations are conducted under transient environmental conditions (such as climate, CO<sub>2</sub> concentrations and nitrogen deposition), therefore, synergistic fluxes between LULCCs and environmental changes are included.

~~Inevitably, the~~ The transient DGVM approach includes the Loss of Additional Sink Capacity (LASC), representing ~~CO<sub>2</sub>-C~~ fluxes in response to environmental changes on managed land (typically croplands with low C sink capacity and fast turnover rates) as compared to potential natural vegetation (typically forests with large C sink capacity and slower turnover rates; Gitz and Ciais 2003; Pongratz et al. 2014; Gasser and Ciais 2013; Peng et al. 2014). As an example, when an area which acted as C sink is deforested, the stored C is ~~typically emitted representing environmental conditions~~ lost at harvest time corresponding to an instantaneous  $f_{LULCC}$ . The resulting agricultural area typically does not constitute a major sink. In the simulation without LULCCs, the forest persists and may increase its C density over time, storing additional C in its slow-turnover woody and soil C pools in response to favourable environmental changes such as increased CO<sub>2</sub> concentrations. Compared to the simulation

without LULCC, the sink capacity would consequently be diminished in the simulation with LULCC. Thus, even after the instantaneous emissions of the deforestation event may have ceased, deforestation continues to ~~cause fluxes attributed to alter~~ the  $f_{LULCC}$  ~~due to since~~ the reference simulation ~~assuming~~ ~~assumes the~~ potential vegetation cover in the absence of LULCCs, and ~~simulates~~ its response to environmental changes. ~~These theoretical emissions via lost~~ This example illustrates an interesting aspect of the LASC: It has been acknowledged that the LASC in its literal sense (a loss of carbon, positive LASC values) is an unrealized C uptake potential due to human Earth system alterations thus capture and is not reflected in any real change in atmospheric CO<sub>2</sub> concentration (Pongratz et al., 2014). However, as the LASC captures the foregone sinks a given LULCC event destroys (or creates, e.g. for reforestation), and accumulate and likely accumulates even in absence of further LULCC as long as environmental conditions keep changing in the same direction.

LULCCs, it manifests in the budget of atmospheric CO<sub>2</sub> as compared to a reference excluding LULCCs (Pongratz et al., 2014). In contrast to the theoretical nature of positive LASC values, negative values counted towards the LASC, for example due to reforestation, depict realized C uptake which is theoretically observable (though observations in the field are highly complex due to co-occurrence of natural carbon fluxes).

The result of a permanent reduction of a C sink on the LASC, as due to ~~a conversion described above~~ deforestation, is difficult to predict over time. Natural C sinks are subject to changes, and can even turn into C sources for periods of time, due to the interplay of multiple factors which control the C balance of ecosystems simultaneously. For example, the LASC may increase because of an increased C uptake via higher NBP resulting from atmospheric CO<sub>2</sub> increases (Albani et al. 2006; Schimel et al. 2015, or review of CO<sub>2</sub> effect in Walker et al. 2021) or global warming induced longer growing seasons in northern latitudes and higher altitudes (Keenan et al., 2014; O'Sullivan et al., 2020). Conversely, environmental driven decreases in C stock turnover times, for example due to an increased frequency and severity of drought and heat stress events (Bastos et al., 2020) or increased fire (included in some DGVMs of the GCB2019), may reduce NBP and thus may cause LASC decreases (and lower  $f_{LULCC}$  estimates) ~~if the C stocks of the potential vegetation in the simulation without LULCCs decrease over time.~~

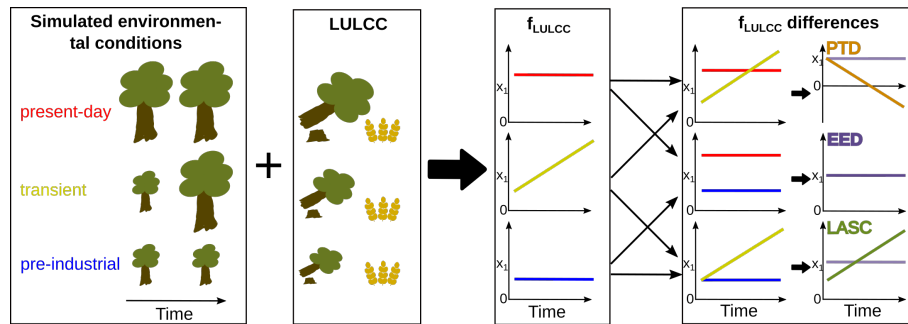
100 The LASC will thus differ in magnitude and direction over time and across space.

Environmentally induced C stock changes not only alter the LASC, but also the instantaneous  $f_{LULCC}$ . For example,  $f_{LULCC}$  from clearing pristine forest is expected to be higher today than during pre-industrial times if the forest has grown denser over time. Additionally, legacy effects result from the ongoing adaption of ecosystems to historical environmental changes (Krause et al., 2020). Such transient environmental effects are excluded in bookkeeping approaches – either through using constant C densities, or through purposefully excluding alterations in C densities from transient DGVM simulations in reduced-complexity Earth system models (Gasser et al., 2020). The independence or dependence of vegetation and soil C densities from environmental conditions is thus another difference between transient DGVM and bookkeeping approaches. Here, DGVM simulations under constant environmental forcing can help to attribute  $f_{LULCC}$  quantities independent of the timing of LULCCs.

DGVM simulations under constant environmental conditions have been performed within the project 'Trends and drivers of the regional-scale sources and sinks of carbon dioxide' (TRENDY; Le Quéré et al. 2013; Sitch et al. 2015), when conducting the simulations for the GCB2019 (Friedlingstein et al., 2019). This included a first set of simulations that quantify  $f_{LULCC}$  based on constant present-day environmental conditions. This approach is more similar to bookkeeping estimates and can be

evaluated against Earth observation or inventory data as it most closely represents the observable state under today's conditions and excludes transient flux alterations. Moreover, recent observations are commonly used to estimate the past, for example by combining observed C densities with vegetation coverage reconstructions to infer C stocks in human absence, or with historical area changes for time-series of C stock losses (Sanderman et al., 2017; Erb et al., 2018).

However, as  $f_{LULCC}$  quantities derived under constant present-day conditions are independent of ~~the time at which specific LULCCs occur (unaffected by long-term environmental trends; compare Fig. 1 for illustration)~~, the increased C stocks due to spin-up with present-day environmental conditions may lead to comparably higher  $f_{LULCC}$  estimates, especially in early simulation years (environmental changes during the industrial period, in general and on global scale, increased C stocks; refer to Fig. 1 for illustration). More realistic  $f_{LULCC}$  estimates for the early period can be derived assuming that pre-industrial environmental conditions prevailed over time (Pongratz et al., 2014; Stocker and Joos, 2015), however, despite being based on the same land use data set, this leads to comparably lower  $f_{LULCC}$  estimates in particular for later LULCCs (Stocker and Joos, 2015).



**Figure 1.** Illustration of the different  $f_{LULCC}$  estimations and their differences. The altered sizes of trees (box 1) indicate that vegetation responds to the historical trends in environmental conditions (such as increased  $\text{CO}_2$  levels and global warming). Historically and globally environmental changes led to an increase in land C stocks, therefore present-day environmental conditions are associated with taller trees in our scheme. When a LULCC occurs that reduces C stocks (box 2) the higher C stocks will cause a higher  $f_{LULCC}$  (box 3: red line (present-day) higher than blue line (pre-industrial); yellow line (transient) increasing with time).  $f_{LULCC}$  is derived by subtracting the net biome productivity from a simulation without LULCCs from one with LULCCs. Additionally, the different  $f_{LULCC}$  estimations can be compared to each other (box 4): the Loss of Additional Sink Capacity (LASC; green line; Eq. 4), Environmental Equilibrium Difference (EED; purple line; Eq. 5) and 'Present-day' vs 'Transient' environmental conditions Difference (PTD; orange line; Eq. 6).

Assuming constant environmental conditions or C densities over time is clearly unrealistic and requires an arbitrary decision on the time period to determine these variables' values. On the other hand, as discussed, the lost sinks in DGVM-based  $f_{LULCC}$  under more-realistic, transient environmental conditions does-do not correspond to observable fluxes. This poses the question about a proper definition of  $f_{LULCC}$  for a robust and realistic attribution which is valid across time and space. In-line, it-It needs to be decided whether the LASC should be included or excluded (as argued e.g. in Gasser and Ciais 2013; Gasser et al. 2020) as part of  $f_{LULCC}$  and consequently into the natural land C sink be counted towards the terrestrial C sink or not. The urgent

need to address this question is underlined by the fact that past LULCCs are estimated to have committed a reduction in the potential global C sink of 80–150 PgC by 2100, which depending on the scenario, translates into a share of  $\sim 70\%$  of total global  $f_{LULCC}$  (Strassmann et al., 2008).

This study aims to strengthen the basis for a decision on how to define  $f_{LULCC}$ , in particular with respect to the ability of different approaches to resolve the LASC, and thus is a guide on the future role of DGVMs in  $f_{LULCC}$  attribution. To this end, we present analyses concerning the relevance of different assumptions on environmental conditions, for which the recent extended set of TRENDY DGVM simulations was performed. In particular, our study (1) discusses and quantifies three DGVM-derived  $f_{LULCC}$  (under pre-industrial, transient, and present-day environmental conditions) and bookkeeping estimates in conjunction with their inherent differences on global scale, (2) quantifies the temporal evolution of the differences in DGVM-derived  $f_{LULCC}$  estimates for 18 regions, (3) separates between climate- and  $\text{CO}_2$ -induced  $f_{LULCC}$  components as derived by DGVMs and (4) aims to approach a spatio-temporally homogenized attribution of  $f_{LULCC}$  as derived by models.

## 2 Data and Methods

This study is based on an ensemble of TRENDY v8 models (<http://sites.exeter.ac.uk/trendy/>) that ran simulations with and without LULCC for the period 1700–2018 (used in the GCB2019 to quantify  $f_{LULCC}$  uncertainty and to estimate the natural terrestrial C sink; Friedlingstein et al. 2019). It is ensured that all models have reached (1) a steady state after spin-up (offset in global NBP  $< 0.1 \text{ PgC yr}^{-1}$  and drift  $< 0.05 \text{ PgC yr}^{-1}$  per century), (2) a net land flux over the 1990s within 90% confidence of constraints by global atmospheric and oceanic observations, and (3)  $f_{LULCC}$  as a C source to the atmosphere over the 1990s (Friedlingstein et al., 2019).

### 2.1 Models and simulations

We use twelve TRENDY v8 DGVMs that provide gridded output of NBP with and without LULCCs under both transient (historically observed) and pre-industrial (constant) environmental conditions (called S0, S2, S3, S4 in the TRENDY v8 protocol; [compare see](#) Table 1), to calculate the LASC on a regional level (see Table 2 for a comparison of [the model output and](#) relevant processes included in the DGVMs, additional information can be found in Table A1 in Friedlingstein et al. 2019). [Note, for SDGVM, model output from TRENDY v9 was used due to erroneous merging of land cover and LULCC datasets in earlier versions that caused a C loss over the period  \$\sim 1900\$ – \$1970\$  mainly in semi-arid regions.](#) For eight models that provided simulations under constant present-day environmental forcing (S5, S6),  $f_{LULCC}$  was also calculated under present-day environmental conditions. All TRENDY v8 simulations were started in 1700 after C stocks reached equilibrium with environmental conditions in the models, to enable reproducible results with minimized initialization effects for the analyzed time period starting 1850. This implies two separate spin-ups, one for simulations conducted under present-day environmental conditions (S5, S6) and one for those starting from or keeping pre-industrial conditions (all others).

The DGVM simulations with observed transient environmental conditions used observation-based temperature, precipitation, and incoming surface radiation data at  $0.5 \times 0.5$  degree spatial resolution of the Climatic Research Unit (CRU) and

**Table 1.** Overview of the TRENDY v8 DGVMs simulations used ~~and of selected processes included relevant for  $f_{LULCC}$~~ . Additionally indicated is if a plausible derivation of the Environmental Equilibrium Difference in our study, comprising transient (EED observed historical evolution), compare Eq. 5 and Sect. 2.2.1 pre-industrial or present-day (constant) and ‘Present-day’ vs ‘Transient’ forcing for environmental conditions Difference (PTD such as climate and atmospheric CO<sub>2</sub> concentrations), compare Eq and transient or fixed pre-industrial land use/cover distribution (with an additional description of their purpose of use). ~~6 For the underlying forcing data and Sect~~ protocol, refer to Friedlingstein et al. (2019). ~~2.2.1) was possible~~ All runs were performed within the TRENDY v8 efforts for the GCB2019.

<u>Simulation</u>	<u>Climate</u>	<u>Wood CO<sub>2</sub> concentration</u>	<u>Shifting-LULCC forcing</u>	<u>Purpose</u>
<u>S0</u>	<u>pre-ind.</u>	<u>pre-ind.</u>	<u>pre-ind.</u>	<u>control to S4</u>
<u>S1</u>	<u>pre-ind.</u>	<u>observed</u>	<u>pre-ind.</u>	<u>vs S0: isolation of CO<sub>2</sub>/Ndepo effects</u>
<u>S2</u>	<u>observed</u>	<u>observed</u>	<u>pre-ind.</u>	<u>control to S3; vs S1: isolation of climate effects</u>
<u>S3</u>	<u>observed</u>	<u>observed</u>	<u>LUH2/HYDE</u>	<u>S2-S3: <math>f_{LULCC}</math> under transient env.</u>
<u>S4</u>	<u>pre-ind.</u>	<u>pre-ind.</u>	<u>LUH2/HYDE</u>	<u>S0-S4: <math>f_{LULCC}</math> under pre-ind. env.</u>
<u>S5</u>	<u>pres.-day</u>	<u>pres.-day</u>	<u>LUH2/HYDE</u>	<u>S6-S5: <math>f_{LULCC}</math> under pres.-day env.</u>
<u>S6</u>	<u>pres.-day</u>	<u>pres.-day</u>	<u>pre-ind.</u>	<u>control to S5</u>

**Table 2.** Overview of the TRENDY v8 DGVM model output provided and used in this study and of selected processes included relevant for  $f_{LULCC}$ . Additionally indicated is if a plausible derivation of the Environmental Equilibrium Difference (EED, Eq. 5 and Sect. 2.2.1) and ‘Present-day’ vs ‘Transient’ environmental conditions Difference (PTD, Eq. 6 and Sect. 2.2.1) was possible.

