The biogeophysical effects of idealized land cover and land management changes in earth system models

Response to reviewers

29/04/2022

We would like to thank all reviewers for their dedicated time reviewing the manuscript and for their useful and constructive suggestions. We carefully addressed all comments by the reviewers and the manuscript has strongly benefited from the proposed changes.

Reviewer 1

Reviewer 1 Comment 1

This manuscript evaluates the local and non-local effects of land use and land management change (LULMC) under present-day climate in three state-of-the art Earth system models. To do so the authors use a dedicated set of experiments of different idealised land use states.

The manuscript is methodologically sound and presents an important contribution to understanding the biogeophysical impacts of LULMC. In particular, the use of three different ESMs enables to provide a more comprehensive picture on the uncertainties and robustness of the simulated features. The number of simulations, ESMs, and variables discussed make a fairly dense reading of the results, which, in my opinion, could be somewhat improved by following a more rigid structure (see below).

Response

We thank the reviewer for the appreciation of the study topic and the work done to enable a multi model study. Below we address every comment in detail and explain the corresponding changes made to the manuscript.

Reviewer 1 Comment 2

The results and section 3.2.1 in particular are hard to follow. Consider clearly separating local and non-local (e.g. move ln 349f to ln 358) and sticking to one order in which you discuss the models in each section (e.g. CESM, followed by EC-Earth, then MPI) throughout the results (or manuscript in general).

Response

We thank the reviewer for the comments on the structure of the results. We implemented these suggestions to make the results section clearer. We made sure there was a logical order in the discussion of these results: first local then non-local and total and finally the comparison across the ESMs if there were noteworthy differences. Additionally, we tried to discuss the results in the same order of ESMs as displayed in the figure hence first CESM, then MPI-ESM and lastly EC-EARTH.

Furthermore, we moved the last paragraph of section 3.2.1. to the discussion (see comment later). Most sections of the results already followed a similar structure but below we highlight the additional changes made to this aim:

> As a consequence of cropland expansion (CROP-CTL), CESM shows a strong local cooling over the NH boreal latitudes which extends into most of the NH mid-latitudes (Figure 5a). ~~This local cooling is amplified by a strong non-local cooling over these regions.~~ The tropics and subtropics show a strong local warming of up to 4 K over the (deforested) tropical rainforests. MPI-ESM shows a similar pattern to CESM in NH boreal latitudes but with a smaller local cooling which does not extend as far south into the NH mid-latitudes. MPI-ESM also simulates local warming over the tropics, but with a different spatial pattern and lower magnitude compared to CESM and EC-EARTH. The local signals in EC-EARTH are similar to CESM, showing a strong local warming in the tropics. However, in NH boreal latitudes the signals are mixed, with a cooling over the (deforested) boreal forests and a strong warming over the permafrost covered areas (Siberia, Northern Canada and Alaska). This NH boreal warming is most likely due to the shift in the EC-EARTH simulation from natural land to managed land, leading shorter duration of frozen soils throughout the year which causes a soil warming.
>
> In CESM the local cooling is amplified by a strong non-local cooling over these regions. The non-local effect in MPI-ESM strongly differs from CESM. While CESM simulates a widespread cooling, MPI-ESM shows a weaker but clear warming over the boreal regions, Europe and Eastern USA. The non-local effect in EC-EARTH is mixed with a warming over the Arctic regions and the Sahara, and a cooling in the mid-latitudes and tropics. In EC-EARTH and CESM, the local signals dominate the total response in the tropics, opposed to MPI-ESM, where the non-local effects dominate the total signal globally. The non-local effect also dominates over NH boreal latitudes in CESM while in EC-EARTH the pattern differs regionally.

Additionally we added the following table at the end of section 3.1. with a summary of the consistent patterns across all ESMs.

Table 3. Summary of local and non-local effects due to the different LCLMC. Each cell indicates where the changes in surface temperature response are consistent in sign.

LCLMC	Local effects	Non-local effects	Total effects
cropland expansion	tropical warming	none	tropical warming
afforestation	tropical cooling	global warming	warming across boreal latitudes and cooling over tropics
irrigation expansion	regional cooling	regional cooling	regional cooling

Reviewer 1 Comment 3

Non-local effects - Winkler et al (2017) recommend prescribed SSTs to isolate non-local LCC effects from background climate. Using a dynamic ocean as done here has the advantage to identify non-local LULMC impacts such as the cooling/warming response in the north Atlantic in CESM. However, it also seems to blur the non-local effects from LULMC and background climate judging based on the appendix figures' widespread - and seemingly robust (?) - non-local effects. I feel this should be discussed to give an indication on how robust these non-local effects are (not requesting another simulation, although this would be instructive in really separating those non-local effects).

Response

Thank you for this feedback. As we understand it, the study by Winckler et al. (2017) does not recommend using prescribed SSTs to get a more robust estimation of the non-local response. This is also highlighted by his later work where he moved to using fully coupled simulations (see Winckler et al. 2019). We have consulted with Johannes Winckler who confirmed our interpretation and recommend using an interactive ocean for studying the question at hand.

