Overview of revisions

[This section is repeated from the response to Reviewer 1] We greatly appreciate the constructive review by Julia Pongratz (below referred to as "reviewer 1") and the anonymous reviewer (below referred to as "reviewer 2"). We hope that added and modified text has served to improve our manuscript. In summary:

- Model simulations have not been repeated and all results remain unchanged since the first submission.
- We conducted additional simulations to investigate and illustrate differences in indirect fluxes, caused by environmental change (Δf) on natural and agricultural land, and how indirect fluxes (Δf^{FF} and Δf^{LUC}) combine linearly (new Fig. 1). This shows that non-linearities are negligible during the historical period. A treatment of non-linearities has been included in our formalism and we show which non-linearity terms remain when deriving *e*RSS and *e*LFB from simulations (Eqs. 14 and 15 in the new manuscript).
- We included an additional figure to illustrate the spatial distribution (map) of the C sinks and sources triggered by environmental change ($\Delta f_{\mathrm{nat}}^{\mathrm{FF+LUC}}$ and $\Delta f_{\mathrm{agr}}^{\mathrm{LUC}}$) and of the non-linearity effect mentioned above ($\Delta f_{\mathrm{nat}}^{\mathrm{FF}} + \Delta f_{\mathrm{nat}}^{\mathrm{LUC}} - \Delta f_{\mathrm{nat}}^{\mathrm{FF+LUC}}$).
- We have re-structured some contents of the text, trying to address both reviewers' comments. Specifically, we now have a separate section for an overview of the D1, D3, and E2 methods, including a formalistic description of their setup (Eq. 2, 3, 4). We then introduce the formalism of flux components rigorously as suggested by reviewer 2 (contents previously in Appendix 1), and use this to identify the conceptual difference between D3 and E2 methods. This rearrangement provides more and more concise information, avoids the appendices and limits additional text.
- In view of the ambiguity of the choice of methods, we dropped the strict recommendations, e.g. the sentence "In summary, we recommend not to rely on results from method D3 or E2 in the context of the global (or regionalized) carbon budget, but to apply method D1 (under preindustrial conditions)."
- While trying to add information and analysis where required by the reviewers, we tried to maintain the conciseness of the paper to qualify it as an ESD Short Communication.

In this document, quoted reviewer comments are indented and in blue font. New and/or modified text is in green font.

Response to Reviewer 2

> The submitted manuscript by Stocker and Joos investigates differences in anthropogenic land use and land-cover change (LULCC) emissions (eLUC) arising from different methodologies in the literature and presents a case with standalone DGVM and a coupled model. The study is a step in the right direction and will help to resolve some existing confusion in the LU literature, but it still needs a sharper focus and clarity. It attempts to cover both a methodological discussion (i.e. different definitions) and an analysis of differences in eLUC estimates in stand-alone and fully coupled models. The current conceptual scope of the former is too idealized and it does not help to understand in depth the latter. I would recommend to expand the analysis of the simulations and to downscale the discussion of the flux definitions to only those relevant to that analysis.

We would like to thank the anonymous reviewer for the time spent on reviewing our manuscript and the very helpful comments. We took several measures to account for the above mentioned points:

- We have expanded the analysis of our model results. Specifically, we demonstrate the validity of the crucial linearity assumption that underlies much of our formalism ($\Delta f^{\mathrm{FF+LUC}} = \Delta f^{\mathrm{FF}} + \Delta f^{\mathrm{LUC}}$, see new figure 1). Furthermore, we included the new Fig. 4 to show maps of the C sink/source on natural and agricultural land and of the non-linearity. In the response document below we also provide maps showing the flux components ($e\mathrm{LUC}_{\mathrm{E2}}$, $e\mathrm{LUC}_0$, eRSS, eLFB).

- We rearranged the text to include the appendix describing the concepts in the main text to better help the reader understand the concepts applied and support the interpretation of our results.

- We restrict the discussion of model setups (D1, D3 and E2) and flux components ($e\mathrm{LUC}_0$, eRSS, eLFB) to those quantitatively analysed in the results section using our model.

- Table 1 and new table 2 provide a description of model setups and flux components. This is a minimum number of model setups, necessary to disentangle these differences and component fluxes treated in our paper.