<u>Model</u>	<u>Reference</u>	<u>Wood harvest &amp; forest degradation</u>	<u>Shifting cultivation &amp; sub-grid-scale transitions</u>	<u>Irrigation</u>	<u>N Fertilisation</u>	<u>EED &amp; PTD</u>	<u>Spatial resolution</u>	<u>Temporal resolution</u>
CLASS-CTEM	Melton and Arora (2016)	no	no	no	no	yes	<u><math>2.79^\circ \times 2.79^\circ</math></u>	<u>monthly</u>
CLM5.0	Lawrence et al. (2019)	yes	yes	yes	no	no	<u><math>0.9^\circ \times 1.25^\circ</math></u>	<u>monthly</u>
DLEM	Tian et al. (2015)	yes	no	yes	yes	yes	<u><math>0.5^\circ \times 0.5^\circ</math></u>	<u>yearly</u>
JSBACH	Mauritsen et al. (2019)	yes	yes	no	no	yes	<u><math>1.875^\circ \times 1.875^\circ</math></u>	<u>monthly</u>
JULES-ES 1.02	Sellar et al. (2019)	yes	no	no	yes	no	<u><math>1.25^\circ \times 1.875^\circ</math></u>	<u>yearly</u>
LPJ-GUESS	Smith et al. (2014)	yes	yes	yes	yes	yes	<u><math>0.5^\circ \times 0.5^\circ</math></u>	<u>yearly</u>
LPJ	Poulter et al. (2011)	yes	yes	no	no	no	<u><math>0.5^\circ \times 0.5^\circ</math></u>	<u>monthly</u>
LPX-Bern	Lienert and Joos (2018)	no	no	no	yes	yes	<u><math>0.5^\circ \times 0.5^\circ</math></u>	<u>monthly</u>
OCN	Zachle et al. (2011)	yes	no	no	yes	no	<u><math>0.5^\circ \times 0.5^\circ</math></u>	<u>monthly</u>
ORCHIDEE	Krinner et al. (2005)	yes	no	no	no	yes	<u><math>0.5^\circ \times 0.5^\circ</math></u>	<u>monthly</u>
ORCHIDEE-CNP	Goll et al. (2017)	no	no	no	yes	yes	<u><math>2^\circ \times 2^\circ</math></u>	<u>monthly</u>
SDGVM	Walker et al. (2017)	no	no	no	no	yes	<u><math>1^\circ \times 1^\circ</math></u>	<u>yearly</u>

Japanese Reanalysis (JRA; Friedlingstein et al. 2019; Harris et al. 2014). Annual time series of global atmospheric CO<sub>2</sub> concentrations for 1700–2018 was derived from ice core data (before 1958; Joos and Spahni 2008) merged with National Oceanic and Atmospheric Administration (NOAA) data (from 1958 onward; Dlugokencky and Tans 2020). Models used ~~the HYDE~~ land-use change data ~~set from the History Database of the Global Environment (HYDE)~~ which provides annual, half-degree, fractional data on cropland, rangeland and pasture areas based on annual ~~FAO statistics (Klein Goldewijk et al., 2017; Goldewijk et al., 2017) statistics of the Food and Agriculture Organization of the United Nations (FAO; Klein Goldewijk et al. 2017; Goldewijk et al. 2017)~~ or the updated harmonised land-use change data (LUH2; Hurtt et al. 2011, 2020). While HYDE agricultural areas are used in LUH2, the main difference lies in LUH2 additionally adding wood harvest from the Global Forest Resources Assessments of the FAO and sub-grid-scale (‘gross’) transitions to capture shifting cultivation in the tropics.

For pre-industrial simulations, the CO<sub>2</sub> concentration and LULCC data from 1700 ~~, and nitrogen fertilization and deposition data from 1860 (no earlier data available) were applied. Climate were applied, and climate~~ was derived by recycling the mean and variability from 1901–1920. For present-day simulations, the CO<sub>2</sub> concentration from 2018 ~~and average nitrogen deposition from 1999–2018~~ were taken constant, and climate was derived by recycling the mean and variability from 1999–2018.

## 2.2 Data processing

### 2.2.1 Three alternative $f_{LULCC}$ estimates and their differences

We ~~estimate infer the~~ three different DGVM-based  $f_{LULCC}$ s ~~as each from the~~ differences in NBP of a simulation with and one without LULCCs (~~compare~~ Eq. 1 to 3, ~~see Table 1 for description of simulations S0 to S6 and Fig. 1 for a schematic of resulting carbon fluxes~~). For example, we derive the  $f_{LULCC}$  under transient environmental conditions by subtracting NBP in S3 from NBP in S2 (Eq. 1). Using yearly aggregated NBP values,  $f_{LULCC}$  is derived for each DGVM, time step and grid cell under transient (subscript *trans*), constant pre-industrial (*pi*), and constant present-day (*pd*) environmental conditions from the TRENDY v8 simulations as follows:

$$f_{LULCC\_trans} = \frac{NBP_{S2} - NBP_{S3}}{NBP_{S2} - NBP_{S3}} \quad (\text{Eq. 1})$$

$$f_{LULCC\_pi} = \frac{NBP_{S0} - NBP_{S4}}{NBP_{S0} - NBP_{S4}} \quad (\text{Eq. 2})$$

$$f_{LULCC\_pd} = \frac{NBP_{S6} - NBP_{S5}}{NBP_{S6} - NBP_{S5}} \quad (\text{Eq. 3})$$

~~A~~ Here, a lower NBP in the simulation including ~~LULCCs~~  $f_{LULCC}$  (S3 to S5) compared to the one excluding ~~LULCCs~~  $f_{LULCC}$  (control, S0 to S2 and S6) represents a net flux of CO<sub>2</sub> out of the terrestrial biosphere into the atmosphere



190 (emissions) due to ~~LULCCs causing LULCC causing reduced C uptake or~~ C losses. Conversely, a higher NBP in the simulation including LULCCs relates to a net flux from the atmosphere into the biosphere due to LULCCs that enhanced C uptake.

~~Illustration of the different  $f_{LULCC}$  estimations and their differences. The altered sizes of trees (box 1) indicate that vegetation responds to the historical trends in environmental conditions (such as increased CO<sub>2</sub> levels and global warming). Historically and globally environmental changes led to an increase in land C stocks, therefore present-day environmental conditions are associated with taller trees in our scheme. When a LULCC occurs that reduces C stocks (box 2) the higher C stocks will cause a higher  $f_{LULCC}$  (box 3: red line higher than blue line; yellow line increasing with time).  $f_{LULCC}$  is derived by subtracting net biome productivity from a simulation without LULCCs from one with LULCCs. Additionally, the different  $f_{LULCC}$  estimations can be compared to each other (box 4): the Loss of Additional Sink Capacity (LASC; compare Eq. 4), Environmental Equilibrium Difference (EED, compare Eq. 5) and ‘Present-day’ vs ‘Transient’ environmental conditions Difference (PTD, compare Eq. 6).~~

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As outlined in the introduction, the derivation of  $f_{LULCC\_trans}$  (Eq. 1; definition as used for uncertainty assessment in the [GCBGCB2019](#); Friedlingstein et al. 2019) inherently includes the LASC. The LASC represents theoretical emissions resulting from transient alterations of environmental conditions since the beginning of the simulation runs (historical changes in climate, atmospheric CO<sub>2</sub> and N deposition, the latter for models including N-cycling), and thus, can be quantified with reference to  $f_{LULCC\_pi}$ , fluxes which would have occurred if pre-industrial environmental conditions prevailed during and after the time LULCCs occurred (Eq. 4; e.g. Strassmann et al. 2008; Pongratz et al. 2009; Gitz and Ciais 2003; Gasser et al. 2020).

205

$$\begin{aligned} \underline{LASC} &= \underline{f_{LULCC\_trans} - f_{LULCC\_pi}} \\ &= \underline{(NBP_{S2} - NBP_{S3}) - (NBP_{S0} - NBP_{S4})} \end{aligned}$$

210  $\underline{LASC = f_{LULCC\_trans} - f_{LULCC\_pi} = (NBP_{S2} - NBP_{S3}) - (NBP_{S0} - NBP_{S4})}$  (Eq. 4)

The LASC hinders comparison of  $f_{LULCC\_trans}$  with flux estimates based on present-day environmental conditions ( $f_{LULCC\_pd}$ ). Per definition, the latter represent the closest approximation of bookkeeping fluxes and recent C density observations via DGVMs. Therefore, we compare  $f_{LULCC\_trans}$  and  $f_{LULCC\_pd}$  to determine times and regions that are most sensitive to the differences introduced when DGVM-derived  $f_{LULCC\_trans}$  is jointly used with bookkeeping estimates, as in the [GCBGCB2019](#). We call this the ‘Present-day’ vs ‘Transient’ environmental conditions Difference (PTD) and derive it according to Eq. 5:

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$$\begin{aligned} \underline{PTD} &= \underline{f_{LULCC\_pd} - f_{LULCC\_trans}} \\ &= \underline{(NBP_{S6} - NBP_{S5}) - (NBP_{S2} - NBP_{S3})} \end{aligned}$$

$\underline{PTD = f_{LULCC\_pd} - f_{LULCC\_trans} = (NBP_{S6} - NBP_{S5}) - (NBP_{S2} - NBP_{S3})}$  (Eq. 5)

220 It is not clear even at global scale if PTD is negative or positive. On the one hand,  $f_{LULCC\_pd}$  can be higher than  $f_{LULCC\_trans}$  because C stocks had been brought into equilibrium with present-day conditions during spin-up, i.e. ecosystems had time to equilibrate with high CO<sub>2</sub> levels, implying more biomass and higher soil C stocks being affected by – historically prevalent – deforestation. On the other hand, the LASC accumulates over time (Sect. 1 and Fig. 1 for illustration) and therefore  $f_{LULCC\_trans}$  could become larger than  $f_{LULCC\_pd}$ . This difference is assumed to be particularly pronounced in former forested areas under  
 225 beneficial environmental conditions over the past where LULCCs happened early, as here the LASC could accumulate for a long time (high sensitivity of forest productivity to rising CO<sub>2</sub> in DGVMs, compare e.g. Peng et al. 2014).

LASC and PTD add up to the difference of  $f_{LULCC\_pd}$  and  $f_{LULCC\_pi}$ . The latter two are derived under constant environmental forcing, meaning that both are indifferent to [the timing of LULCCs and their legacy effects \(compare long-term environmental trends \(see Fig. 1 for illustration\)\)](#). However, the choice of the time period from which constant environmental conditions are  
 230 taken is arbitrary. Nonetheless, comparison of these two simulations is interesting, as they span the minimum and maximum range of assumptions on environmental conditions that would make sense to consider under typical industrial-era simulations. Up to now, no comparison of  $f_{LULCC\_pi}$  with  $f_{LULCC\_pd}$  exists in the literature, which is why we derive their difference and introduce it as the Environmental Equilibrium Difference (EED; [compare Eq. 6](#)):

$$\begin{aligned}
 \underline{EED} &= \underline{f_{LULCC\_pd} - f_{LULCC\_pi}} \\
 235 \quad &= \underline{(NBP_{S6} - NBP_{S5}) - (NBP_{S0} - NBP_{S4})}
 \end{aligned}$$

$$\underline{EED = f_{LULCC\_pd} - f_{LULCC\_pi} = (NBP_{S6} - NBP_{S5}) - (NBP_{S0} - NBP_{S4})} \quad (\text{Eq. 6})$$

Twelve TRENDY v8 DGVMs were compared regarding  $f_{LULCC\_pi}$ ,  $f_{LULCC\_trans}$  and LASC.  $f_{LULCC\_pd}$  (consequently also EED and PTD) could not be derived for CLM5.0, JULES, LPJ and OCN (no S5 and S6 simulation; eight models). A discussion  
 240 on the performance of individual models can be found in the appendix [section \(Sect. A1\)](#).

To get an insight into the spatial trends and drivers of the three DGVM-derived  $f_{LULCC}$  estimates and their differences, a regional analysis was conducted based on the [REgional Carbon Cycle Assessment and Processes', Phase 2 \(RECCAP2\)](#) regions defined in Tian et al. (2019) and shown in Fig. A2. Since all global and regional analyses were performed based on the original model output, the RECCAP2 map was regridded to each model's native resolution using largest area fraction remapping (to  
 245 compare globally summed NBP in this study and in the GCB2019, refer to Supplementary Fig. A13). Note, for grid point-wise comparison, all model output was regridded to 720 × 360 grid boxes using first-order conservative remapping (Jones, 1999).

Due to high interannual NBP variability, the resulting regional and global  $f_{LULCC}$  estimates were smoothed by a Savitzky–Golay filter using 5% of the spatially summed annual data points (16 years). Savitzky–Golay smoothing was applied to preserve peak heights and widths which are known to be removed by other smoothing practices such as moving averages.

250 All data pre-processing and statistical analysis was performed using Climate Data Operator software (CDO, v1.9.3; Schulzweida 2019), netCDF Operators (NCO, v4.7.7; Rew et al. 1997), and raster- (v2.8-4; Hijmans and van Etten 2014), ncd4- (v1.16.1;

Pierce 2019), matrixStats- (v0.56.0; Bengtsson et al. 2020), and pracma- (v2.2.9; Borchers 2019) packages of the CRAN R universe (v3.4.4; R Core Team 2018).

### 2.2.2 Relative climate- vs CO<sub>2</sub>-induced $f_{LULCC}$ components

255 Climate change-related environmental alterations might increase or decrease NBP over time (compare Sect. 1), and thus, cause higher or lower  $f_{LULCC\_trans}$  and  $f_{LULCC\_pd}$  compared to  $f_{LULCC\_pi}$  or bookkeeping estimates. While increasing CO<sub>2</sub> concentrations are assumed to generally increase C stocks across the globe, alterations by other environmental changes (mainly precipitation- and temperature-related) are more heterogeneous. To gain knowledge about the underlying environmental drivers [for changes in  \$f\_{LULCC}\$  quantities](#), this study aims to separate between [their](#) climate- and CO<sub>2</sub>-induced components [of  \$f\_{LULCC}\$](#) .  
260 We approximate them using S1 and S2 simulations, which differ only with respect to inclusion of climatic changes (Table 1). [Assuming These simulations do not include transient LULCCs and can therefore not directly be used to estimate the climate vs CO<sub>2</sub> related alteration of  \$f\_{LULCC}\$ . However, assuming](#) that the proportions of climate- [versus vs](#) CO<sub>2</sub>-induced C [stocks-stock](#) changes (we use the total C stocks in vegetation and soil, cTot) translate linearly into the CO<sub>2</sub>-induced  $f_{LULCC\_trans}$  component at each grid cell ( $f_{LULCC\_CO_2}$ ), we derive the latter based on the ratio of cTot in S1 to S2 simulations (Eq. 7). The validity of this  
265 approach is supported by  $f_{LULCC}$  in many regions correlating well with biomass stocks across models (Li et al., 2017). Thus, although LULCCs may affect C stocks with different strengths – based on the extent, practice and local ecosystem conditions (including C stock distribution) – it seems appropriate to assume that  $f_{LULCC}$  is not independent from the environmental driver of C stock changes.

$$f_{LULCC\_CO_2} = f_{LULCC\_trans} \times (cTot_{S1}/cTot_{S2}) \quad (\text{Eq. 7})$$

270 Ratios of cTot were derived based on the annual averages in the last decade of the simulation period across all models (2009–2018). Due to generally increased differences and ratios of cTot<sub>S1</sub> and cTot<sub>S2</sub> over the simulated period ([compare Fig. A1](#)), our  $f_{LULCC\_CO_2}$  provides the maximum possible contribution of CO<sub>2</sub>-induced change in  $f_{LULCC}$ . [Here we note, interacting effects of elevated CO<sub>2</sub> concentrations and temperature or precipitation on biomass productivity \(observed under experimental setups; e.g. Obermeier et al. 2017\) might obscure this attribution \(Lombardozzi et al., 2018\). Nevertheless, the assessment of](#)  
275 [the relative contribution as done by this approach seems valid as no significant interactions between these influencing factors on C stocks were observed within the TRENDY ensemble \(Fernández-Martínez et al., 2019\) nor within a fully coupled single model investigation \(Devaraju et al., 2016\).](#)

C stocks from LPX-Bern and CLM5.0 were excluded from derivation of multi-model mean C stocks due to very high values in particular in high latitudes of the Northern Hemisphere due to inclusion of peatlands (for LPX-Bern, compare Spahni et al.  
280 2013). C stock outliers smaller than zero were excluded.