The non-local effects derived from prescribed SST simulations have the advantage of being less noisy due to constrained internal climate variability. This helped constraining the results in the study of Winckler et al. (2017) as he performed relatively short simulations (only 30 years). While the noise associated with natural variability can be expected to be larger in fully coupled simulations, our reasoning was that this noise could be averaged out by running long-term simulations (160 years per GCM).

By performing these fully coupled simulations we allow for a more realistic climate response (as in reality oceanic processes may affect the climate response of LCLMC), which allows for the ocean to respond to large scale climate changes and create for example the strong AMOC response in CESM. We assess the uncertainty due to internal variability by splitting the timeseries in 5 ensemble members and checking the sign of change across these members. We acknowledge that this is not an optimal approach to sample internal variability and additional simulations adding more ensemble members would be beneficial especially in constraining the uncertainty regarding non-local effects.

In the revised manuscript, several sentences were added regarding this specifically within the first paragraph of limitations and outlook in the discussion section:

> These represent an underestimate in magnitude of the non-local effects in a simulation of global LCLMC, as due to the checkerboard pattern, non-local effects are the consequence of LCLMC applied to only half of the grid cells around the globe. As the non-local effects, by design, also capture all internal climate variability they are more uncertain than the local effects presented here. To limit the uncertainty related to climate variability as much as possible, the simulations could be repeated within an ensemble setup. However, such setup would require substantial additional computation and storage resources.

We acknowledge that Winckler et al. (2017) did recommend prescribing SSTs for applications where a robust identification of the local effects is the main goal. Although our manuscript mainly focusses on the local effects, it has always been the goal within the LAMACLIMA project to include results that are as informative as possible for both local and non-local effects. Further analyses using these simulations are currently being prepared which focus more on the non-local aspects of the biogeophysiscal response.

Reviewer 1 Comment 4

ln 23 Depending on the land use forcing higher estimates exist (139 PgC for the last 1000 years in Kaplan et al 2011).

Kaplan, Jed O., Kristen M. Krumhardt, Erle C. Ellis, William F. Ruddiman, Carsten Lemmen, and Kees Klein Goldewijk. "Holocene Carbon Emissions as a Result of Anthropogenic Land Cover Change." The Holocene 21 (5): 775–91. https://doi.org/10.1177/0959683610386983.

Response

We thank the reviewer for this suggestion. We have adapted lines 21 to 23 to reflect the most recent state of knowledge as assessed by the IPCC AR6 WG1 and GCP's annual carbon budgets:

> Land cover change and land management change have been intrinsically connected to human development throughout history. The impact of land cover change and land management change (LCLMC) on the global carbon cycle was estimated at 116 PgC based on global compilations of carbon stocks for soils (Sanderman et al., 2017) and for vegetation as 447 PgC (Erb et al., 2018; a loss of about half of the world's terrestrial biomass), with substantial shares already in the pre-industrial period (Canadell et al., 2021). About 10% of anthropogenic CO2 emissions have been caused by LCLMC over the last decade (Friedlingstein et al., 2022).

Reviewer 1 Comment 5

ln 103ff In the CESM description it would be informative to add the horizontal resolution (currently buried in ln 159)

ln 160 consider moving the information on the grid resolution into the model description

Response

Thank you for this suggestion, we added the horizontal resolutions of each model at the end of each paragraph describing the ESMs, here below an example for CESM:

> The CESM simulations were performed at a spatial resolution of 0.90°x1.25°.

Reviewer 1 Comment 6

ln 125 If possible give grid resolution TL255 as degree or km2 equivalent.

Response

Thanks for this suggestion, we added the information in km.

> The atmospheric component is the Integrated Forecast System (IFS) developed by the European Centre for Medium Range Weather Forecasts (ECMWF) that uses the TL255 horizontal grid (+-80 km) and 91 vertical model levels with the top level at 0.01 hPa.

Reviewer 1 Comment 7

ln 128 This seems important, could you please state briefly what happens instead?

Response

We thank the reviewer for this suggestion and added a sentence to describe what happens instead.

> Note that this is a dynamic vegetation model which does not explicitly solve the energy balance as the previous ESMs did. The atmosphere model IFS has a dedicated land surface component: the Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL) to handle the surface water and energy fluxes to the atmosphere.

Reviewer 1 Comment 8

ln 181 - Do you mean "the native parameterization of irrigation"?

Response

Indeed, we do. I clarified it within the sentence as follows.

> For the IRR simulation, we apply the same land cover maps as in the CROP simulation, but here, the native irrigation parameterisation of each model is activated and applied at the global scale

Reviewer 1 Comment 9

ln 274 Are the 0.1 W m-2 the global imbalance?

Response

Yes they are, we added the word global to make this more explicit.

> While applying this approach, a modest global imbalance of less than 0.1 W m^{-2} is found over all land grid cells for all different cases, indicating the general applicability of the method.

Reviewer 1 Comment 10

ln 338-344 Consider moving this into the discussion.

ln 365ff - Consider moving this extended comparison to other published work into the discussion.

Response

We thank the reviewer for this suggestion, after consideration we decided to move both paragraphs to the discussion section. The section regarding the shortcomings of the evaluation approach was added to limitations and outlook and the section regarding the extended comparison was added as a separate section in the discussion with the heading 'Inconsistent non-local effects across ESMs due to idealised cropland expansion' and shown here below.