- The level of complexity chosen here is very comparable to the one in PG14 (no time, no space, only distinction between natural and managed land). We added discussion on limitations of our formalism (e.g., choice of the reference state) and on interactions of interannual climate variability and eLUC derived from differencing modelled land-atmosphere fluxes.

> My first criticism is that the manuscript needs a cleaner presentation of the mathematical formalisms relevant to analysis of the experiments (may be in an appendix):
>
> - It does not present mathematical equations used to produce figures 1-3 and table 3, just conceptual definitions. How such definitions are used for the cases with heterogeneous and time-varying LULCC? Can they be as easily linearized?

To clarify this, we now provide additional information in the figure captions. For example added text in caption of Fig. 2:

Time series are calculated following Eqs. 2-4, where F is the global total land-atmosphere $\mathrm{CO_2}$ flux in the respective simulation.

Added text in caption of Fig. 2 reads:

Time series are calculated following Eqs. 2, 4, 13, and 14.

Added text in caption of Tab. 2 reads:

Note that fluxes F generally refer to global totals for a given point in time t. Thus, for example $F_0^{\mathrm{FF}}(t) = \int_{x,y} A_0(x,y)\,\Delta f_{\mathrm{nat}}^{\mathrm{FF}}(x,y,t)\,dx\,dy$. For simplicity, we have dropped the time and space dimensions.

Table 1 and new table 2 together now provide the necessary information of how the model is set up in each simulation, and how total fluxes in each of these setups can be decomposed. The linearity assumption is now explicitly assessed (see new Figure 1).

- It also would help to state from the beginning if the formalisms refers to cumulative or net fluxes. It appears that figures show the net fluxes but the methods section states that the equations 5, 6, and 7 compute cumulative CO2 emissions from land use change as a difference in terrestrial C storages.

This was described wrongly in our manuscript ("Cumulative CO_2 emissions from land use change are calculated as the difference in terrestrial C storage [...]"). This is inconsistent with the formalism and calculations we present and has probably caused confusion here. We modified respective text in Section 4:

LUC-related CO_2 emissions are calculated as the difference in the land-atmosphere CO_2 exchange flux between the simulation with and without LUC using Eq. 2 for the bookkeeping, 4 for the coupled, and Eq. 3 for the offline setup.

All equations are valid irrespective of whether they describe annual fluxes or cumulative fluxes. Generally, we describe F to the be land-atmosphere CO_2 exchange **flux**, i.e. not cumulative. Also Figures show annual fluxes. We added text in Section 2.1 (Introduction of D1) reads:

In general, F refers to a global annual flux, but equations provided here are valid also for cumulative fluxes and smaller spatial domains.

Wherever we refer to cumulative fluxes, this is clearly expressed (Captions of Figures and Table 3, Section 5).

- Furthermore, it would be useful to include a list of all mathematical terms and what experimental setups they represent. There are a number of Fs with different sub- and super-scripts and it's hard to follow the equations without having all notations in one place.

For a better overview, model setups and their component fluxes are now all given in Table 1 and new Table 2. Mathematical terms used to describe model setups, areas, and flux components are described in the text and in captions of Table 1 and 2. E.g., in Section 3, where we introduce the formalism to describe component fluxes, we write:

F denotes again a carbon flux (e.g. in GtC yr^{-1}), f a carbon flux per unit area, and Δ a change with respect to the reference period/start of the simulation. Superscripts '0', 'LUC', and 'FF' refer to the driver of environmental conditions: no forcing, emissions from LUC, and fossil fuel plus other non-LUC forcings. Subscript 'agr' refer to converted land and subscripts 'nat' to land that has not changed its status over the course of the simulation. ΔA is the total area that has been converted, e.g., from natural to agricultural, up to the point in time of interest. A_0 is the initial (reference) area. $\Delta f_{\mathrm{nat}}^{\mathrm{FF+LUC}}$ is the change of the area-specific flux occurring on unconverted land due to environmental impacts caused by the combination of FF and LUC.

- The methods used also make a critical assumption that the environmental effects from LUC and FF combine linearly. I think the validity of this assumption needs to be demonstrated and discussed, both for local and global scales.

We added such analysis, now provided in new Figure 1. In section 3, where we use this assumption to decompose fluxes, we write:

Figure 1 reveals that global fluxes due to FF and due to LUC forcing alone combine in an almost perfectly linear fashion to the flux induced by the combined effect of FF and LUC up to present and discernible deviations (δ) emerge only in a future scenario of continuously rising CO_2 and changing climate and contribute ~10–20% by 2100 in RCP8.5.