As no TRENDY v8 control simulation with pre-industrial LULCC and CO<sub>2</sub> concentrations and observed (transient) climate exists, we indirectly assess the climate-only  $f_{LULCC}$  component ( $f_{LULCC\_Climate}$ ; Eq. 8). [Synergies-Note, by subtracting  \$f\_{LULCC\\_CO\_2}\$  from the total  \$f\_{LULCC}\$  to derive the climate-only flux shares, this approach assumes zero synergies](#) between effects

of CO<sub>2</sub> concentrations and climatic changes on  $f_{LULCC\_NBP}$  in the DGVMs ~~are assumed zero in this case~~. While in reality they may be substantial (e.g. increased water use efficiency due to stomatal closure under elevated CO<sub>2</sub>), it is beyond the possibilities of available data to quantitatively assess these synergistic effects.

$$\begin{aligned} \underline{f_{LULCC\_Climate}} &= \underline{f_{LULCC\_Climate} - f_{LULCC\_CO_2}} \\ &= \underline{f_{LULCC\_trans} - f_{LULCC\_trans} \times (c_{TotS1}/c_{TotS2})} \end{aligned}$$

$$290 \quad \underline{f_{LULCC\_Climate} = f_{LULCC\_trans} - f_{LULCC\_CO_2} = f_{LULCC\_trans} - f_{LULCC\_trans} \times (c_{TotS1}/c_{TotS2})} \quad (\text{Eq. 8})$$

Note, ~~this climate impact roughly represents the trend in the last hundred years as within the TRENDY v8 simulations~~, pre-industrial and present-day climate ~~conditions are the recycled climate~~ forcing is defined as a recycling of climates in the earliest decades of the 20th and 21st century, respectively (see Sect. 1). ~~Consequently, the climate change impact derived in this study roughly represents the last hundred years, which seems a reasonable approximation of the history, given that~~ for example proxy-based temperature reconstructions cannot detect a warming earlier than the beginning of 20th century (Hegerl et al., 2019).

### 3 Results and discussion

#### 3.1 Differences in $f_{LULCC}$ estimates on global scale

A general overview of most recent annual and cumulative estimates of  $f_{LULCC}$  shows that our estimates are in good agreement to the published ones (Friedlingstein et al. 2019; Gasser et al. 2020; Tables 4-3 to 6). Slight differences (<0.1 PgC yr<sup>-1</sup>) between  $f_{LULCC\_trans}$  derived in this study and the DGVM-derived GCB2019 estimates are attributable to the fact that we used only a subset ( $n = 12$ ) of the models analyzed within the GCB2019 ( $n = 15$ ), to consistently use the same models ~~for the flux and bias estimates on a spatio-temporal level, where possible~~ where possible. Additionally, the inclusion of TRENDY v9 model output for SDGVM (for reasons refer to Sect. 2) caused, for example, a lower LASC of 0.8 PgC yr<sup>-1</sup> for 2009–2018 in this study (0.84 PgC yr<sup>-1</sup> with two decimal places) as compared to consistently using TRENDY v8 output, where the resulting LASC (usually rounded to one decimal place) is 0.9 PgC yr<sup>-1</sup> due to rounding of 0.85 PgC yr<sup>-1</sup>.

As expected (Sect. 1),  $f_{LULCC\_pd}$  is the DGVM-based  $f_{LULCC}$  estimate that is most similar to the bookkeeping mean in the GCB2019 when compared over multiple years. The LASC explains the relatively high difference of  $f_{LULCC\_trans}$  to the bookkeeping estimates in the GCB2019 and by Gasser et al. (2020), since ~~bookkeeping-bookkeeping~~ models, by their nature, do not include the LASC. Lower LASC estimates in the GCB2019 compared to our findings are based on an early version of the reduced-complexity Earth system model OSCAR which was constrained to the land sink without LULCC perturbation as estimated by DGVMs (Gasser and Ciais, 2013; Gasser et al., 2017). Later revised OSCAR versions, constrained to the net

**Table 3.** Overview of global annual  $f_{LULCC}$  estimates and their differences (Loss of Additional Sink Capacity, LASC; ‘Present-day’ vs ‘Transient’ environmental conditions Difference, PTD; Environmental Equilibrium Difference, EED) for the time period 2009–2018. Mean and standard deviation refer to the DGVM model ensemble.

$f_{LULCC}$ formula	Mean $\pm$ 1SD (PgC yr <sup>-1</sup> )	Differences formula	Mean $\pm$ 1SD (PgC yr <sup>-1</sup> )
$f_{LULCC\_trans} = NBP_{S2} - NBP_{S3}$	2.0 $\pm$ 0.6	LASC = $f_{LULCC\_trans} - f_{LULCC\_pi}$	0.8 $\pm$ 0.3
$f_{LULCC\_pi} = NBP_{S0} - NBP_{S4}$	1.2 $\pm$ 0.4	EED = $f_{LULCC\_pd} - f_{LULCC\_pi}$	0.5 $\pm$ 0.3
$f_{LULCC\_pd} = NBP_{S6} - NBP_{S5}$	1.6 $\pm$ 0.7	PTD = $f_{LULCC\_pd} - f_{LULCC\_trans}$	-0.3 $\pm$ 0.4

land flux as residual from fossil emissions, atmospheric growth, and the ocean sink, yielded higher LASC estimates (more similar to our study; Gasser et al. 2020). ~~Note, the LASC of 0.8 PgC yr<sup>-1</sup> (0.84 PgC yr<sup>-1</sup>) presented here is an estimate based on the TRENDY v8 model output combined with newer (TRENDY v9) output from SDGVM model (erroneous code in earlier versions caused a C loss over the period ~1900-1970 mainly in semi-arid regions), while consistently using TRENDY v8 model output even results in a higher LASC of 0.9 PgC yr<sup>-1</sup> (0.85 PgC yr<sup>-1</sup>).  $f_{LULCC\_pd}$  is the DGVM-based  $f_{LULCC}$  estimate that is most similar to bookkeeping results as expected (Sect. 1).~~

**Table 4.** Overview of global annual  $f_{LULCC}$  estimates from this study, the ensemble of all 15 DGVMs and of two bookkeeping models (BLUE and H&N2017) from the annual global carbon budget (GCB2019; Friedlingstein et al. 2019), plus another recent bookkeeping estimate (Gasser et al., 2020). Emissions from peat fire and drainage were removed from the bookkeeping estimates to be better comparable to the DGVMs. Note that the error estimate of GCB2019’s bookkeeping estimate of 0.7 PgC yr<sup>-1</sup> is an expert judgement, not direct model output. Minimum, maximum and mean with standard deviation refer to the model ensemble.

Source	annual $f_{LULCC}$ (PgC yr <sup>-1</sup> )					
	2018			2009–2018		
	Min	Mean $\pm$ 1SD	Max	Min	Mean $\pm$ 1SD	Max
$f_{LULCC\_trans}$	1.5	2.4 $\pm$ 0.6	3.4	0.8	2.0 $\pm$ 0.6	3.4
$f_{LULCC\_pi}$	0.9	1.5 $\pm$ 0.5	2.4	0.5	1.2 $\pm$ 0.4	2.4
$f_{LULCC\_pd}$	1.2	2.0 $\pm$ 0.8	3.5	0.7	1.6 $\pm$ 0.7	3.5
GCB2019 – DGVMs	–	2.3 $\pm$ 0.6	–	–	2.0 $\pm$ 0.5	–
GCB2019 – bookk. models	0.7	1.5 $\pm$ 0.7	2.1	1.0	1.5 $\pm$ 0.7	1.8
Gasser et al. 2020	–	1.4 $\pm$ 0.4	–	–	1.4 $\pm$ 0.4	–

~~Multi-model means of smoothed global annual values (upper row) and cumulative sums (lower row) of  $f_{LULCC}$  estimates, the Loss of Additional Sink Capacity (LASC), the ‘Present-day’ vs ‘Transient’ environmental conditions Difference (PTD), the Environmental Equilibrium Difference (EED), and the relative contributions of LASC and EED to  $f_{LULCC\_trans}$  and  $f_{LULCC\_pd}$~~

**Table 5.** Overview of global annual LASC estimates from this study, Friedlingstein et al. 2019 (GCB2019) and Gasser et al. 2020. LASC estimates from GCB2019 and Gasser et al. 2020 are based on two different versions of OSCAR, which is constrained by DGVM estimates. Minimum, maximum and mean with standard deviation refer to the model ensemble.

Published in	annual LASC (PgC yr <sup>-1</sup> )								
	2018			2005-2014			2009-2018		
	Min	Mean ± 1SD	Max	Min	Mean ± 1SD	Max	Min	Mean ± 1SD	Max
This study	0.5	0.9 ± 0.3	1.4	0.1	0.7 ± 0.3	1.4	0.2	0.8 ± 0.3	1.4
GCB2019	-	-	-	-	0.4 ± 0.3	-	-	-	-
Gasser et al. 2020	-	0.8 ± 0.6	-	-	-	-	-	0.7 ± 0.6	-

325 respectively from 1800 to 2018. Additionally,  $f_{LULCC}$  from the bookkeeping models BLUE and H&N2017 as well as their average is plotted (data for GCB2019; not shown for cumulative sums due to shorter data coverage). For absolute values from this study also the 95% confidence intervals are shown. See Figs. 3 and 4 for individual model's results for  $f_{LULCC}$  estimates and their differences, respectively.

A closer look at the historical evolution of the three global  $f_{LULCC}$  estimates reveals similarities, despite the substantial differences in their annual and cumulative quantities shown before. In particular, trends remain similar over time, with an increase since the start of the simulations peaking in the 1950s and in again at the end of the simulation period (see multi-model means in Fig(Figs. 2a and 3a,b,c)). Congruent patterns of  $f_{LULCC\_pd}$  and bookkeeping mean values highlight the validity of our  
330 approach to investigate regions that are most sensitive towards choice of transient DGVM- vs bookkeeping-based estimates -(Figs. 2a and 3c). A widely congruent trend was also found across the DGVMs, while their absolute values partly differ strongly across models, for example global  $f_{LULCC\_trans}$  and  $f_{LULCC\_pi}$  from OCN is largely higher than in the other models, with estimates more than twice as large as the one from ORCHIDEE and LPX-Bern (Fig. 3a,b, and Sect. A1 for a discussion on individual model results). Note, a high internal climate variability translates into a high interannual variability in NBP and  
335 consequently a high variability of  $f_{LULCC}$  estimates (Figs. 3, 5 and A13) and of their respective differences (Figs. 4 and 6). For the differences in  $f_{LULCC}$  estimates some artefact might additionally arise due to comparison of simulations with different forcing cycles (e.g. on global scale, with periodic fluctuations in annual relative shares of EED to  $f_{LULCC\_pd}$  in Fig. 2c and, on regional scale, in Figs. 6 and A4 to A6 with pronounced oscillations in some regions).

340 Throughout the 19th century, no hardly any differences are found between  $f_{LULCC\_trans}$  and  $f_{LULCC\_pi}$  (i.e. LASC around zero, FigFigs. 2ba,b,c,d and 4a,d) indicating a negligible impact from environmental changes (i.e. CO<sub>2</sub> concentrations and climate). In line with this, the constantly higher and faster increasing annual and cumulative  $f_{LULCC\_pd}$  (concomitantly PTD and EED, FigFigs. 2b,ea,b,d,e and 4b,c,e,f) can be explained by higher C stocks due to their equilibration to present-day conditions rather than pre-industrial ones (compare-see Fig. 8 for historical C stock changes in the transient simulation). Similarly, the  
345 higher bookkeeping mean values compared to  $f_{LULCC\_trans}$  and  $f_{LULCC\_pi}$  up to the 1950s are attributable to their use of recent

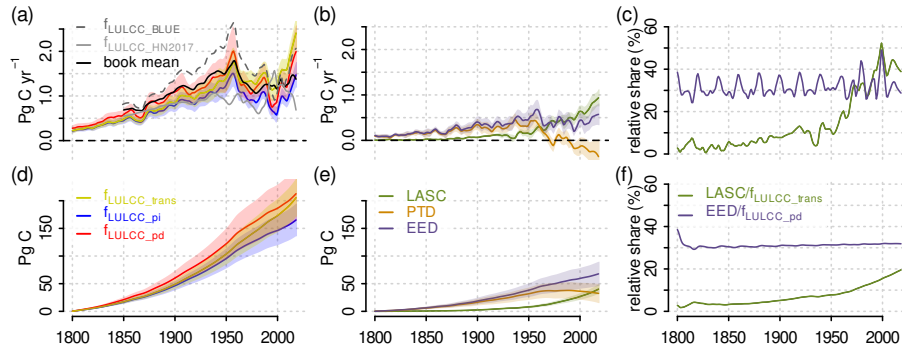
**Table 6.** Overview of global cumulative  $f_{LULCC}$  and LASC estimates from this study, the ensemble of 15 DGVMs and of two bookkeeping models (BLUE (Hansis et al., 2015) and Houghton and Nassikas (2017)) from the annual global carbon budget (GCB2019, Friedlingstein et al. 2019), plus another recent bookkeeping estimate (Gasser et al., 2020). Emissions from peat fire and drainage were removed from the bookkeeping estimates to be better comparable to the DGVMs. Note that mean cumulative GCB2019 estimates are based on bookkeeping models, while their uncertainty is derived from DGVMs. LASC estimates from GCB2019 and Gasser et al. (2020) are based on two different versions of OSCAR, which is constrained by DGVM estimates. Minimum, maximum and mean with standard deviation refer to the model ensemble.

Published in	cumulative $f_{LULCC}$ (PgC)						
	1750–2018			1850–2018			
	Min	Mean $\pm$ 1SD	Max	Min	Mean $\pm$ 1SD	Max	
This study, $f_{LULCC\_trans}$	118	215 $\pm$ 63	336	106	189 $\pm$ 56	290	
This study, $f_{LULCC\_pi}$	83	175 $\pm$ 55	287	72	149 $\pm$ 47	242	
This study, $f_{LULCC\_pd}$	147	224 $\pm$ 73	336	127	192 $\pm$ 64	292	
GCB2019	–	235 $\pm$ 75	–	–	205 $\pm$ 60	–	
Gasser et al. 2020	–	206 $\pm$ 57	–	–	178 $\pm$ 50	–	
Published in	cumulative LASC (PgC)						
	This study	11	40 $\pm$ 15	65	11	40 $\pm$ 15	64.0
	GCB2019	–	–	–	–	20 $\pm$ 15	–
	Gasser et al. 2020	–	32 $\pm$ 23	–	–	31 $\pm$ 22	–

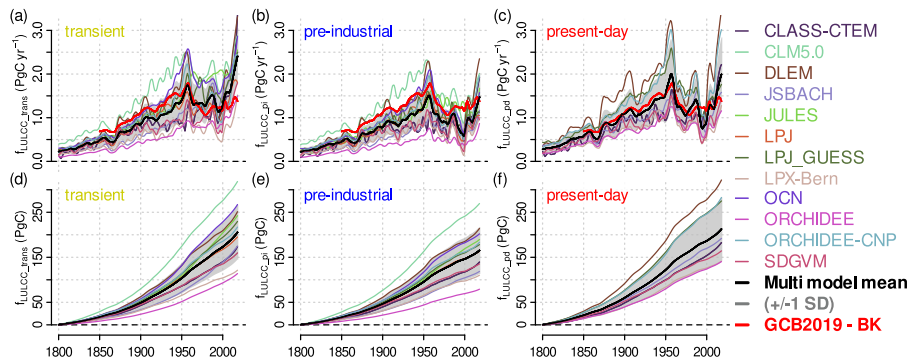
inventory-based C densities (Fig. 2a and 3a,b).

By the end of 19th century, annual and cumulative  $f_{LULCC\_trans}$  estimates start to exceed  $f_{LULCC\_pi}$  estimates (Fig. 2a,d). This can be related to higher C stocks due to an accelerated atmospheric CO<sub>2</sub> increase where LULCCs leading to net loss in C stocks occurred (e.g. deforestation). Additionally, the aforementioned nature of the LASC as synergistic effect of changes in environmental conditions and any LULCC that occurred since the simulation start comes to play. As overall into play. In general, beneficial environmental alterations for C sequestration widely increased the potential C stocks (Fig. 8), and thus, the LASC steadily increased (Fig. 2b,e and 4a,d), reaching about ~40% in recent annual and ~20% in cumulative contributions to  $f_{LULCC\_trans}$  (Fig. 2c,f). Despite this LASC increase, global annual and cumulative  $f_{LULCC\_pd}$  estimates still increase faster than the other estimates in the during this period (first half of the 20th century; EED and PTD remain increasing), indicating that synergistic effects of LULCCs with higher C stocks under present-day conditions still outweigh the amount of additional emissions accumulated by the LASC (EED greater LASC represented also by positive PTD values; Figs. 2b and 4c).