> The global non-local cooling in CESM is consistent with the findings in a previous global deforestation simulation performed by Winckler et al. (2019a) with MPI-ESM. However, these results strongly contrast with the non-local response found in MPI-ESM here. Some

methodological differences should be noted here: Winckler et al. (2019a) performed a fully idealised response of MPI-ESM and CESM in CROP-CTL, in contrast to their consistent results for CROP-FRST: (i) MPI-ESM shows a weaker albedo effect when compared to CESM (Figure 5c), additionally (ii), the MPI-ESM model shows a strong decrease in annual boreal cloud cover (see Figure C5), which is especially strong in boreal summer (not shown) and could cause an additional warming, possibly offsetting any non-local cooling caused by changes in albedo. In summary we can state that the non-local effects due to full deforestation presented here are in line with literature (Winckler et al., 2019a). However, the non-local effects display a larger uncertainty when it comes to the non-local effects of deforestation from present day conditions (i.e. CROP-CTL as presented here). It should be noted that due to the strong albedo bias in CESM over NH mid-latitudes (see Figure 4d) and the crucial role of albedo in determining the non-local effects, it is probable that the strong non-local cooling shown over CESM is an overestimation.

Reviewer 1 Comment 11

ln 354 - Please clarify, do you mean MPI-ESM shows a similar pattern to CESM in the local effects?

Response

Indeed, we do. To make it clearer we added ‘local’.

MPI-ESM shows a similar pattern to CESM in NH boreal latitudes but with a smaller local cooling which does not extend as far south into the NH mid-latitudes.

Reviewer 1 Comment 12

ln 390 - So really just the extratropics, not most of the globe?

Response

Thank for this remark, this can indeed be phrased better. I have rewritten the sentence as follows.

This is also indicated by the fact that the non-local warming dominates over the extratropics for all ESMs, in contrast to the local cooling which dominates over the tropics and parts of the subtropics (depending on the ESM).

Reviewer 1 Comment 13

ln 482 - "This indicates that extra-tropical afforestation is dominating the global picture for these models due to a strong albedo response largely counteracted by the turbulent heat fluxes" - Unlear to me, do you mean that the albedo response to extra-tropical afforestation is dominating the global energy balance response to afforestation?

Response

Thanks for flagging this, the sentence indeed is not completely clear, we adapted it as follows:

This indicates that the albedo response due to extra-tropical afforestation is dominating the global climate response for these models which is locally counteracted by the changes in turbulent heat fluxes.

Reviewer 1 Comment 14

Irrigation as an adaption strategy? Surely only where there is no future water stress as the authors point out further down. Is there any specific reference supporting this idea?

Response

This is a good point, however we feel like we already largely address this in the later part of this paragraph. Studies such as Rosa et al. (2020) and Van Maanen et al (2021) show that biophysical and socio-economic conditions will enable irrigation to increase towards the future making which indicates it could be considered as an adaption strategy. We acknowledge however that this is a relatively limited possibility as it can only be done when water is available. Therefore, we have softened the tone of this statement as indicated below.

> Irrigation clearly decreases temperature in both CESM and MPI-ESM, constituting another demonstration that deploying irrigation could entail side-benefits for local temperature reduction especially over agricultural land (Thiery et al., 2017; 2020; Hirsch et al., 2017). These results even suggest that achieving climate benefits could become an objective of irrigation deployment, making it potentially a deliberate adaptation strategy if constraints to its implementation – related for example to water availability or socio-economic enabling conditions – can be overcome.

Reviewer 1 Comment 15

ln 660 - URL missing

Response

We thank the reviewer for spotting this error, there were 2 URLs missing in the acknowledgements, these have been added now.

Reviewer 2

Reviewer 2 Comment 1

The manuscript investigates local and non-local climatic effects of LCLMC by three ESMs using four unique idealized experiments under the current climate. The study involves much work and brings novelty to the scientific community. I recommend accepting it after considering the comments below that could help to improve the paper.

Response

We thank the reviewer for the appreciation of the study topic and the work done to enable a multi-model study. Below we address every comment in detail and explain the corresponding changes made to the manuscript.

Reviewer 2 Comment 2

As I understand and as the abstract states, there is much uncertainty in the three models on the central questions of the study. The differences are well explained for each model, but could you go one step further and give overall conclusions (taking into account various model biases, etc.) and specific recommendations to the model developers on reducing this uncertainty?