> Second, manuscript does not discuss implication of unforced climate variability for the eLUC in the coupled and stand-alone simulations. I don't think the SM08 and GC13 approach takes care of natural climate variability; it would be good to include that aspect into consideration as well.

We thank the reviewer for this suggestion. Added text in the revised manuscript addresses the issue of unforced climate variability and *e*LUC. In our formalism, the land-atmosphere CO_2 exchange flux due to unforced climate variability is F_0^0. We have added explanations to clarify this issue. In the introduction, we now write:

Internal, unforced climate variability may affect the quantification of *e*LUC as climate variability affects the land-atmosphere carbon flux F. Ideally, the model setup should be such that internal, unforced variability evolves identically in both simulations. Then the land-atmosphere fluxes from land not affected by LUC and caused by internal variability would cancel when evaluating Eq. 2. In practice, this may be difficult to achieve for some state-of-the-art Earth System Models as LUC affects heat and water fluxes and thus climate. A potential solution is to run the land module offline in both simulations or to force the land module in the simulation with LUC by using climate output from the reference simulation without LUC.

And in Sect. 2.3 addressing *e*LUC derived from coupled models, we now write:

Unforced climate variability will evolve differently in the two ESM simulations as the applied forcing is different. The component in $F_{\mathrm{LUC}}^{\mathrm{FF+LUC}}$ and F_0^{FF} arising from differences in internal variability will be attributed to $e\mathrm{LUC}_{\mathrm{E2}}$ according to Eq. 4. This misattribution could be significant in particular when considering small regions and short time scales. Ensemble simulations would be required to quantify the impact of internal climate variability on $e\mathrm{LUC}_{\mathrm{E2}}$. Alternatively, averaging over a large spatial domain and temporal smoothing tends to moderate the influence of unforced variability on $e\mathrm{LUC}_{\mathrm{E2}}$.

> Furthermore, I am not sure if it's actually possible for many current DGVMs and ESMs to compute the difference between sources on agricultural and natural lands (i.e delta fs) in the same experiment, because most models cannot separately compute physical and biogeochemical soils under agricultural and natural lands. Perhaps the authors could provide figures illustrating how delta fs compare to one another in their model, which would be fairly novel illustrations.

The model applied here, as well as other DGVMs, rely on a gridcell-tiling to separately simulate C dynamics on natural land, croplands, and pastures, affected by land conversion and environmental conditions. This is described in more details in SM08. Some models, including the one applied here, include separate gridcell tiles for primary and secondary (abandoned agricultural) land (Stocker et al., 2014), and some even distinguish between cohorts of agricultural land (GC13) or secondary land (Shevliakova et al., 2009) of different age (time after abandonment).

We appreciate the reviewer's suggestion to include results for how Δf_{nat} and Δf_{agr} compare. We now included new Figure 4 that provides this information and added text:

Secondary emissions are determined by the magnitude of C sinks and sources induced by environmental change, occurring differently on disturbed (agricultural) and undisturbed (natural) land. Fig. 4 reveals that the C sink capacity on natural land under rising CO_2 and a changing climate (year 2100, RCP8.5) is greatest in semi-arid regions of the Tropics and Subtropics and along the boreal treeline. In contrast, agricultural land at low latitudes acts as a net C source under environmental change and a net sink at high latitudes. The difference between the sink strength on natural and agricultural land is related to the *e*RSS component flux and reveals that the Tropics are the most efficient potential C sinks. Interestingly, at high latitudes, agricultural vegetation is an even more efficient C sink than natural vegetation. Fig. 4 also provides information about the spatial distribution of non-linearities from the combination of the FF and LUC forcings, corresponding to the differences between the red and the black curves in Fig. 1 in year 2100. The sum of individual effects is greater than their combination in almost all vegetated areas, but most pronounced along the transition zone between forest and open woodland. Opposite effects are simulated in individual gridcells and are likeley related to the threshold-behavior of the dominant vegetation type.

> Third, if models compute spatial fluxes why does analysis focuses only on global totals and ignores spatial details? It will be useful to go beyond global net flux trajectories, such as in figures 1 and 2, and show maps of LULCC effects. Unlike the global effect of CO2 on climate, the effect of LULCC on carbon is not global but local, and is highly heterogeneous and time varying. If the Bern model is able to compute delta f values separately for agricultural and natural lands in their simulations, they can actually clarify how changes in the C fluxes on different kinds of lands (at the core of the used formalism) relate to differences in total fluxes. Furthermore,.