In the 1950s, global peaks in annual  $f_{LULCC\_pi}$  and  $f_{LULCC\_pd}$  estimates were observed (Figs. 2a and 3b,c). As these estimates neglect transient environmental conditions and do not include the LASC, these peaks simply relate to a strongly increased



**Figure 2.** Multi-model means of smoothed global annual values (upper row; a,b,c) and cumulative sums (lower row; d,e,f) of  $f_{LULCC}$  estimates (a,d), the Loss of Additional Sink Capacity (LASC; b,c), the ‘Present-day’ vs ‘Transient’ environmental conditions Difference (PTD; b,c), the Environmental Equilibrium Difference (EED; b,c), and the relative contributions of LASC and EED to  $f_{LULCC\_trans}$  and  $f_{LULCC\_pd}$  respectively (c,f) from 1800 to 2018. Additionally,  $f_{LULCC}$  from the bookkeeping models BLUE and H&N2017 as well as their average is plotted (data for GCB2019; not shown for cumulative sums due to shorter data coverage). For absolute values from this study also the 95% confidence intervals are shown. See Figs. 3 and 4 for individual model’s results for  $f_{LULCC}$  estimates and their differences, respectively.

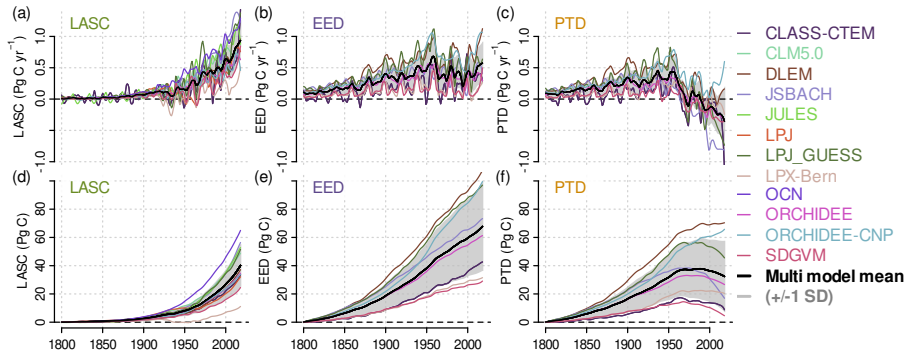


**Figure 3.** Smoothed global annual means (upper row) and cumulative sums (lower row) of  $f_{LULCC\_trans}$  (a&d),  $f_{LULCC\_pi}$  (b&e), and  $f_{LULCC\_pd}$  (c&f) for the investigated DGVMs from 1800 to 2018. For the derivation formulas refer to Eqs. 1 to 3, and for discussion on individual models refer to Sect. A1.  $f_{LULCC\_pd}$  was not derived for CLM5.0, JULES, LPJ and OCN (compare Table 2). For comparison, we also included the GCB2019 bookkeeping mean (same values in all panels).

360 amount of LULCCs depleting C stocks, in particular on C-dense land where historic environmental changes would have highly increased the potential C stocks (compare Fig. 8). The latter is highlighted by the simultaneous peak in EED which **basically in essence** is the intersection of LULCCs with the difference in standing biomass and actual soil C stocks due to altered environmental conditions over the **historic-period-last hundred years** (under pre-industrial **versus** vs present-day environmental conditions) **and is independent from timing of LULCC occurrence**; compare Fig. 2a with Fig. 2b and Sect. 2.2.2).

365





**Figure 4.** Smoothed global annual values (upper row) and their cumulative sums (lower row) of the differences in  $f_{LULCC}$  estimates for the investigated DGVMs from 1800 to 2018: Loss of Additional Sink Capacity (LASC; panel a&d), Environmental Equilibrium Difference (EED; b&e), and ‘Present-day’ vs ‘Transient’ environmental conditions Difference in  $f_{LULCC}$  (PTD; c&f). For the derivation formulas refer to Eqs. 4 to 6, and for discussion on individual models refer to Sect. A1. EED and PTD were not derived for CLM5.0, JULES, LPJ and OCN (compare Table 2).

The LASC becomes particularly evident after the 1950s (Figs. 2b and 4a,d), when the global peak of converted C stocks by LULCCs was passed and a reduced amount of LULCCs decreasing C stocks caused strongly decreased annual  $f_{LULCC_{pi}}$  and  $f_{LULCC_{pd}}$  (and EED) estimates. By contrast,  $f_{LULCC_{trans}}$  decreased only slightly, as the LASC grows largely due to a combination of large areas that have been transformed from natural vegetation to fast-turnover agricultural areas (not least during the 1950s peak in global LULCCs) and CO<sub>2</sub> levels accelerating their increase (Fig. A1). This accelerating increase of the LASC causes annual  $f_{LULCC_{trans}}$  estimates to surpass those of  $f_{LULCC_{pd}}$  starting, for the multi-model mean, around 1960. PTD, as a consequence, becomes small, then negative (a small temporal lag is caused by the reduced subset of models used for PTD derivation). Around the same time, the LASC becomes larger than the EED, indicating that the foregone sinks by LULCCs outweigh the flux changes upon LULCCs under present-day vs pre-industrial environmental conditions post 1950 (with presumably higher estimates from DGVMs as compared to bookkeeping models). These changing differences in  $f_{LULCC}$  estimates over time highlight how sensitive the choice of  $f_{LULCC}$  definition is to considered timescales even on the global scale

~~Overview of global cumulative  $f_{LULCC}$  and LASC estimates from this study, the ensemble of 15 DGVMs and of two bookkeeping models (BLUE (Hansis et al., 2015) and Houghton and Nassikas (2017)) from the annual global carbon budget (GCB2019, Friedlingstein et al. 2019), plus another recent bookkeeping estimate (Gasser et al., 2020). Emissions from peat fire and drainage were removed from the bookkeeping estimates to be better comparable to the DGVMs. Note that mean cumulative GCB2019 estimates are based on bookkeeping models, while their uncertainty is derived from DGVMs. LASC estimates from GCB2019 and Gasser et al. (2020) are based on two different versions of OSCAR, which is constrained by DGVM estimates. Minimum, maximum and mean with standard deviation refer to the model ensemble. (lr)2-7(lr)2-4(lr)5-7Published in Min Mean  $\pm$  1SD Max Min Mean  $\pm$  1SD Max This study,  $f_{LULCC_{trans}}$  118 215  $\pm$  63 336 106 189  $\pm$  56 290 This study,  $f_{LULCC_{pi}}$~~

83-175 ± 55-287-72-149 ± 47-242 This study, (with a relative contribution of EED to  $f_{LULCC\_pd}$  147-224 ± 73-336-127-192 ± 64-292 GCB2019 — 235 ± 75 — 205 ± 60 — Gasser et al. 2020 — 206 ± 57 — 178 ± 50 — (lr)2-7(lr)2-4(lr)5-7 This study 11-40 ± 15-65-11-40 ± 15-64.0 GCB2019 — 20 ± 15 — Gasser et al. 2020 — 32 ± 23 — 31 ± 22 — of ~35%, Fig. 2c,f).

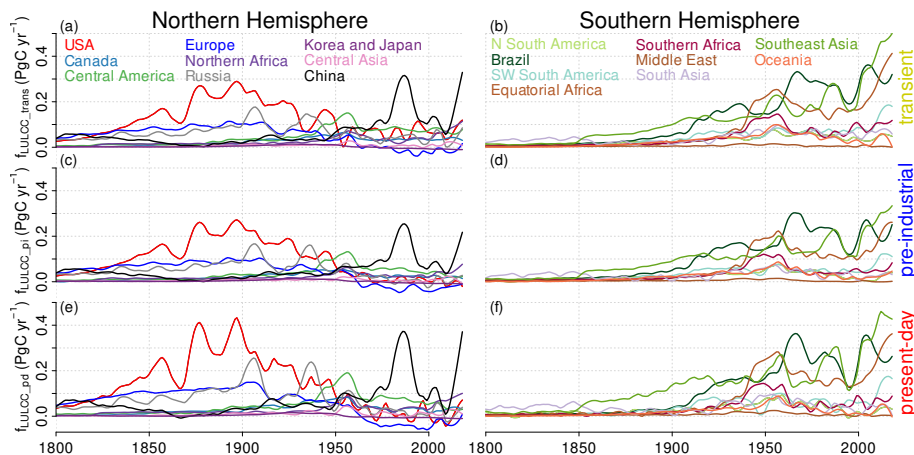
390 Smoothed global annual means (upper row) and cumulative sums (lower row) of  $f_{LULCC\_trans}$  (a&d),  $f_{LULCC\_pi}$  (b&e), and  $f_{LULCC\_pd}$  (c&f) for the investigated DGVMs from 1800 to 2018. For the derivation formulas refer to Eqs. 1, 2 and 3, and for discussion on individual models refer to Sect. A1.  $f_{LULCC\_pd}$  was not derived for CLM5.0, JULES, LPJ and OCN (compare Table 2). For comparison, we also included the GCB2019 bookkeeping mean (same values in all panels):

395 Smoothed global annual values (upper row) and their cumulative sums (lower row) of the differences in  $f_{LULCC}$  estimates for the investigated DGVMs from 1800 to 2018: Loss of Additional Sink Capacity (LASC; panel a,d), Environmental Equilibrium Difference (EED; b,e) and ‘Present-day’ vs ‘Transient’ environmental conditions Difference in  $f_{LULCC}$  (PTD; c, f). For the derivation formulas refer to Eqs. 4, 5 and 6, and for discussion on individual models refer to Sect. A1. EED and PTD were not derived for CLM5.0, JULES, LPJ and OCN (compare Table 2):

### 3.2 Differences in $f_{LULCC}$ estimates on regional level

400 Where does the LASC occur, and which regions are most sensitive towards the investigated DGVM-based  $f_{LULCC}$  definitions (under constant pre-industrial and present-day or transient environmental conditions)? Compared to smoothed global curves, where signals average out, it must be expected that synergistic effects of C stock alterations in combination with the occurrence and timing of LULCCs cause higher differences between the three  $f_{LULCC}$  estimations on regional scale. We assess these differences on a spatio-temporally explicit level using the RECCAP2 regions (Fig. A2) and show regional annual values of  
405 multi-model mean  $f_{LULCC\_trans}$ ,  $f_{LULCC\_pi}$  and  $f_{LULCC\_pd}$  (Fig. 5) and of their differences LASC, PTD and EED in Figures A4 to A6 (with corresponding cumulative estimates (Fig. 6; cumulative estimates are shown in Figs. A10 to A12; for a map refer to Fig. 10) and the underlying annual  $f_{LULCC\_trans}$ ,  $f_{LULCC\_pi}$  and  $f_{LULCC\_pd}$  in the appendix (Figs. A7 to A9; for a map refer to Fig. 10)). Global maps of the cumulative sums and most recent annual mean estimates are shown in Figures 9 and 10; individual model results are discussed in Sect. A1 and shown in Figures A4 to A12.

410 The largest A large sensitivity of cumulative  $f_{LULCC}$  towards choice of pre-industrial vs present-day environmental forcing is found in vast stretches of the eastern USA, Southern Brazil, Eastern Europe to Central Asia, tropical Africa, India, China, across the globe: EED cumulated >8 PgC in the USA (mainly eastern parts), Brazil (mainly southern parts) and Southeast Asia, >5 PgC in Russia, China, Equatorial Africa, Southern Africa, and Southeast Asia >2 PgC in Europe (mainly eastern parts), Southwest South America and South Asia from 1800 until 2018 (Figs. A6 and 10e ). They reflect the areas of 10e and A12).  
415 Strikingly, the last decade saw the tropics to become more dominant in positive EED than other regions due to recent clearings (Figs. 5 and 10f). All these reflect particularly forested areas where LULCCs caused highest  $f_{LULCC}$  (Fig. quantities (Figs. 5 and 9a,c,e; compare increasing deviation of linear model from 1:1 line with higher values) , although there is some variation in the relative contribution of EED to  $f_{LULCC\_pd}$  across regions that the global value of ~35% (Fig. 2c,f) did not reveal (Fig. 7)-



**Figure 5.** Regionwise smoothed multi-model mean annual Loss of Additional Sink Capacity  $f_{LULCC\_IRMS}$  (LASC) (a&b),  $f_{LULCC\_PI}$  (c&d), and  $f_{LULCC\_PD}$  (e&f) in the investigated DGVMs from 1800 to 2018, derived according to EqEqs. 41 to 3. For discussion on individual models refer to Sect. A1 and Figures A7 to A9. The last two panels show regional ensemble means on uniform scale  $f_{LULCC\_PI}$  was not derived for CLM5.0, JULES, LPJ and OCN (Table 2).

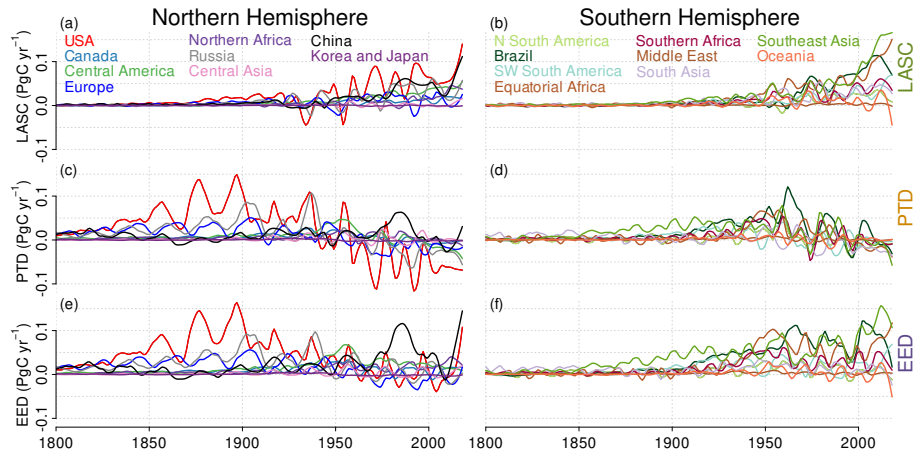
Regionwise smoothed annual ‘Present-day’ vs ‘Transient’ environmental conditions Difference in  $f_{LULCC}$  (PTD) in the used models from 1800 to 2018, derived according to Eq. 5. For discussion on individual models refer to Sect. A1. PTD was not derived for CLM5.0, JULES, LPJ and OCN (compare Table 2). The last two panels show regional ensemble means on uniform scale.

Multi-model means of the relative share of cumulative Environmental Equilibrium Difference (EED) to  $f_{LULCC\_PD}$  from 1800 to 2018. Grid-points with cumulative  $f_{LULCC\_PD} < 0.5$  and  $> 0.5$  were excluded from mapping.