Response

We acknowledge the point the reviewer makes here, and we propose to add a paragraph in the limitations and outlook section which highlights the most important biases for the different LCLMC for modelling teams to address, as shown here below:

> The results shown within this paper highlight some clear consistencies across the ESMs, however, often the ESMs tend to show differences. For example, more work needed to improve the representation of irrigation, especially for EC-EARTH and MPI-ESM. The MPI-ESM's idealized approach to implement irrigation in our simulations leads to unrealistic irrigation amounts especially in the boreal regions while underestimating the potential irrigation in the subtropics such as India. Furthermore, EC-EARTH is currently not a viable model for a study of the biogeophysical effects of irrigation, as water fluxes from land are not communicated to the atmosphere. This limitation is worth addressing as the implementation of irrigation in ESMs has been shown to make them more realistic over regions of intense irrigation (Al-Yaari et al., under review). Regarding land cover change, all ESMs still struggle to replicate observed patterns in energy fluxes (Figure 4). CESM has a strong overestimation of the albedo in the intermediate latitudes (30°N-50°N) with clear temperature biases over these regions, an issue which could be considered in future development of this ESM. For EC-EARTH, even though it has a highly advanced land model (LPJ-GUESS), the interface with the atmosphere is handled by a rather simple submodel (HTESSEL) within the atmosphere model IFS. This leads to some clear biases (e.g., an unrealistic response in the turbulent energy fluxes and albedo). Addressing these biases could be a useful strategy when further developing this ESM to make land cover induced climate effects more realistic.

Reviewer 2 Comment 3

As the other reviewer recommended, please consider revising the structure. It may be helpful for the reader if some text on the differences of the results (experiments/models/local and non-local effects) could be summarized in a table. Many findings are hidden in the text. A table that summarizes what models agree on disagree with, and overall conclusions would be helpful .

Response

We thank the reviewer for the comments on the structure of the results. We implemented some of these suggestions to make the results section clearer. We made sure there was a logical order in the discussion of these results: first local then non-local and total and finally the comparison across the ESMs if there were noteworthy differences. Additionally, we tried to discuss the results in the same order of ESMs as displayed in the figure hence first CESM, then MPI-ESM and lastly EC-EARTH. Furthermore, we replaced the last paragraph of section 3.2.1. to the discussion (see comment later). Most sections of the results already followed a similar structure but here below we highlight the additional changes made:

> As a consequence of cropland expansion (CROP-CTL), CESM shows a strong local cooling over the NH boreal latitudes which extends into most of the NH mid-latitudes (Figure 5a). ~~This local cooling is amplified by a strong non-local cooling over these regions.~~ The tropics and subtropics show a strong local warming of up to 4 K over the (deforested) tropical rainforests. MPI-ESM shows a similar pattern to CESM in NH boreal latitudes but with a smaller local cooling which does not extend as far south into the NH mid-latitudes. MPI-ESM also simulates local warming over the tropics, but with a different spatial pattern and lower magnitude compared to CESM and EC-EARTH. The local signals in EC-EARTH are similar to CESM, showing a strong local warming in the tropics. However, in NH boreal latitudes the signals are mixed, with a cooling over the (deforested) boreal forests and a strong warming over the permafrost covered areas (Siberia, Northern Canada and Alaska). This NH boreal warming is most likely due to the shift in the EC-EARTH simulation from natural land to managed land, leading shorter duration of frozen soils throughout the year which causes a soil warming.
> In CESM, the local cooling is amplified by a strong non-local cooling over these regions. The non-local effect in MPI-ESM strongly differs from CESM. While CESM simulates a widespread cooling, MPI-ESM shows a weaker but clear warming over the boreal regions, Europe and Eastern USA. The non-local effect in EC-EARTH is mixed with a warming over the Arctic regions and the Sahara, and a cooling in the mid-latitudes and tropics. In EC-EARTH and CESM, the local signals dominate the total response in the tropics, opposed to MPI-ESM, where the non-local effects dominate the total signal globally. The non-local effect also dominates over NH boreal latitudes in CESM while in EC-EARTH the pattern differs regionally.

Additionally we added the following table at the end of section 3.1. with a summary of the consistent patterns across all ESMs.

Table 3. Summary of local and non-local effects due to the different LCLMC. Each cell indicates where the changes in surface temperature response are consistent in sign.

LCLMC	Local effects	Non-local effects	Total effects
cropland expansion	tropical warming	none	tropical warming
afforestation	tropical cooling	global warming	warming across boreal latitudes and cooling over tropics
irrigation expansion	regional cooling	regional cooling	regional cooling

Reviewer 2 Comment 4

Could you add some info on how the PFTs distribution differs spatially among the models in the year 2014 (I expect they all may deviate from LUH2)? Can part of the inter-model differences be attributed to this? Also, is there a large inter-model difference in the distribution of forest types? (deciduous and evergreen forests may have very different implications for albedo). Similarly, can you state that any afforestation (from any previous land cover and to any type of forest) causes warming in the north and cooling in the tropics? Is it universal, or can you make some conclusions (although this may require additional analysis), e.g., conversion of specific forest type to forest gives more/less warming to make more implementable conclusions?

Response

For each ESM the land cover maps for the CTL simulation are based on the LUH2 dataset. However, in LUH2 there is no distinction in PFTs for forest, the only categories that exist are primary and secondary forest with no implications on which species belong to these categories. Therefore, each ESMs has their own approach to translate the LUH2 dataset in there different PFT categories, which also vary strongly across ESMs as is shown by the summary here below:

CESM: 8 PFTs: needleaf evergreen temperate, needleaf evergreen boreal, needleaf deciduous boreal, broadleaf evergreen tropical, broadleaf evergreen temperate, broadleaf deciduous tropical, broadleaf deciduous temperate, broadleaf deciduous boreal

MPI-ESM: 4 PFTs: Tropical deciduous, tropical evergreen, extratropical evergreen and extratropical deciduous

EC-EARTH: 4 PFTs: broadleaf deciduous, needleaf deciduous, broadleaf evergreen and needleaf deciduous

So, some differences will exist between the distribution of forest in the default land cover maps, here below we add a figure comparing the fraction of deciduous forest and evergreen forest for the 2015 CTL map across the 3 ESMs.