Again, we appreciate the reviewer's suggestion to provide more details on spatial information. As mentioned now in the manuscript, secondary emissions (*e*RSS and *e*LFB) are determined by the magnitude of C sinks and sources induced by environmental change, occurring differently on disturbed (agricultural) and undisturbed (natural) land. This information is provided by new Figure 4. Below, we show cumulative component fluxes across space (Figures 1 and 2). However, we chose not to include this figure in the manuscript to keep the presentation of results to a minimum.

> Fourth, the used definition of the bookkeeping flux as a difference between two experiments is incorrect. The original bookkeeping approach of Houghton 83 and all subsequent Houghton's estimates compute LULCC emissions (i.e. eLUCD1 in the manuscript) only for the lands affected by LULCC in the same simulation (there is no F_0^0), not as a difference between fluxes in two experiments as presented in equation 5. The difference equation 5 was introduced in stand-alone models and EMICs studies.

This is absolutely true. We did not clearly distinguish between actual bookkeeping models and process-based models following a "bookkeeping method". Added/modified text in Section 2.1, where we describe the D1 method, reads:

Process-based vegetation models can be run in a conceptually corresponding setup ("bookkeeping method" in SM08 and thereafter) by holding environmental boundary conditions constant. While bookkeeping models are designed to derive LUC-related C emissions from a single simulation, process-based models commonly take the difference in net land-to-atmosphere carbon flux (F) between a simulation with and one without LUC:

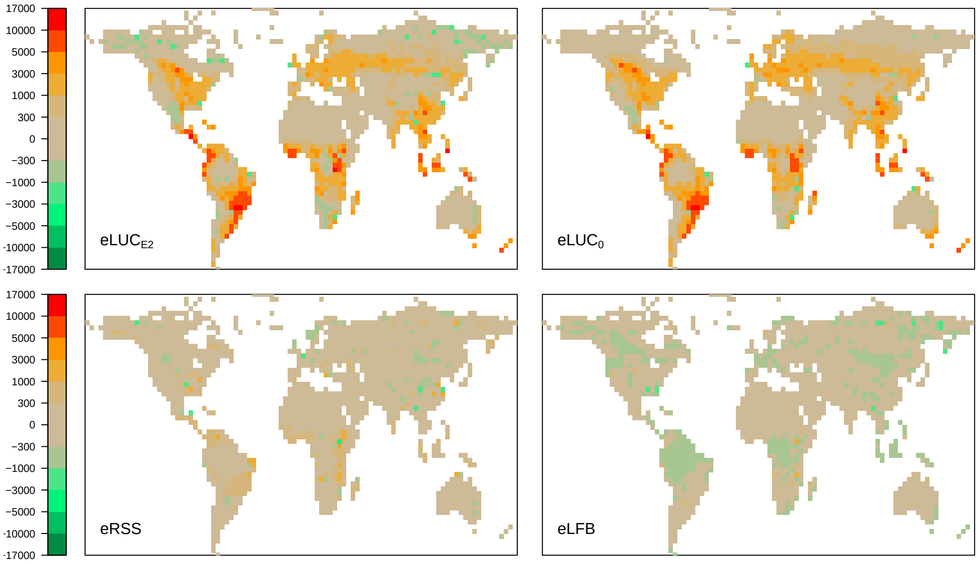

Figure 1: Cumulative component fluxes for the historical period (1850-2004). $e\mathrm{LUC}_0 = e\mathrm{LUC}_{\mathrm{D1}}$.