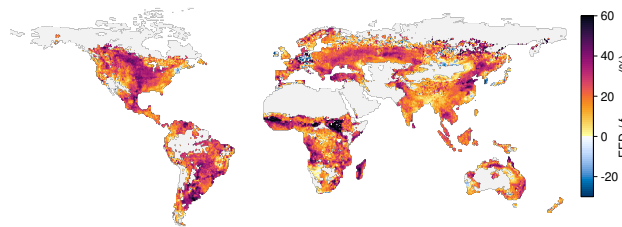
The pattern of LULCC thus dominates the pattern of EED while ecosystem sensitivity to environmental conditions in general seems to play a minor role. Particularly forested regions show due to the conversion of land with high NBP where positive changes in potential C stocks between 1800 and 2018 occurred (Fig. 8) but not all sensitive regions show up in EED, e.g. remote rainforests have (so far) been less affected by clearing than temperate forest regions. The very distinct region

Conversely, very distinct regions of negative cumulative EED in Central Europe (Fig. 10e) reflects relatively increased reflect increased C storage, and thus, a relatively stronger negative  $f_{LULCC\_PI}$  due to early and widespread reforestation causing increased C uptake (Fig. 9e). The associated C uptake with reforestation causes Such a strong C uptake due to reforestation causes also globally wide-spread negative EED values in the last decade (Fig. 10f and 9f). Here we note that; with hotspots in northeastern Brazil, southern Africa and the Eurasian steppe zone), while the poor representation of positive effects of recent large-scale reforestation programs on the with a concomitantly increased C sink in China (Lu et al., 2018; Chen et al., 2019) in the LUH2 data prevents EED (and also  $f_{LULCC}$  estimates) to become negative in the affected regions. More strikingly, the last decade saw the tropics to become more dominant in positive EED than other regions due to recent clearings this region.

Regions, for example remote rain forests, that were only affected little by LULCCs hardly show up in EED. The pattern of EED is thus dominated by the pattern of LULCC with variations due to ecosystem sensitivity (namely in NBP) to environmental



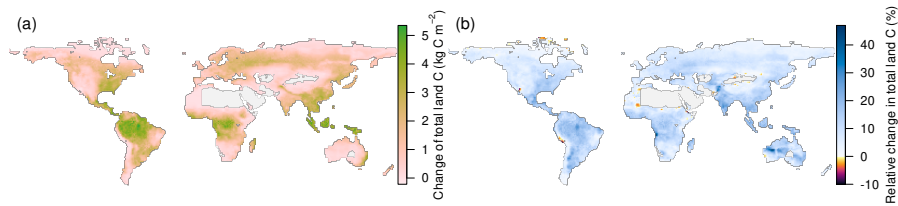
**Figure 6.** Regionwise smoothed multi-model mean annual Loss of Additional Sink Capacity (LASC; a&b), difference between  $f_{LULCC}$  under present-day and pre-industrial environmental conditions (Environmental Equilibrium Difference, EED; c&d), and 'Present-day' vs 'Transient' environmental conditions Difference in the used models- $f_{LULCC}$  (PTD; e&f) from 1800 to 2018, derived according to EqEqs. 4 to 6. For discussion on individual models refer to Sect. A1 and Figures A4 to A6 and A10 to A12. EED-PTD was not derived for CLM5.0, JULES, LPJ and OCN (compare Table 2). The last two panels show regional ensemble means on uniform scale.



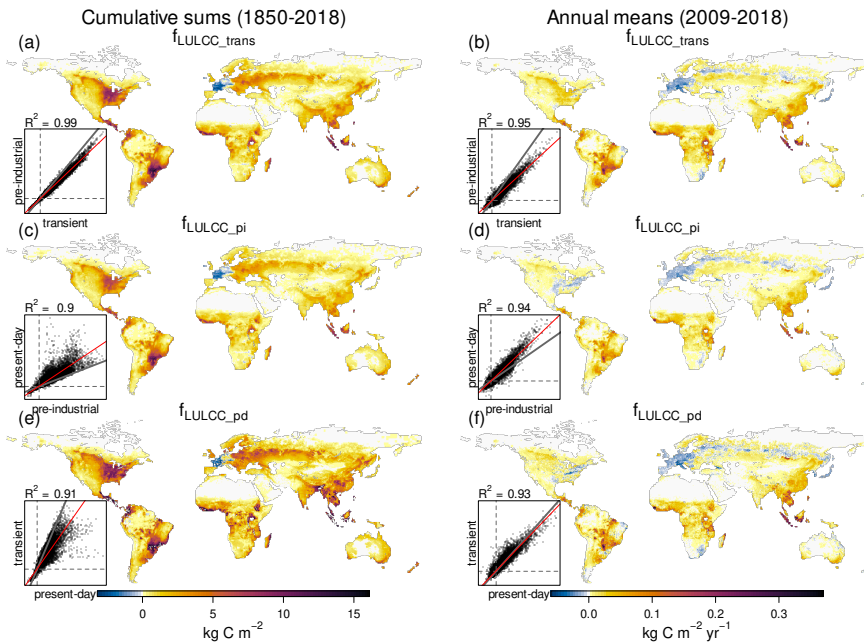
**Figure 7.** Multi-model means of the relative share of cumulative Environmental Equilibrium Difference (EED) to  $f_{LULCC\_pd}$  from 1800 to 2018. Grid points with cumulative  $f_{LULCC\_pd} < 0.5$  and  $> 0.5$  were excluded from mapping.

435 conditions (see Fig. 7). This shows that the choice of pre-industrial vs present-day environmental conditions can play a  
substantial role in regional  $f_{LULCC}$  attribution: EED cumulated  $> 8$  PgC in the USA, Brazil and Southeast Asia,  $> 5$  PgC in  
Russia, China, Equatorial Africa, Southern Africa, and  $> 2$  PgC in Europe, Southwest South America and South Asia from  
1800 until 2018 (Figs. 10e and A12).

440 As seen for the global estimates, the approach to derive  $f_{LULCC}$  under transient environmental conditions introduces even  
more complexity, as it includes the LASC and strongly depends on the timing of LULCCs. In line, PTD undergoes a trend  
reversal with widely negative values in the most recent period in many regions (Figs. 6c,d and 10d), which we discuss in detail  
in the next section.



**Figure 8.** Multi-model means of absolute (a) and relative changes (b) in total carbon stocks ( $c_{Tot}$ ; soil and vegetation carbon combined) from  $\sim 1800$  (average from 1800–1809) until today (average from 2009–2018) in the S2 simulation (including all environmental changes) within the vegetation extent of 1700. Grid points  $< 1 \text{ kg C m}^{-2}$   $c_{Tot}$  in the later period were excluded.

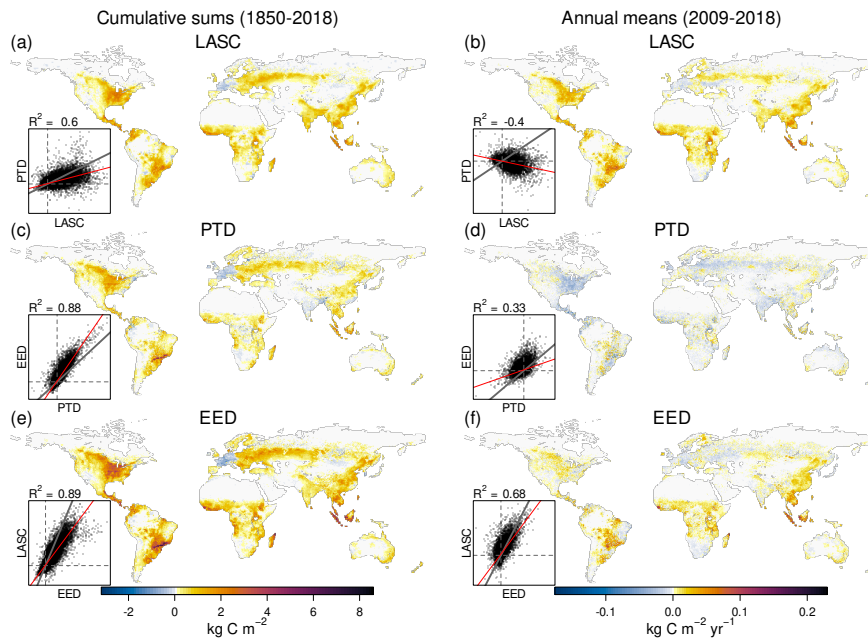


**Figure 9.** Cumulative sums from 1850 onward (left column) and annual means for 2009–2018 (right column) of  $f_{LULCC\_trans}$  (upper row),  $f_{LULCC\_pi}$  (middle), and  $f_{LULCC\_pd}$  (lower row) averaged across the models. Additionally, correlation plots between the pixel-wise estimations are shown; here the grey line represents the 1:1 line, the dashed grey lines depict zero lines, and the red line shows a fitted linear model.  $f_{LULCC\_pd}$  was not derived for CLM5.0, JULES, LPJ and OCN models (compare Table 2).

### 3.2.1 Regions of positive loss of additional sink capacity - A lost carbon sink?

Not surprisingly, the regions of the largest LASC values are related to EED (compare [Fig. 10a and e](#), and [Figs. 6 and 10a,e](#), [with](#) strong correlation between LASC and EED [in inlet Fig. 10e shown in the latter](#)) and similar values to PTD (Fig. 10c) are in line with the cumulative LASC amounting to about half of EED globally (Fig. 2e). But marked differences in patterns exist, which reflect that although the LASC is driven by environmental differences, just as EED, it differs in causing [legacy](#) fluxes on

any area cleared in the past via the reference simulation seeing the potential vegetation within its pre-industrial extent. These differences are pronounced in the last decade (Fig. Figs. 6 and 10b,d,f): Regions, in particular forested ones, that were cleared between 1700 and the middle of the 20th century (when the accelerated CO<sub>2</sub> increase causes a strongly accumulating LASC) and stayed non-forested create emissions continuously during later times when the LASC is included and cause LASC to be larger than EED (i.e. negative PTD values) e.g. in the eastern USA, Eastern Europe to Central Asia, and India.).



**Figure 10.** Cumulative sums from 1850 onward (left column) and annual means for 2009–2018 (right column) of the Loss of Additional Sink Capacity (LASC; upper row), the ‘Present-day’ vs ‘Transient’ environmental conditions Difference (PTD; middle row) and the Environmental Equilibrium Difference (EED; lower row) averaged across the models. Additionally, correlation plots between the different pixel-wise estimations are shown; here the grey line represents the 1:1 line, the dashed grey lines depict zero lines, and the red line shows a fitted linear model. EED and PTD were not derived for CLM5.0, JULES, LPJ and OCN models (see Table 2).

While EED is more relevant than the LASC for cumulative industrial-era emissions (stronger change of sign in correlation in inlet Fig. 10e compared to Fig. 10f), the accumulating LASC heavily alters recent  $f_{LULCC}$  estimates – Fig. 10b shows which regions would be attributed much higher emissions when the LASC is included in the  $f_{LULCC}$  definition. Small areas exist where EED is larger than the LASC (i.e. positive PTD values) even for the recent decade: in the tropics (mainly Brazil, Tanzania, Indonesia), sub-tropics (Eastern China, Southern Australia), and in the transition zones from temperate to boreal zone (Scandinavia, Russia). These regions experienced more recent LULCCs that reduced the C stocks, thus the LASC could only shortly accumulate. These regions would likely be attributed higher emissions by bookkeeping approaches (which are similar to  $f_{LULCC\_pd}$ ) than by  $f_{LULCC\_trans}$  from DGVMs. This highlights another difficulty especially in regional  $f_{LULCC}$  attribution: as the LASC accumulates emissions caused by past LULCCs, recent LULCCs are given less weight in relative terms. This also

~~applies to recent LULCCs reducing atmospheric CO<sub>2</sub> such as reforestation, which cannot quickly compensate for past LULCC in approaches including the LASC, while they could in  $f_{LULCC\_pi}$  and  $f_{LULCC\_pd}$  estimates.~~

Aggregated time series for the RECCAP2 regions reveal that the LASC started to increase ~1850 in the USA, Russia and Southeast- and South Asia, ~1900 in SW South- and Central- America and Southern Africa (Fig-Figs. 6a,b and A4). It then becomes even more pronounced ~1950 in Brazil, Equatorial Africa and China, with the latter two and Southeast Asia showing a particular strong increase after 2000 (Figs. A4 and 10a,b, 10b and A4). Overall, the LASC accumulated to more than 4 PgC in the USA, Brazil, Equatorial Africa and Southeast Asia, and to 2–4 PgC in China, Russia, SW South- and Central- America, Southern Africa and South Asia (Figs. 10a and A10). ~~These As stated above, these~~ high cumulative and annual LASC estimates mainly result from an initial high forest coverage and subsequent C losses in particular on areas where higher C stocks resulted from environmental changes over time (Sect. 3.4 and Fig. 8). Due to the different start of organized human agricultural, the forest clearings in the USA (mid of 19th century, with an early LASC initiation) though on forests with comparably low C stocks (Fig. A3) have caused ~~an early LASC initiation, which cumulated to ~5 PgC until today (Fig. A10), while similar cumulative sums as a much later onset of wide-spread LULCCs (beginning of 20th century) in Brazil, Equatorial Africa, China, and Southeast Asia ; a much later onset of wide-spread LULCCs (beginning of 20th century) caused similar cumulative sums (Fig. A10)~~ due to rapidly increasing and pronounced higher vegetation C stocks in ~~the converted forests (these regions (with strong response to CO<sub>2</sub> increase; Fig. A3)).~~

The widely negative PTD values across the globe for the period 2009–2018 indicate that the LASC causes recent  $f_{LULCC}$  estimates from the current DGVM approach (under transient conditions) to be higher compared to bookkeeping estimates (which are similar to  $f_{LULCC\_pd}$ ). However, small areas exist where EED remains larger than the LASC (i.e. positive PTD values) for the recent decade, here, more recent LULCCs caused even shorter period for the LASC to accumulate: in the tropics (mainly Brazil, Tanzania, Indonesia), sub-tropics (Eastern China, Southern Australia), and in the transition zones from temperate to boreal zone (Scandinavia, Russia). These regions would likely be attributed higher emissions by bookkeeping approaches than by  $f_{LULCC\_trans}$  from DGVMs. This highlights another difficulty especially in regional  $f_{LULCC}$  attribution: as the LASC accumulates emissions caused by past LULCCs, recent LULCCs are given less weight in relative terms. This also applies to recent LULCCs reducing atmospheric CO<sub>2</sub> such as reforestation, which cannot quickly compensate for past LULCC in approaches including the LASC, while they could in  $f_{LULCC\_pi}$  and  $f_{LULCC\_pd}$  estimates.

### 3.2.2 Regions of negative loss of additional sink capacity - A gained carbon sink?

While it has been shown above that the LASC ~~globally is a strong positive term adding is strong positive in many regions, adding globally~~ almost 1 PgC yr<sup>-1</sup> to recent annual  $f_{LULCC}$ , the LASC may be negative in some regions. Negative cumulative LASC estimates from 1800 onward are seen for wide areas of Europe, small areas in Brazil (eastern parts) and Southern Africa (eastern parts), and, with lower quantities spread over Canada, Russia and China (Figs. A10 and 10a-10a and A10). Negative annual LASC estimates for the period 2009–2018 are observed in the same regions, but more wide-spread in Brazil and Southern Africa and striking negative values in the Ukraine (Figs. A4 and 10b-6, 10b and A4). These negative LASC estimates can mainly be explained by LULCCs beneficial for C stocks (e.g. reforestation) on areas that experienced beneficial

environmental conditions afterwards, with a negative cumulative LASC indicating that the positive effects of LULCCs on the C stocks outweighed the effects of, mostly earlier, LULCCs that decreased C stocks. Note, this depends on the time LULCCs occurred, as the LASC accumulation periods differ, in their duration as well as the underlying transient environmental conditions. The In line, the strong negative cumulative and annual LASC estimates across France, Germany and Italy result from widespread reforestation after 1700, but also from the fact that the pre-industrial land use already had low forest coverage due to pre-1700 deforestation (Klein Goldewijk et al., 2017), despite belonging to the forest biome. Most recent negative LASC values in the Ukraine can be linked to recultivation of post-Soviet abandoned agricultural land in particular in the Steppe zone (Smaliychuk et al., 2016). However, a negative LASC may also represent a negative climate change impact on C stocks (e.g. reduced precipitation) in areas where LULCCs decreasing C stocks happened (e.g. Iberian peninsula and eastern parts of South Africa).