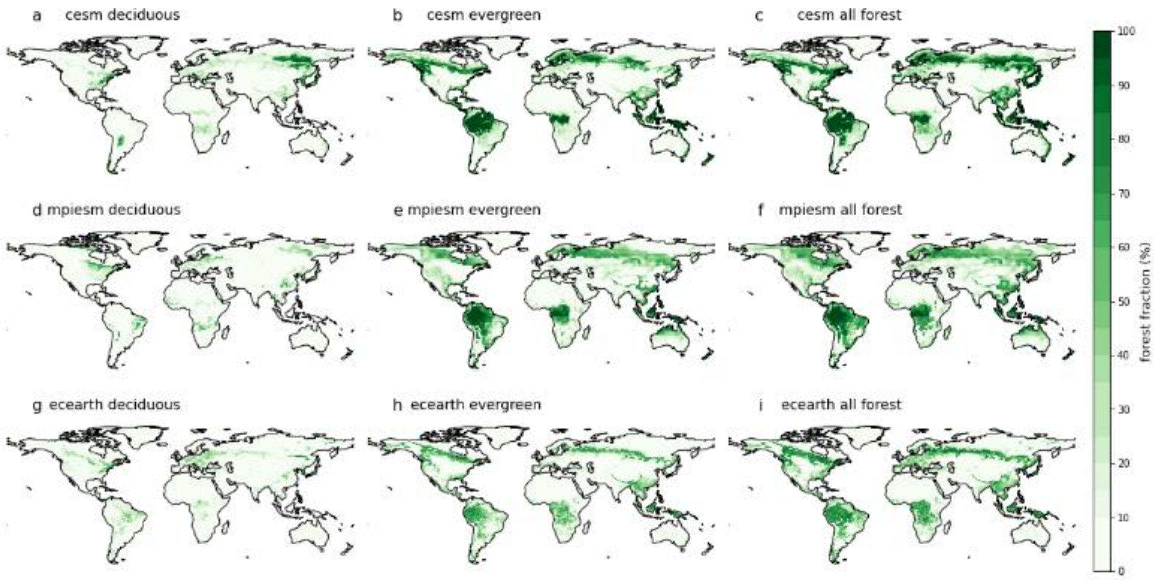

Figure B2. Total amount of forest (%) is shown for the 2015 CTL map for each ESM displaying different forest types. The amount of deciduous forest for CESM is shown in panel (a), the amount of evergreen forest in panel (b) and total amount of forest in panel (c). For MPI-ESM the amount of deciduous forest is shown in panel (d), evergreen forest in panel (e) and total amount of forest in panel (f). For EC-EARTH the amount of deciduous forest is shown in panel (g), evergreen forest in panel (h) and total amount of forest in panel (i).

All ESMs seem to show deciduous forest in similar areas across the globe, however the amounts do differ across the ESMs. With CESM showing the largest fraction of deciduous forest and MPI-ESM the lowest. Similarly for the evergreen forests, all ESMs show forest over the same locations, but the amounts vary strongly. EC-EARTH generally has the lowest amounts of forest which is again probably related to it using a dynamic vegetation model. Finally, some spatial patterns differ across the ESMs where EC-EARTH shows a much smaller area of forest in the boreal latitudes compared to the other ESMs.

To answer the question on whether it depends on the forest type whether warming or cooling would occur in a given region appropriately, one would need to look at the PFT level output. However, due to data constraints we did not investigate this in this much detail, instead we assume that any afforestation in a given grid cell would be containing similar forest types as today. We now added the figure shown here in the appendix of the revised manuscript.

Reviewer 2 Comment 5

Figures: consider adding a row of ensemble means of three models to some figures where appropriate

Response

As the study only contains 3 ESM and the responses tend to deviate strongly (in sign sometimes, but often in magnitude), we prefer not adding an ensemble mean of the 3 ESMs. We feel that this can often give a misleading value which is meaningless. The biogeophysiscal effects of LCLMC remain a difficult process to model. Although the separation between local and non-local as shown here helps increase consistency across ESMs, the results presented in the energy balance decomposition section also show that some models agree for the wrong reasons (different energy balance response yielding similar temperature change).

Reviewer 2 Comment 6

Figures 2 and 3: consider merging these two figures

Response

We thank the reviewer for this suggestion, however, we prefer to keep this data spread over two figures as we prefer to keep the distinction clear between the sections where we discuss annual mean changes and seasonal changes.

Reviewer 2 Comment 7

- Line 91: Second,
- Line 159: space missing
- Line 354: less cooling
- Line 458: both in both?

Response

We thank the reviewer for highlighting these errors, they have all been corrected in the revised manuscript.