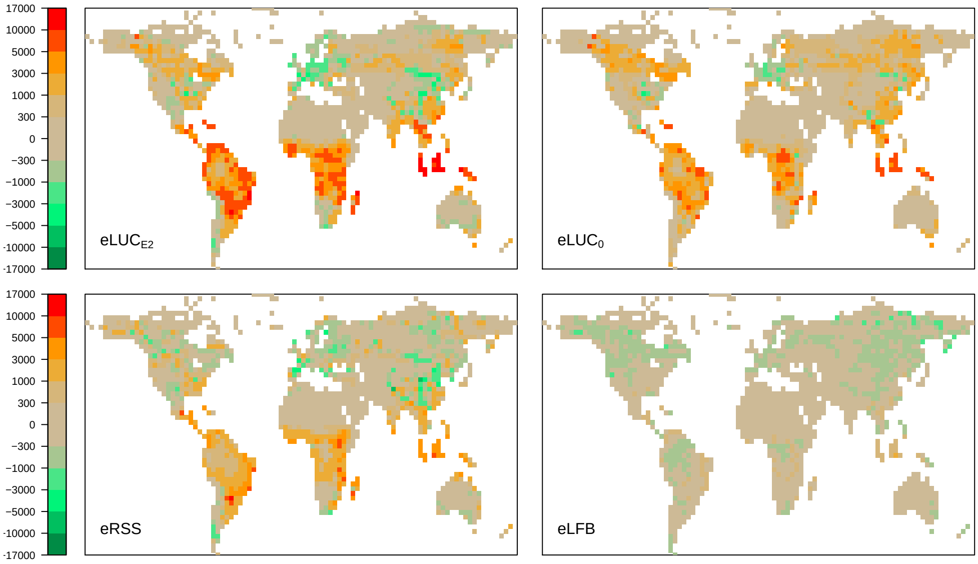

Figure 2: Cumulative component fluxes for the future period (2005-2100). $e\mathrm{LUC}_0 = e\mathrm{LUC}_{\mathrm{D1}}$.

I personally believe that the differencing approach, even if it's the most widely used in the literature, is not a good strategy for characterizing emissions from lands affected by LULCC. The difference in total land fluxes under the method in equation 1, 6 and 7 is caused by LULCC but it does not represent emissions from lands affected by LULCC, it's a different metric. Perhaps the authors can clarify this in the results sections. Most models have to invoke differencing approach because of their technical limitations: stand-alone land models and ESMs do not keep track of belowground soil BGC pools separately on lands affected by LULCC and natural lands; as a result, cannot compute soil respiration on natural and agricultural lands. A few models do (e.g. JSBACH and MPI-ESM, GFDL's LM3 and ESMs, as well as some EMICs). In ESMs the fluxes on natural land are not the same in F^0_{LUC} and F^0_0 because of climate variability and a biophysical feedback on climate (the two are of about the same magnitude).

We agree with the reviewer in that the differencing approach implies that effects of LUC-related changes of climate variability on the land-atmosphere CO_2 fluxes are ascribed to *e*LUC. As noted above, we have added text discussing this aspect (“Internal unforced climate variability ...” in Sect. 2.1 and “Unforced climate variability will evolve differently ...” in Sect. 2.3). In the model used here, climate variability is not internally simulated but prescribed from the observational data (31-year baseline climatology, see Sect. 4). The differencing approach thus largely cancels this effect and what is ascribed to *e*LUC is only the LUC-related modification of this flux. This is also valid for other models that use prescribed climate (and climate variability). However, we note that “Emissions from lands affected by LULCC” are by definition not the same thing as “emissions attributable to LULCC”. The differencing approach allows a separation of the latter by comparing a world with and a world without LUC, rigorously achieved by the E2 method, using coupled ESMs.

> While it’s beyond the scope of this manuscript, generally it would be much more productive to analyze how LULCCs affect stored carbon in vegetation and soils where such LULCC are taken place – not just differences in fluxes between a simulation X and simulation Y.

Clearly, analysing LUC effects on C pools (before and after conversion) , e.g., by comparing simulations and observations has a high priority for future research. Such benchmarking activities are under way and will provide essential information to constrain models and quantify uncertainty. Here, we are restricted in space (ESD Short Communication), and we have to limit the analysis of results.

References

Shevliakova, E., Pacala, S. W., Malyshev, S., Hurtt, G. C., Milly, P. C. D., Caspersen, J. P., Sentman, L. T., Fisk, J. P., Wirth, C., and Crevoisier, C.: Carbon cycling under 300 years of land use change: Importance of the secondary vegetation sink, Global Biogeochem. Cycles, 23, GB2022, doi:10.1029/2007GB003176, 2009.

Stocker, B. D., Feissli, F., Strassmann, K., Spahni, R., and Joos, F.: Past and future carbon fluxes from land use change, shifting cultivation and wood harvest, Tellus B, 66, doi:10.3402/tellusb.v66.23188, URL `http://www.tellusb.net/index.php/tellusb/article/view/23188`, 2014.