The areas with a negative LASC are consequently attributed lower  $f_{LULCC}$  emissions to the atmosphere when the LASC is included in the calculation. If political reporting were based on DGVM-based  $f_{LULCC\_trans}$  estimates of the GCB, instead of a bookkeeping approach, these regions would ‘profit’ the most (be attributed less emissions). In other areas of widespread reforestation, most recent annual LASC estimates remain positive albeit decreasing, depending on how much the LASC has accumulated before as synergy between timing of LULCCs and later environmental C stock alterations. Here, a negative PTD indicates that the LASC accumulated more than the difference of the actual fluxes upon detrimental LULCCs under transient vs present-day conditions (e.g. due to a long accumulation period), or that beneficial LULCCs caused smaller negative emissions in  $f_{LULCC\_trans}$  as compared to  $f_{LULCC\_pd}$ .

~~Cumulative sums from 1850 onward (left column) and annual means for 2009–2018 (right column) of  $f_{LULCC\_trans}$  (upper row),  $f_{LULCC\_pi}$  (middle), and  $f_{LULCC\_pd}$  (lower row) averaged across the models. Additionally, correlation plots between the pixel-wise estimations are shown; here the grey line represents the 1:1 line, the dashed grey lines depict zero lines, and the red line shows a fitted linear model.  $f_{LULCC\_pd}$  was not derived for CLM5.0, JULES, LPJ and OCN models (compare Table 2).~~

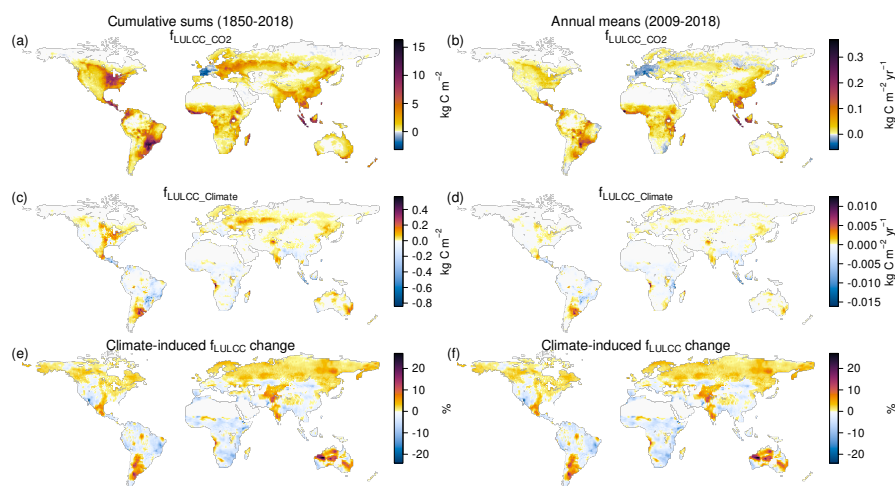
~~Cumulative sums from 1850 onward (left column) and annual means for 2009–2018 (right column) of the Loss of Additional Sink Capacity (LASC; upper row), the ‘Present-day’ vs ‘Transient’ environmental conditions Difference (PTD; middle row) and the Environmental Equilibrium Difference (EED; lower row) averaged across the models. Additionally, correlation plots between the different pixel-wise estimations are shown; here the grey line represents the 1:1 line, the dashed grey lines depict zero lines, and the red line shows a fitted linear model. EED and PTD were not derived for CLM5.0, JULES, LPJ and OCN models (compare Table 2). Comparing the different  $f_{LULCC}$  estimates over time and across space, previous discussion has shown that the choice of method to derive  $f_{LULCC}$  strongly impacts the estimated quantities. The effects of the interaction of the environmental forcing with the timing of the actual LULCC is particularly pronounced for estimates under transient environmental forcing and where NBP was strongly altered by environmental changes.~~

### 3.3 Relative climate- and CO<sub>2</sub>-induced $f_{LULCC\_trans}$ components

As discussed (Sect. 2.2.2), patterns of CO<sub>2</sub> and climate changes may have very different effects on  $f_{LULCC}$  across the globe. The mean simulated global vegetation C stock increased by ~23% from 664 PgC to 815 PgC from 1800 until today, in both the



530 S1 and S2 simulation ([which by protocol exclude effects from LULCCs](#); see Figs. 8 and A3 for maps and Fig. A1b for global estimates). The mean simulated global soil C stock increased from 1494 PgC to 1569 PgC (~5%) in S1 and to 1553 PgC (~4%) in the S2 simulation (see Fig. A1c). In line with the more pronounced soil C stock increase in the S1 simulation (excluding climatic changes), the general increase in cTot can mainly be attributed to an altered CO<sub>2</sub> exposure under rising atmospheric CO<sub>2</sub> (Lal, 2008). However, although climate change (here roughly the last 100 years due to model assumptions; [compare](#)  
 535 [Sect. 2.2.2](#)) induces lower changes in C stocks on global scale, it has high impact on local and regional scale.



**Figure 11.** [Cumulative sums from 1850-2018 \(left column\) and annual means for 2009-2018 \(right column\) of  \$f\_{LULCC\_{CO\_2}}\$  \(upper row\),  \$f\_{LULCC\_{Climate}}\$  \(middle\) and percentage change in  \$f\_{LULCC\_{trans}}\$  due to climate change only \(lower row;  \$100 \times \(f\_{LULCC\_{trans}} - f\_{LULCC\_{CO\_2}}\) / f\_{LULCC\_{trans}}\$ \). Grid boxes  \$< 1 \text{ kg C m}^{-2}\$  total C stock excluded from mapping.](#)

Climate change increased cTot mainly through vegetation changes in mid and high latitudes, which can be explained by increased temperatures leading to longer growing seasons, boreal expansion of biomes to mention a few (Peng et al., 2014; Piao et al., 2019) and increased precipitation in some regions (e.g. CMIP5 precipitation changes of last century in Becker et al. 2013; van den Besselaar et al. 2013). Negative climate change impacts on C stocks are mainly found across the tropics  
 540 for vegetation and in most regions of the world for soil C. These negative climate-induced stock alterations likely relate to reduced precipitation amounts (e.g. Ren et al. 2013; van den Besselaar et al. 2013) with an increased frequency and intensity of droughts (e.g. Bastos et al. 2020), increased temperatures further increasing the vapor pressure deficit (potentially enhancing transpirational water losses) and increasing soil respiration and mineralization processes (reducing soil C stocks; Lal 2008; Crowther et al. 2016; Davidson and Janssens 2006), and disturbances such as forest fires (Bowman et al., 2009; Archibald et al.,  
 545 2018). The apparent dipoles in climate-induced vegetation and total C stock alterations in the USA and over Europe are most likely triggered by environmental changes during the 20th century with reduced stocks in [Western](#) USA and Southern Europe where precipitation decreased (and droughts happen more frequent) and higher stocks in the Eastern USA where precipitation

widely increased (and droughts get less likely; e.g. Peterson et al. 2013; van den Besselaar et al. 2013) and ~~northern~~ Northern Europe due to global warming induced longer growing seasons (e.g. Keenan et al. 2014; O’Sullivan et al. 2020) .

550 In line with the homogeneously altered C stocks due to increased CO<sub>2</sub>, spatial patterns of the CO<sub>2</sub>-induced  $f_{LULCC}$  component ( $f_{LULCC\_CO_2}$ ) widely reflect  $f_{LULCC\_trans}$ , and thus LULCC activities, while the climate-induced  $f_{LULCC}$  component is much more heterogeneously spread (Sect. 2.2.2 and Fig. 11). Highest  $f_{LULCC\_CO_2}$  occurs in the tropics and in mid latitudes, where changes in vegetation C dominate the C pool changes and vast areas have been transformed by LULCCs that decreased C stocks (Figs. A3 and 11a,b). Negative  $f_{LULCC\_CO_2}$  estimates are mainly found where also  $f_{LULCC\_trans}$  is negative and can be  
555 explained by agricultural abandonment and/or reforestation (for small areas in NE USA and NE Brazil, wide areas in Europe, parts of Russia, Georgia, Korea and Japan, and South Africa).

Although comparably low in absolute values, climate change induced alterations in  $f_{LULCC}$  are much more heterogeneously spread over the globe and range from -23 to +28% with particular high alterations on areas with comparably low C stocks (compare Figs. ~~A3 and~~ 11c,d,e,f and A3). A reduced  $f_{LULCC\_Climate}$  occurs where also vegetation C is reduced due to climate,  
560 mainly in the tropics and sub-tropics with particular hotspots in North East Brazil, the Mediterranean region, Southern and Eastern Africa, China, Southern Asia, Southwestern Australia, and Central America (the latter, despite higher vegetation C), and in the temperate zone, in Western USA and Mongolia. In contrast to this climate-induced  $f_{LULCC}$  reductions, climate strongly increased  $f_{LULCC}$  in particular in colder environments of higher latitudes and altitudes where higher C stocks resulted from climate change (Sect. 2.2.2).

565 ~~Cumulative sums from 1850–2018 (left column) and annual means for 2009–2018 (right column) of  $f_{LULCC\_CO_2}$  (upper row);  $f_{LULCC\_Climate}$  (middle) and percentage change in  $f_{LULCC\_trans}$  due to climate change only (lower row;  $100 \times (f_{LULCC\_trans} - f_{LULCC\_CO_2}) / f_{LULCC\_trans}$ ). Grid boxes  $< 1 \text{ kgC m}^{-2}$  total C stock excluded from mapping.~~

#### 4 Proposal for a standard $f_{LULCC}$ estimation

Previous chapters, for the first time, have shown that  $f_{LULCC}$  patterns depend not only on the timing of occurrence and type of  
570 LULCCs, but also on the simulated time period and the assumptions on environmental conditions (with spatially very diverse effects from climate alterations). ~~Disregarding~~ From a policy standpoint and disregarding considerations from the natural land sink perspective, these results highlight the need for a  $f_{LULCC}$  estimate that is comparable over time and across space. For example, including the LASC in  $f_{LULCC}$  estimates may be perceived as appropriate because LULCCs could have destroyed or created vegetation with long C turnover (e.g. deforestation or reforestation) leading to de- or increased C sinks (while current  
575  $f_{LULCC}$  reporting neglects such foregone sinks). However, including the LASC implies attributing fluxes to a region’s emission budget that are partly a fate of history; in particular in the temperate regions, LULCCs detrimental to C stocks historically happened earlier compared to LULCCs increasing C stocks. Thus, the committed emissions included in the LASC often have longer accumulation periods for detrimental as compared to beneficial LULCCs whose accumulation periods are more likely to be cut off at the simulation end (2018 in the GCB2019). The accumulation periods may further be altered if,  
580 the historic period, various LULCCs occurred on the same area. This is further complicated because environmental changes

over the historic period modified the LASC, with a widely accelerated accumulation rate in later periods due to higher, and faster increasing CO<sub>2</sub> concentrations but very heterogeneously spread alterations by climatic changes. Thus, even for the same LULCC with the same accumulation duration, the LASC will be different dependent on timing and location of the LULCC.

To circumvent these issues, as could be desired in the political context, one could ~~use  $f_{LULCC,PI}$  (which neglects transient conditions) as the base emissions and separately add an adapted LASC which is derived from defined reference accumulation periods for different LULCC types. By using such reference periods, the LASC could fully be captured also for most recent LULCCs (may they act positive or negative on C stocks) and foregone sinks would be more equally counted. Additionally, to exclude LASC differences due to~~ derive  $f_{LULCC}$  and the LASC based on simulations forced with the cycled climate and CO<sub>2</sub> conditions that occurred during the actual LULCC event. However, this would still result in differing accumulation periods and varying environmental conditions during and following a LULCC event. While the influence of the latter could be reduced using cycled pre-industrial or present-day environmental forcings, these neglect transient C stock changes. To consider the LASC but counteract spatial heterogeneity in  $f_{LULCC}$  differences resulting from synergistic effects of environmental conditions and the timing of LULCCs, ~~the adapted LASC accumulation periods should be~~ one could derive  $f_{LULCC}$  and LASC from a defined reference period which is independent of the actual time that LULCCs occurred and ~~share~~ share the same reference conditions, ~~for example the adapted~~. For example,  $f_{LULCC}$  and LASC could always be modeled for the second half of the 21st century, as here the environmental C stock changes have been amplified due to the accelerating increase of atmospheric CO<sub>2</sub> concentrations (alternative start times are of course conceivable). By using such reference period, the LASC could fully be captured also for most recent LULCCs (may they act positive or negative on C stocks) and foregone sinks would be more equally counted (same length of accumulation period with similar environmental changes). Along these

600 lines, it may be considered to calculate ~~the such~~ adapted LASC based on CO<sub>2</sub>-only simulations as here the impact of humans is more homogeneously distributed, while the spatially heterogeneous climate impact on  $f_{LULCC}$ s, determined foremost by action outside the location of LULCCs, causes a questionable attribution of regional  $f_{LULCC}$  when compared across the globe (without even considering externalized  $f_{LULCC}$ s e.g. due to remote market demand of food and timber; Lambin and Meyfroidt 2011; Meyfroidt et al. 2013). To detach  $f_{LULCC}$  estimates from the timing of LULCCs and the spatially heterogeneous climate

605 evolution, we argue to address the delineation of an adapted LASC in future studies, where, in particular, the reference to calculate the LASC should further be investigated. Such methodology could limit  $f_{LULCC}$  to locally determined factors (namely LULCCs) and reduce the dependence on the timing of LULCCs while still reflecting the foregone C sink capacity by human intervention.

## 5 Conclusions

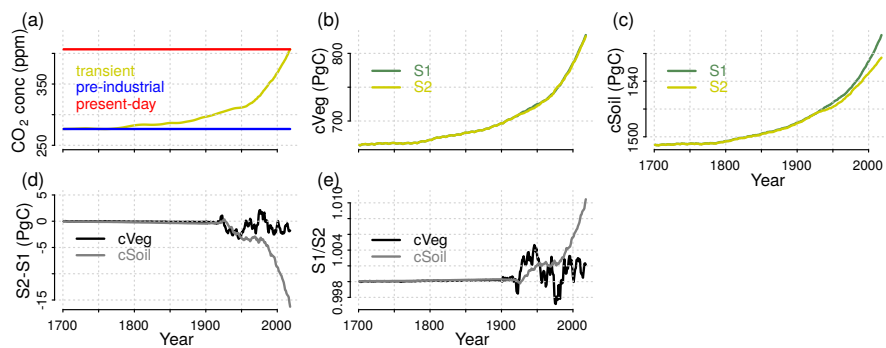
610 Accurate quantification of the net carbon flux from land use and land cover changes ( $f_{LULCC}$ ) is essential, foremost to project carbon (C) cycle dynamics and estimate the strength of negative CO<sub>2</sub> emission technologies. However,  $f_{LULCC}$  can only be estimated by models – typically bookkeeping or dynamic global vegetation models (DGVMs) – and requires decisions on how to account for effects of environmental changes. We show that these decisions have major consequences for flux attribution,

particularly at regional scale because C stocks evolve very heterogeneously in both space and time. DGVM estimates under present-day environmental forcing most closely resembled bookkeeping estimates (used in the annual global carbon budgets, GCBs) and are generally higher compared to  $f_{LULCC}$  under pre-industrial environmental conditions. This Environmental Equilibrium Difference (EED; accounting for  $\sim 35\%$  of global  $f_{LULCC}$  ~~under when using~~ present-day C stocks) is caused by higher C stocks, mainly in response to increased present-day atmospheric CO<sub>2</sub> and only to a smaller extent by climatic changes. ~~Noteworthy~~, EED becomes negative in some regions, mainly due to environmental conditions decreasing C stocks (e.g. increased frequency and intensity of droughts and reduced precipitation). In the GCB, cumulative bookkeeping  $f_{LULCC}$  estimates are jointly published with DGVM-derived uncertainties under transient environmental conditions, which we show implies pronounced regional differences (named ‘Present-day’ vs ‘Transient’ environmental conditions Difference; PTD), strongly depending on the timing and placement of land use and land cover changes. We explain PTD values mainly by the loss of additional sink capacity (LASC), emissions due to destroyed C uptake potential that are only captured by the transient DGVM approach. In our multi-model mean for 2009–2018, a LASC of  $0.8 \pm 0.3$  PgC yr<sup>-1</sup> accounts for  $\sim 40\%$  of recent global  $f_{LULCC}$  estimates of  $2.0 \pm 0.6$  PgC yr<sup>-1</sup> (under transient conditions).