Reviewer 2 Comment 8

Lines 160-170: Explanation of the methods. As I understood from the text, if the grid has at least some forest, then the grid becomes 100% forest. If it does not have forest but has other vegetation, then this vegetation becomes forest in a ratio of different forest types determined via latitudinal averaging. Is this so? The explanation requires clarification as it is quite misleading in its current state.

Line 165: for forest PFTs or for grids that have forest PFTs?

Response

This is indeed correct. We thank the reviewer for flagging the ambiguity in the existing text and adapted it accordingly:

> The different LCLMC scenarios used in the sensitivity experiments are outlined in Table 1. The idealised land cover maps for CESM and MPI-ESM are constructed following the approach described in Davin et al. (2020) using prescribed idealised land cover maps. To create the idealised FRST land cover map, we start from the 2015 land cover map of each model. All PFTs that are neither forest nor bare soil were removed. The remaining forest fractions are increased such that fractions within a grid cell add up to 100 %. As the bare soil fraction is preserved, the resulting land cover map only contains forest PFTs and bare soil. The approach mimics forest expansion across all vegetated, cropland and urban areas but avoids that trees are planted in e.g. desert, high altitude, and tundra regions (Figure 1d-f). Note that this approach is only possible for grid cells containing forest PFTs. For grid cells without forest PFTs

present, we calculate the latitudinal average (at each ESMs native resolution) of the relative forest PFT distribution consisting of different species. This value is then considered as representative for this latitudinal band and is used to replace all other vegetation in the grid cell. The same approach is followed for constructing the CROP map by keeping the crop fraction constant within a grid cell and removing all non-cropland PFTs (e.g. pasture, bush, forest and grassland; Figure 1a-c).

Reviewer 2 Comment 9

Line 182 and around: Please double-check the letters of figure panels shown in text, they do not always match

Response

We sincerely thank the reviewer for highlighting this issue, the referencing of the figure within the text has been corrected in the revised manuscript.

Reviewer 2 Comment 10

Lines 351-354: "conditions in which the frozen soils are less extensive throughout the year which causes a soil warming". Please revise the sentence to make it clearer.

Response

We agree with the reviewer that this sentence is a bit oddly formulated, we tried to make things clearer in the revised manuscript as is shown below.

> The local signals in EC-EARTH are similar to CESM, showing a strong local warming in the tropics. However, in NH boreal latitudes the signals are mixed, with a cooling over the (deforested) boreal forests and a strong warming over the permafrost covered areas (Siberia, Northern Canada and Alaska). This NH boreal warming is most likely due to the shift in the EC-EARTH simulation from natural land to managed land, leading to a shorter duration of frozen soils throughout the year which causes a soil warming.

Reviewer 2 Comment 11

There is much warming in the CROP experiment simulated by EC-EARTH due to local effects (fig. 5), but I cannot see to what local effects can this warming be attributed to in the decomposition analysis.

Response

Indeed, we had also noted this but could not find an explanation for this behavior. This caveat is acknowledged in the manuscript in lines 458-463:

> In EC-EARTH, the energy balance components do not explain the simulated warming over boreal latitudes, which is most likely related to the fact that EC-EARTH uses the temperature of the first whole soil layer as surface temperature. As a consequence, other processes that are not related to the surface energy balance (e.g. permafrost thawing) also affect the surface

temperature in this model. Finally, contrasting to the other models, the albedo in EC-EARTH does not influence the local surface temperature changes, as there is no change in local albedo This followed from the simplicity of the energy balance model used for the decomposition analysis. In MPI-ESM and CESM the surface temperature is defined as a radiative temperature hence exactly matching with the solution of this simplistic energy balance calculation. In EC-EARTH in contrast there is no radiative surface temperature variable and generally the temperature of the first soil layer is used as surface temperature. This implies that there are also several soil processes which affect the temperature for this model which are not included in the energy balance decomposition approach.

Reviewer 2 Comment 12

Figure 5 and C1 seem to have the same legend but vary. What are they standing for?

Response

We thank the reviewer for flagging this issue, the legend of C1 was indeed not clear and has been adapted now.

Annual mean surface temperature response to full idealised deforestation (CROP-FRST) of CESM, MPI-ESM and EC-EARTH. The local effect in CESM (a), the non-local effect (b) and the total effect (c). The latitudinal average of the local (blue), non-local (yellow) and total (green) signals of CESM (d). (e-h): same as (a-d), but for MPI-ESM. (i-l): same as (a-d), but for EC-EARTH. The stippling on the maps shows grid cells where all 5 ensemble members agree on the sign of change.

Reviewer 2 Comment 13

There seems to be a mix-up as the appendix does not always give info that is promised in the text, and there is no Appendix D that you refer to.

Response

Thanks for highlighting this issue, we went through the manuscript and corrected the references to the appendices.

Reviewer 2 Comment 14

Lines 388-400: Although you mention that Boysen et al. (2020) already show the biophysical impact of LULMC on AMOC, I think this finding deserves more discussion.

Response

We agree that it is a major result, a climate response that is strong enough to affect the ocean circulation in this magnitude is indeed very important. As CESM is showing strong non-local temperature changes in these simulations which appear to be strong enough to affect global circulation both through the atmosphere and the ocean. We highlight this result and note that it is not a single model feature (as was shown by Boysen et al, 2020). Yet we acknowledge that the analysis presented in this paper mainly focusses on understanding the local effects. To gain a better understanding of the non-local effects found here, one would need to look further in atmospheric and oceanic metrics indicating the changes made to global circulation which is beyond the scope of this study. However we should note that within the LAMACLIMA project Iris Manola is conducting an analysis focussing on the understanding of these non-local effects presented in these simulations.

To illustrate clearly what is discussed we add the paragraphs from the results (line 375-386) and discussion (line 569-574) sections which explain the AMOC feature.

> In CESM, this albedo-induced warming causes a cooling blob in the North Atlantic (Figure 6b). A similar but opposite pattern is also apparent in the cropland expansion experiment with CESM (Figure 5b), but appears as a warming blob with lower magnitude. The same warming blob was also found in the LUMIP deforest-glob experiments by Boysen et al. (2020). A plausible explanation for this dynamic is the different latitudinal effect of the LCLMC option. With a high-latitude hemispheric warming and a slight cooling in low latitudes, the thermodynamic response of the Atlantic Meridional Overturning Circulation (AMOC) would indicate a weakening due to a decrease in the temperature gradient, similar to thermodynamic driven AMOC weakening due to arctic amplification under climate change scenarios (Schleussner et al., 2014). Inversely, global-scale cropland expansion causes non-local cooling except for a localised warming over the North Atlantic. It should be noted, however, that this strong North Atlantic response in CESM is not consistent throughout the entire simulation period despite its high magnitude. The global non-local warming pattern has large implications for future deployment of land-based mitigation strategies, especially for boreal afforestation. However, it should be noted that non-local signals are highly dependent on the spatial pattern as well as the extent of the prescribed land cover change (Winckler et al., 2019a)

> In CESM a large scale land cover change even appears to affect global ocean circulation, as was illustrated by the strong AMOC response within this model. It should be noted that this is not a single model feature, as similar AMOC anomalies were visible for 2 other ESMs in the LUMIP deforestation simulations (Boysen et al., 2020). More research is needed to fully understand the processes that cause the non-local biogeophysical effects related to large scale land cover change shown here

Community comments

Before replying to any of the comments we would like to thank David Wårlind, Paul Miller and Lars Nieradzik for their constructive comments. We also had a small call during the review process to clarify some aspects regarding these comments. I think they have been helpful in increasing my understanding of the biogeophysics in EC-EARTH and the quality of the manuscript overall.

Community Comment 1
LPJ-GUESS does vegetation dynamics, but not energy balance. So how is the surface energy then calculated would be the first question of a reader? I'm puzzled that nowhere in the manuscript is HTESSEL, that does the surface energy and water balances, mentioned. HTESSEL is the main component you need to understand to figure out why EC-Earth is behaving as it does in this study. HTESSEL receives vegetation fractions, LAI, and type for high and low vegetation from LPJ-GUESS. The types have specific parameters for albedo, roughness length etc associated with them in hard-coded look-up tables in HTESSEL. In this section, you will need to add a description of HTESSEL and its biogeophysics.

Response

Thanks for flagging this issue, it was also remarked by Reviewer 1 that the way EC-EARTH handles the energy balance was too cryptic, we added a sentence regarding HTESSEL and what it does in IFS. However, we did not go into the details on how the biogeophysics is modelled as this is also not done for any other ESM in the current state of the manuscript, these descriptions are meant to give a short overview rather than explain this exhaustively. We intend to add an additional paragraph at the end of the section where we discuss the differences in the way the different models implement their biogeophysics. This paragraph will be added in the revised manuscript.

Community Comment 2
Spinup (row 149-150) Have any legacy effects, on climate, vegetation, C and N pool/fluxes, disappeared after these 10 years? Or you are not after an equilibrium state after these 10 years for the CTRL simulation? And for the FRST you would need more than 10 years to get a fully mature forest in areas of transitions to natural land cover (where trees grow), in LPJ-GUESS.

Response

These are good questions, we address these here separately:

1. The legacy effects on carbon and nitrogen pools have not disappeared yet after 10 years, some of these pools are not even in equilibrium after the full 160 year period. This was also explicitly not the intention here, as we focus on the biogeophysics which does not depend on the pools being in equilibrium, which is a common strategy when studying the biogeophysics (e.g. Duveiller et al. (2018), Thiery et al. (2017,2020)). Another colleague of mine within the LAMACLIMA project (Suqi Guo) is analysing these transient responses on the carbon pools and these will be published in a separate study.
2. We checked for the 'delay' in the establishment of the new FRST in EC-EARTH by plotting forest cover after the first 30 years and after the 160 year period (not shown here). These illustrated that a large amount of the forest was already established at an early stage in the

simulation. This is also apparent when comparing the surface temperature response of the first 30 years to the last 30 years of the analysis period, which show no clear differences indicating that although the forest was definitely not mature at that time, it does appear that the biogeophysical response was of a similar magnitude. This is probably due to the relatively simple way these are implemented in HTESSEL.