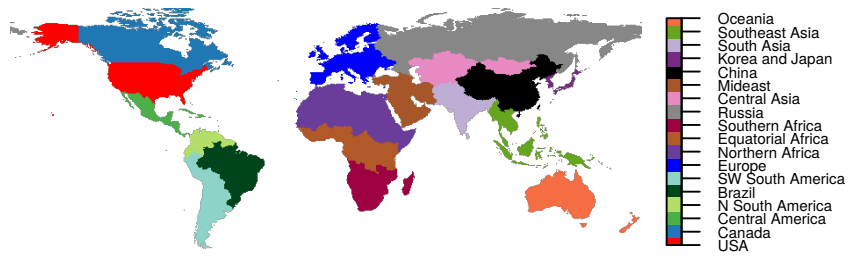
The LASC causes ~~strongly regionally strong~~ increased transient  $f_{LULCC}$  ( $>0.1$  PgC yr<sup>-1</sup>) where LULCCs detrimental to C stocks, such as deforestation, happened early within the simulated period (long accumulation period for lost potential C uptake; foremost in the USA) or later on areas with strong positive C stock response to environmental changes (e.g. in Brazil, Southeast Asia and Equatorial Africa). ~~In contrast is LASC from deforestation is unaccounted for in nations that deforested prior to the beginning of the accounting period (e.g. wide-spread deforestation in Europe). Further, in many of these cases LASC is negative and~~ transient  $f_{LULCC}$  strongly decreased ~~where early reforestation occurred on areas profiting from climate due to early reforestation on previously deforested land where re-established forest carbon stocks profited from environmental change (e.g. wide-spread in Europe). If Within the political context, if~~ environmental effects on ~~potential C stocks should C sink capacity are to~~ be accounted for ~~fully, we argue to include the LASC into regional budgets, thereby highlighting the need for DGVMs. However, as in~~ regional budgets (requiring DGVMs for the assessment) we argue for a consistent method which includes the LASC and emphasize that care must be taken in choosing the beginning of the accounting period. As LASC values derived by the ~~common approach~~ approach taken so far in the GCB are widely independent of locally determined environmental changes ~~but depend on the arbitrary length of their accumulation period (rather depend on globally determined climatic changes) and strongly dependent on accumulation periods~~ (defined by the ~~simulated period, i.e. the start and timing of LULCCs and the~~ end year of the simulations), ~~it could be considered to derive~~ we argue for a  $f_{LULCC}$  attribution that is ~~more robust against choices of environmental drivers and accumulation period by using~~ an adapted LASC, ~~for example,~~ based on a defined common reference period and homogeneously altered environmental conditions (such as only driven by CO<sub>2</sub> alterations).

645 *Code and data availability.* Scripts and data are available upon request from the corresponding author.

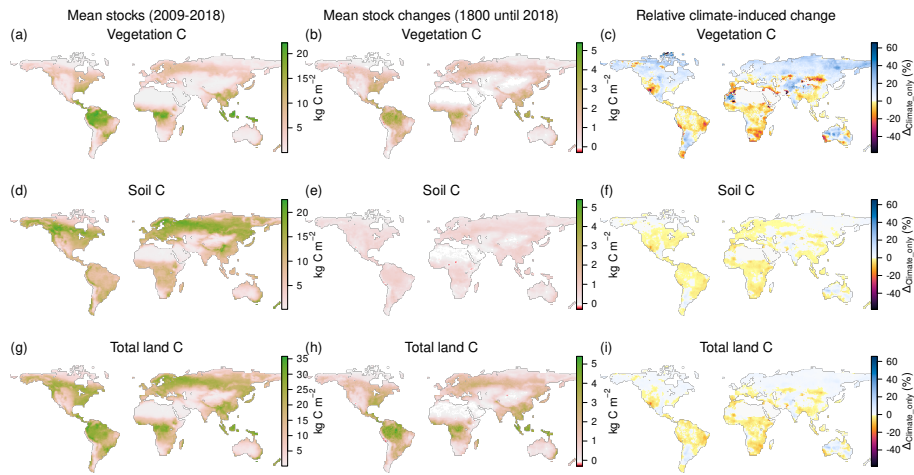
## Appendix A



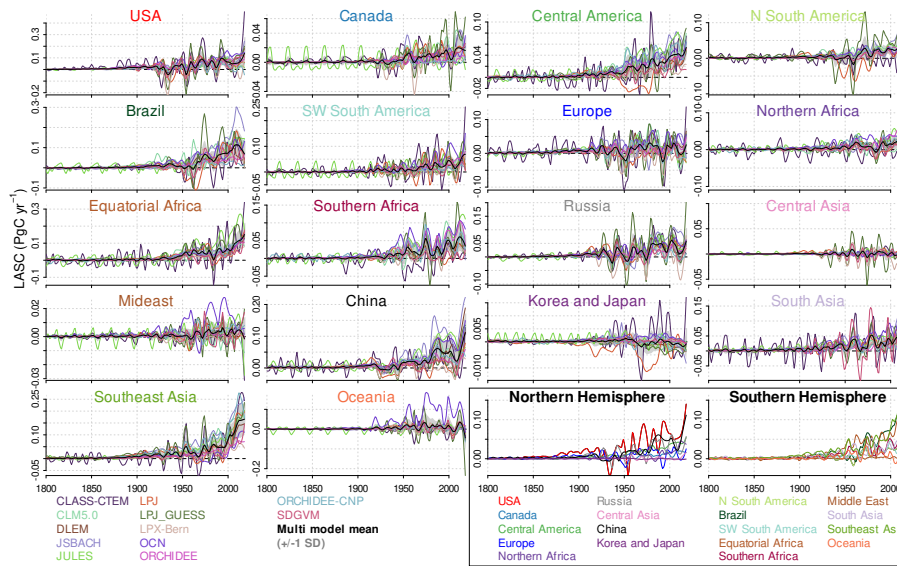
**Figure A1.** Global forcings of annual CO<sub>2</sub> fields and ensemble mean C stocks in vegetation and soil of the S1 (pre-industrial climate and transient CO<sub>2</sub>) and S2 (transient climate and CO<sub>2</sub>) simulation runs. Additionally, the differences and ratios in S1 and S2 C stocks in vegetation and soil are plotted.



**Figure A2.** REgional Carbon Cycle Assessment and Processes', Phase 2 (RECCAP2~~global~~) regions as defined in Tian et al. 2019.

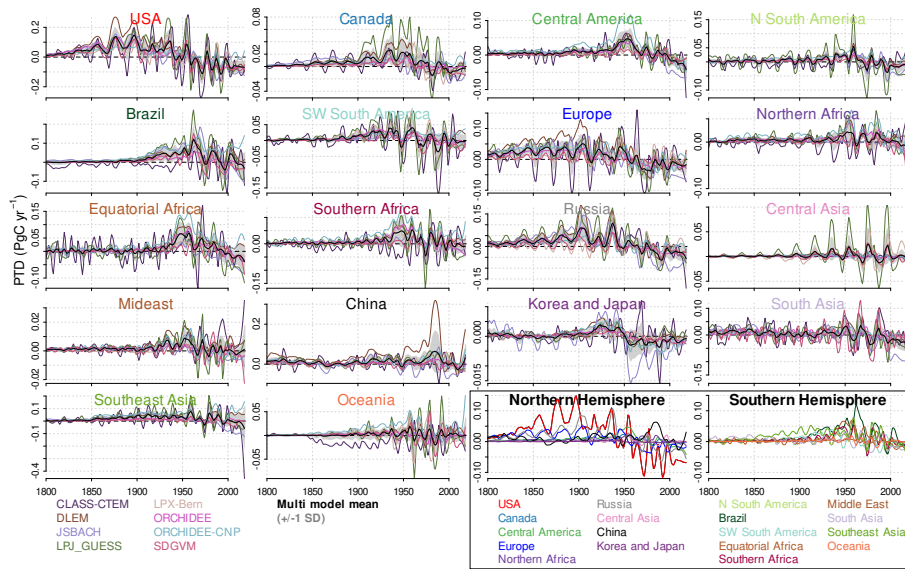


**Figure A3.** Ensemble mean C stocks from 2009–2018 in S2 simulation (left column; observed environmental conditions and pre-industrial land use and land cover), mean C stock changes between 1800 and 2018 (middle), and their climate-induced percentage changes (right column,  $100 \times (S2 - S1)/S2$ ) of vegetation (upper row; for relative change, values  $< -60\%$  were set to  $-60\%$ ), soils (middle), and their totals (lower row). The relative climate-induced changes indicate additional (blueish) and reduced (reddish) stocks due to historic climate change (grid points  $< 1 \text{ kgC m}^{-2}$  total C stock excluded).

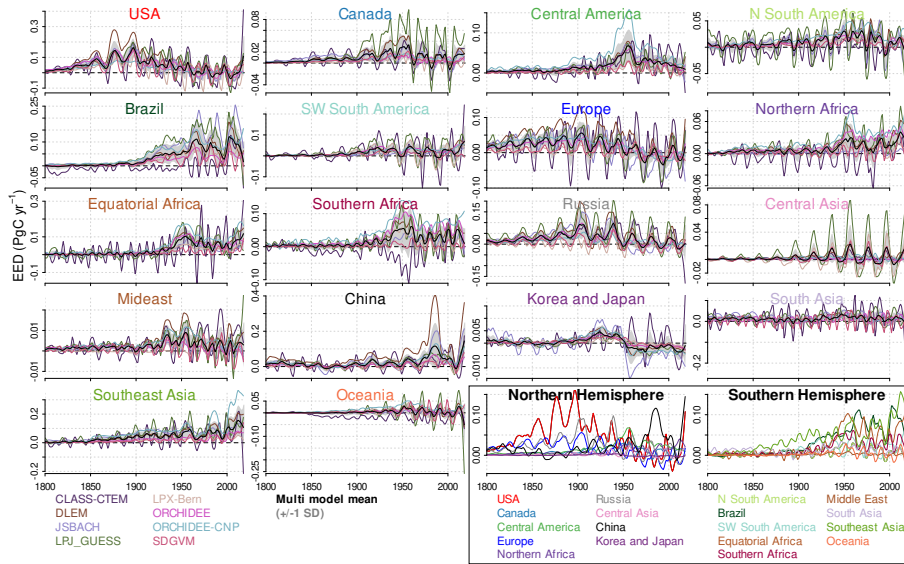


**Figure A4.** Regionwise smoothed annual Loss of Additional Sink Capacity (LASC) in the investigated DGVMs from 1800 to 2018, derived according to Eq. 4. For discussion on individual models refer to Sect. A1. The last two panels show regional ensemble means on uniform scale.

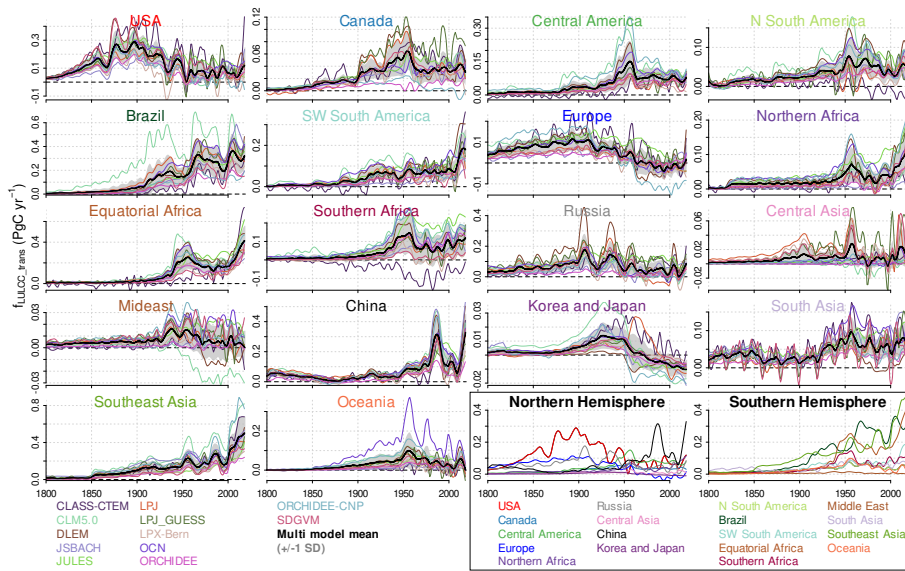




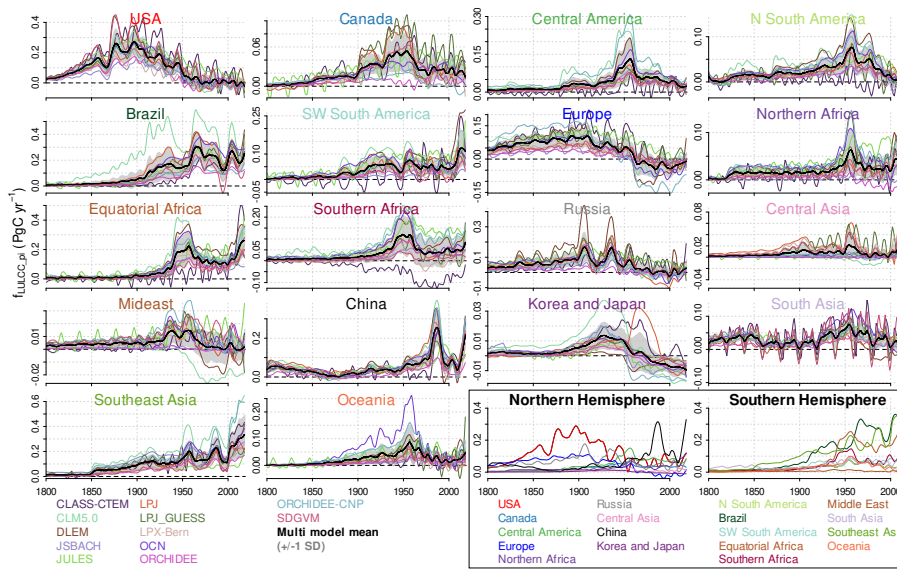
**Figure A5.** Regionwise smoothed annual ‘Present-day’ vs ‘Transient’ environmental conditions Difference in  $f_{LULCC}$  (PTD) in the used models from 1800 to 2018, derived according to Eq. 5. For discussion on individual models refer to Sect. A1. PTD was not derived for CLM5.0, JULES, LPJ and OCN (compare Table 2). The last two panels show regional ensemble means on uniform scale.