Community Comment 3

100% forested world (Figure 1, row 174)

If you set the Natural land cover fraction to 1 for all gridcells in the input file for LPJ-GUESS, then you have a 100% potential forest world. But then the question comes. Will trees grow everywhere with 2015s climate? In reality, it doesn't, and nor for EC-Earth/LPJ-GUESS, as you see in figure 1. The other models have set the physical parameters to represent a forest, but they don't either have a forest with biomass in all the areas (the forest isn't growing at high latitudes, tundra regions). Why hasn't EC-Earth done the same with prescribing a 100% forest world in HTESSEL and then letting LPJ-GUESS do the biogeochemical cycles as in the other models?

EC-Earth doesn't have any bushes (shrubs) (row 175).

Response

Thank you for the comment, at the time of simulation setup we weren't aware of the option to perform a full afforestation experiment as you describe here in EC-EARTH. When setting up the simulation we were faced with the fundamental differences in how each ESM handled land cover (MPI-ESM and CESM use prescribed maps while EC-EARTH had a dynamic vegetation module), eventually it was decided to move forward in the best way possible (given the information available to us at that time). We were aware of the potential inconsistencies which might occur with EC-EARTH especially for FRST but given the understanding we had at that time this was the best we could do. We would also like to thank you for flagging the error in line 175, it's been adapted for the revised version.

Community Comment 4

Latent and Sensible heat (figure 4)

Here you need to study and understand what HTESSEL is actually doing (not LPJ-GUESS). Opposite sign for both latent and sensible heat compared to the other models (sign convention in HTESSEL)? How have the different vegetation types in HTESSEL affected this? Especially for fig 4c as the albedo effect between a crop type world in HTESSEL can't have the same value as a forest type world.

Response

The opposite signs of the latent and sensible heat as shown here cannot be attributed to different sign conventions in the different ESMs. It seems indeed that, similar to what Boysen et al. (2020) found for grasses in the tropics, we see that crops also seem to be over productive causing anomalous energy balance responses. It is very strange that albedo is not showing any local differences for EC-EARTH as HTESSEL has different hard coded values for cropland and forest, it appears that somehow this effect due to albedo change is or captured by the non-local effects or just completely negligible. These are odd behaviours of the ESM which we currently don't fully understand but we are willing to look further into these issues outside the scope of this paper in order to improve our understanding of the biogeophysical response to land cover changes in EC-EARTH.

Community Comment 5

No FRST-CTL (row 368-388)

The only fraction of gridcells that get afforested in EC-Earth is areas that used to be cropland or pasture. When do you start to look at the effects of afforestation? LPJ-GUESS won't be able to have a fully-grown forest after the 10 years of "spinup" that you have after the change. It will take a while for bare soil after the transition to grow a mature forest. For some areas, it may be 100s ofyears. So, if you look at the effect after a shorter time period than that, then you will not have the effect of a forest, but rather a grassland mixed with trees. How is it in the other models? Do they have a mature forest directly after a transition into a 100% forest world? The tress is just there from one day to the next and growing?

Response

For the other ESMs the change is instantaneous, meaning that the atmosphere sees a forest (causing biogeophysical effects) but this forest has very little biomass in the beginning of the simulation. This is indeed not consistent with the way this is implemented in EC-EARTH, however as mentioned above we kept the same analysis approach across the ESMs as when comparing the signals of surface temperature between the first 30 years and the last 30 years of the simulation they were showing consistent patterns. We assume this might be related to how HTESSEL interprets the biogeophysics for a growing forest.

Community Comment 6

Irrigation expansion (row 410-412 and 489-490)

As there is no effect in HTESSEL from the irrigation in LPJ-GUESS (water cycles are disconnected) I wonder if there is an idea to look at this setup with EC-Earth? Also, crop vs irrigated crop type physical parameters in HTESSEL doesn't differ.

Response

Thank you for this comment, this is something we were not fully aware of when starting these simulations. We agree fully with the comment that within its current setup EC-EARTH is not a useful model to study the effects of irrigation. We still include them here as irrigation will affect other components in the earth system such as the biogeochemistry which will be analysed in later LAMACLIMA studies. As this study also presents these simulations we kept all available simulations, also considering that greening effects of crops due to irrigation are in theory included, in practice they have a negligible effect.

Community Comment 7

HTESSEL will be using cropland vegetation type values instead of forest values. How do these differ? Boysen et al. 2020 found that HTESSEL didn't run out of water despite high AET from the overproductive grass. But here we have crops, which will only be present at a fraction of the year, and then there will be bare soil (high LAI during crop growing season and zero when crops have been harvested), which should result in high sensible heat. But HTESSEL will see it as a crop type the whole year, so might be that the HTESSEL values aren't affected that much by the zero in LAI?

Response

We thank you for this comment, the way we understand it from the HTESSEL documentation is the following, each crop has a given roughness length and albedo value which is used throughout the entire year and these values are generally intermediate between the values of grass and forest. It seems that the crops simulated in our study suffer from the same bias as grasses did in Boysen et al. (2020). From the results shown in this study, it is clear that this is an important bias for understanding the effects of LCLMC on climate and which could be taken into account in future developments of HTESSEL.