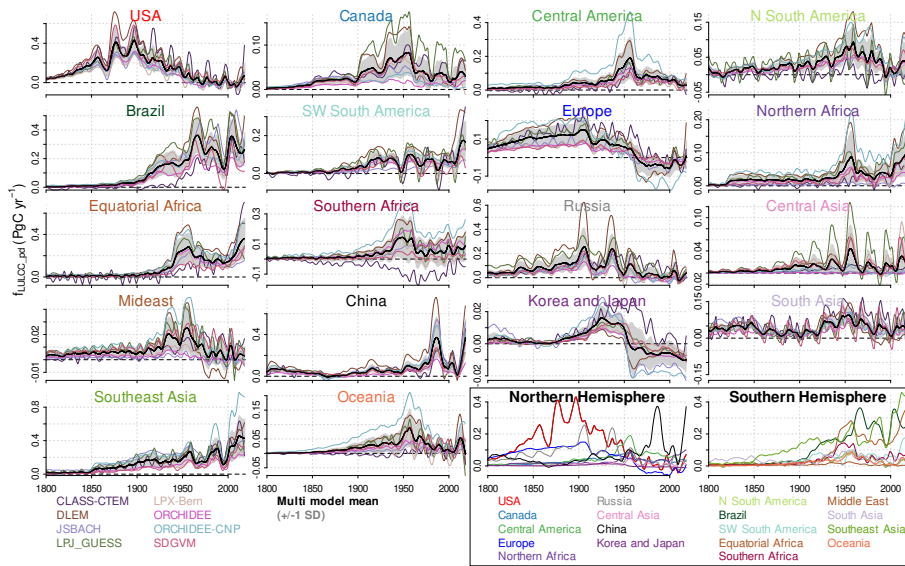
**Figure A6.** Regionwise smoothed annual difference between  $f_{LULCC}$  under present-day and pre-industrial environmental conditions (Environmental Equilibrium Difference, EED) in the used models from 1800 to 2018, derived according to Eq. 6. For discussion on individual models refer to Sect. A1. EED was not derived for CLM5.0, JULES, LPJ and OCN (compare Table 2). The last two panels show regional ensemble means on uniform scale.



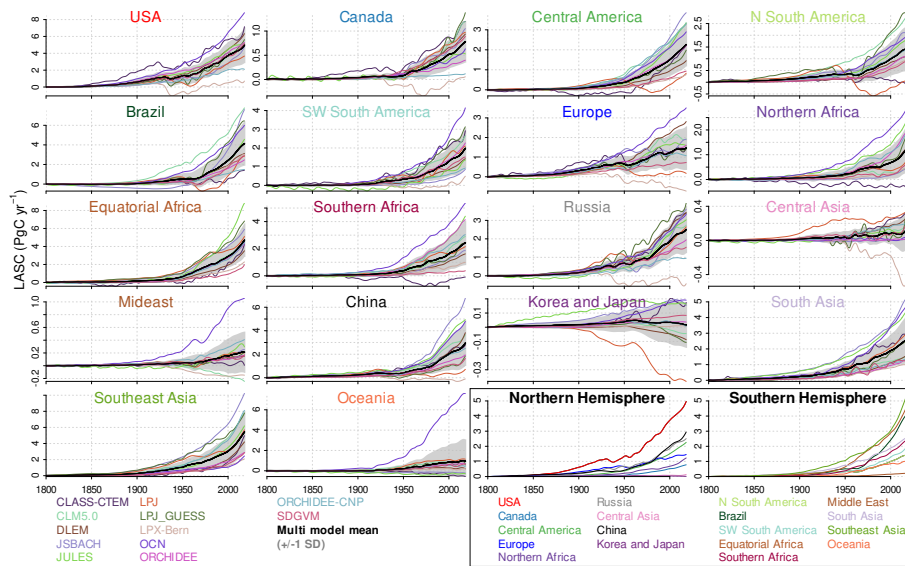
**Figure A7.** Regionwise smoothed annual  $f_{LULCC\_trans}$  for different models from 1800 onward (compare Eq. 1). For discussion on individual models refer to Sect. A1. The last two panels show regional ensemble means on uniform scale.



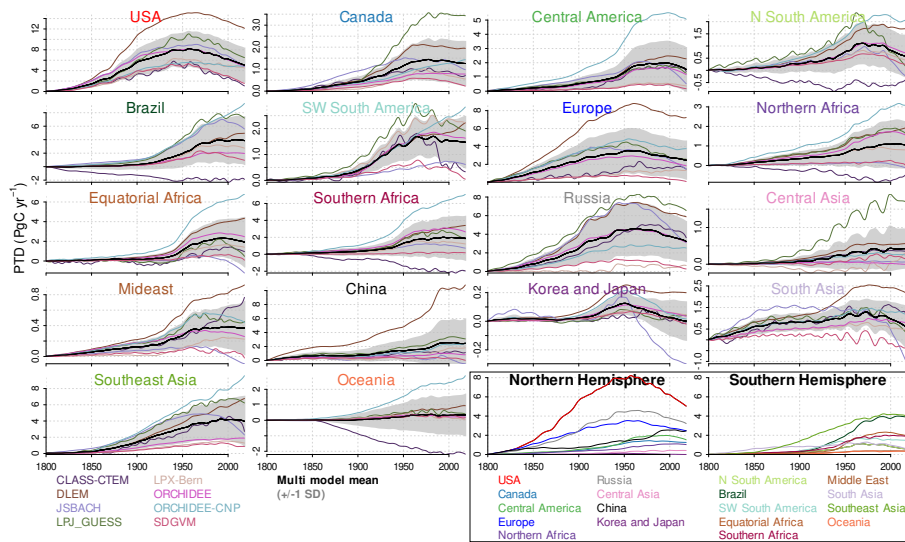
**Figure A8.** Regionwise smoothed annual  $f_{LULCC_{pi}}$  for different models from 1800 onward (compare Eq. 2). For discussion on individual models refer to Sect. A1. The last two panels show regional ensemble means on uniform scale.



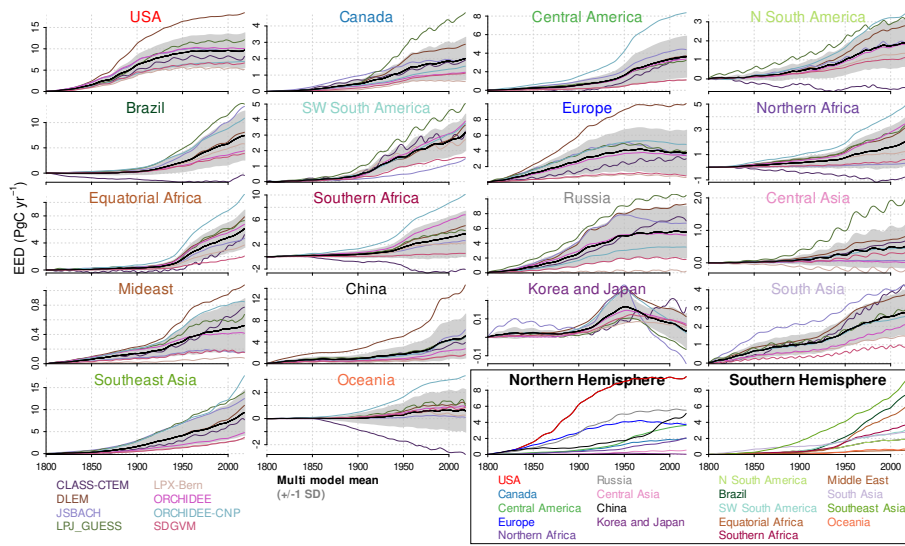
**Figure A9.** Regionwise smoothed annual  $f_{LULCC\_pd}$  for different models from 1800 onward (compare Eq. 3).  $f_{LULCC\_pd}$  was not derived for CLM5.0, JULES, LPJ and OCN models (compare Table 2). For discussion on individual models refer to Sect. A1. The last two panels show regional ensemble means on uniform scale.



**Figure A10.** Regionwise smoothed cumulative Loss of Additional Sink Capacity (LASC) from 1800 onward (compare Eq. 4). For discussion on individual models refer to Sect. A1. The last two panels show regional ensemble means on uniform scale.

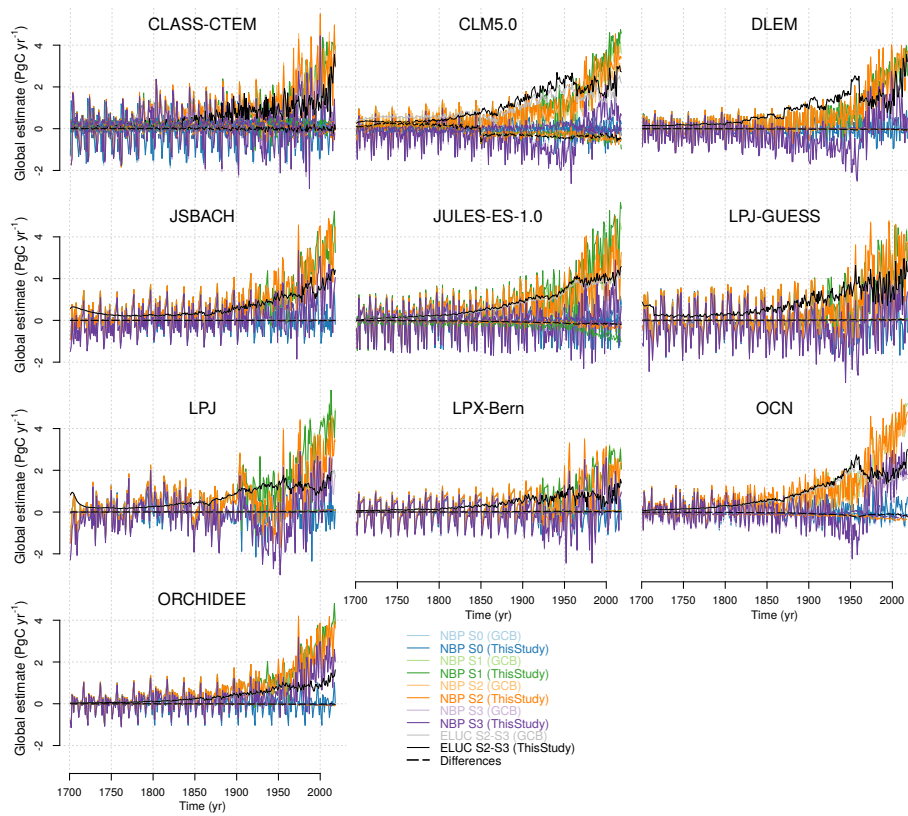


**Figure A11.** Regionwise smoothed cumulative ‘Present-day’ vs ‘Transient’ environmental conditions Difference in  $f_{LULCC}$  (PTD) from 1800 onward (compare Eq. 5). PTD was not derived for CLM5.0, **JULES****JULS**, LPJ and OCN models (compare Table 2). For discussion on individual models refer to Sect. A1. The last two panels show regional ensemble means on uniform scale.



**Figure A12.** Regionwise smoothed cumulative difference between  $f_{LULCC}$  under present-day and pre-industrial environmental conditions (Environmental Equilibrium Difference, EED) from 1800 onward (compare Eq. 6). EED was not derived for CLM5.0, JULES, LPJ and OCN models (compare Table 2). For discussion on individual models refer to Sect. A1. The last two panels show regional ensemble means on uniform scale.





**Figure A13.** Comparison of global annual NBP of S0, S1, S2 and S3 simulation runs and derived  $f_{LULCC\_trans}$  as aggregated in this study and published in the GCB2019 (Friedlingstein et al., 2019). The thick dashed lines (near or at zero) depict the differences (with respective colors). For the global values of this study, CDOs were used to convert NBP data per second to per year (multiplying seconds per day and, depending on the original temporal resolution, days per month or days per year), regrid data to the grid cell (multiplying with the area per grid cell). ORCHIDEE-CNP and SDGVM estimates were not shown since no data from the GCB2019 were available.

## A1 Model variability in $f_{LULCC}$ differences

The model spread in annual and cumulative  $f_{LULCC}$  estimates and their differences (LASC, PTD and EED) has been shown to be large (compare Tables 4, 5 and 6), and increasing over time, in particular from 1950s onwards onward in Brazil, Northern Africa, Equatorial Africa and Southeast Asia (shaded areas in Figs. 3 and 4, showing the multi-model mean  $\pm 1$  standard deviation). This pronounced model spread can be explained by intertwining issues, such as the low quality of historical LULCC data (with different data bases), the consideration or neglect of relevant processes (e.g. nitrogen fertilisation), the simplified representation and uncertainty in the parameterization of management and natural processes, uncertainties in soil and vegetation C stocks, and the lack of observational constraints (Friedlingstein et al., 2019; Gasser et al., 2020; Lienert and Joos, 2018; Goll et al., 2015; Li et al., 2017). Additionally, a high interannual variability in the NBP data translated into a high variability of  $f_{LULCC}$  estimates (Fig. A13) and their respective differences (even in the smoothed data; not shown). This e.g. partly results some artificial periodic climate signal that might arise due to comparison of simulations with differently cycled constant (present-day and pre-industrial) vs transient environmental conditions (e.g. on global scale, for relative share of EED to  $f_{LULCC_{pd}}$  in Fig. 2c and, on regional scale, in Figs. A4 to A6 with pronounced oscillations in some regions).

Global EED and PTD were higher than in the other models for LPJ-GUESS, ORCHIDEE-CNP and DLEM and lower for CLASS-CTEM, LPX-Bern and SDGVM. PTD and EED show highest model spread at the time of maximum LULCCs and towards the end of the simulation period in particular in regions where vast areas of land were transformed (Brazil, Equatorial Africa, Central, South and Southeast Asia).

A particular high model spread for global LASC at the end of the simulation period was found in Canada, N- and SW South America, Brazil, Middle East, Korea and Japan, South and Southeast Asia and Oceania with particularly high estimates for OCN, CLASS-CTEM, LPJ-GUESS and JSBACH models (Figs. A4 and A10).

High values in LPJ-GUESS likely result from high  $f_{LULCC}$  estimates with pronounced inter-annual variability (particularly prominent in Canada and Russia). This variability may be partially caused by stochastic components of the Globfirm fire model, which was used in the TRENDY LPJ-GUESS runs, causing fire emissions not necessarily synchronous in time between simulations runs.

High LASC estimates in JSBACH in Brazil and South and Southeast Asia can be explained by the strong positive response of forest productivity to rising  $CO_2$  concentrations in the model, and a consequently large LASC particularly upon clearing of tropical evergreen forests. High EED and PTD estimates in ORCHIDEE-CNP in particular in Brazil, Southeast Asia and Equatorial and Southern Africa, might result from accounting of phosphorus constraints on the biomass built-up under elevated  $CO_2$ . ORCHIDEE-CNP simulates a more realistic sensitivity of plant productivity to elevated  $CO_2$  than the version without nutrients, ORCHIDEE (discussed in detail in Sun et al. 2020), but more models are needed to draw robust conclusions about phosphorus effects on  $f_{LULCC}$ .

LPX-Bern showed very low LASC, EED and PTD estimates throughout the simulated period which result from low  $f_{LULCC}$  estimates due to the exclusion of wood harvest and shifting cultivation, and, in particular in most recent decades, due to the lack of tropical peatlands in the used configuration (for a detailed discussion refer to Lienert and Joos 2018).

Low EED and PTD estimates in CLASS-CTEM likely result from a model change that led to different S0 simulations (control) for S1–S3 vs S4–S6 simulations which most probably also led to a pronounced variability and extreme values in some regional estimates.

JULES showed a remarking high inter-annual variability for the LASC already in the early simulated period in particular in  
685 Canada, SW South America, Middle East and Korea and Japan.

LPJ exhibited different IAV magnitudes for the pre-industrial and present-day land cover representation causing EED and PTD unable to be calculated. The LPJ divergence in IAV may be due to differences in the carbon-climate sensitivity for managed grasslands and croplands compared to natural ecosystems and further work is needed to understand the mechanisms responsible.

690 *Author contributions.* JP and WO designed the study. JN and JP conducted preliminary analysis. AB, JN, JP, FH, KH, and TL contributed to processing and evaluation of the data. PA, AA, DG, JN, SL, DL, SL, PM, JM, BP, SS, MS, HT, APW, AJW, and SZ provided the TRENDY v8 data used in this study. WO processed the data, led the analysis and drafted the paper with contributions from all coauthors.

*Competing interests.* The authors declare that they have no conflict of interest.

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