Comments on "A global map of Earth system interactions"

The authors use simulations from the land model LPJmL to map some Earth system interactions. Specifically, they map the effects of climate change and land use change on natural vegetation cover, surface water runoff, and carbon storage density (on land). They aggregate the results from different grid cells into clusters, either based on predefined partitions of the Earth system (top-down approach) or on partitions obtained using clustering algorithms (bottom-up approach). They use clustering quality metrics to identify the best top-down partitions for each interaction and for all interactions collectively. This gives insights into the drivers of interactions. It also shows how some important local information can be lost when averaging results over common Earth system partitions (by continents, biomes, ...). They compare top-down and bottom-up partitions and find that the latter are generally better. They then discuss a specific bottom-up partition where the constructed clusters are of good quality and are spatially compact. This allows the identification of high-impact clusters relative to climate change and land-use change.

I found the study interesting, and I can see how applying the same framework to outputs from other models or focusing on different components within the Earth system could be highly valuable. The introduction and methods sections are well written, clear, and provide a nice overview of the study's key aspects. The results are also presented clearly, but I feel there is a slight mismatch between the paper's framing (interactions) and the actual analysis performed, which is about the response of Earth system components to land use and climate change. I elaborate on these points in my comments below. Overall, I recommend reconsideration after major revisions.

Just a small note: I'm not an expert in the biophysical processes or clustering techniques covered in this study, so I may not be in the best position to fully evaluate the interpretations (though they seem well founded). Similarly, I'm not very familiar with most of the cited literature, so I can't confidently assess the relevance of the references.

Major comments :

1. I think giving a bit more information on the LJPmL simulations would be helpful, even if this information is accessible in Lade et al (2021). For example what reanalysis variables are used to force the model ? Also, since the model is forced with reanalysis data, I assume it is a one way coupling, i.e. changes in natural vegetation cover and carbon storage density do not impact albedo,precipitation patterns or CO2 concentrations. This could be explicitly mentioned given that you are studying land→climate interactions.
2. From my understanding, the authors primarily quantify the effects of land-use change and climate change on specific variables, rather than directly examining Earth system interactions. The authors themselves state this in lines 57–60: *"More precisely, we quantify the effects of change in natural vegetation cover on surface runoff and on carbon storage density, as well as the effects of climate change on surface runoff and on natural vegetation cover, based on previously performed simulations with the spatially resolved dynamical global vegetation model LPJmL"*. I think these lines nicely summarize what the paper is about, and this focus is valuable on its own. Of course, many processes can be framed in terms of interactions, but I'm not entirely convinced that this framing adds clarity or additional insight in this particular case. If the focus was on interactions, I would have expected for instance :

    - A separation of the effects of climate change on surface runoff into the "direct" effect of climate (through precipitation and evaporation) and the "indirect" effect mediated by changes in natural vegetation cover and its influence on runoff.
    - A discussion or quantification of feedback loops, and how the interactions may amplify the initial responses. For example, climate change may alter natural vegetation cover, which in turn affects radiative, moisture, and carbon fluxes locally, potentially feeding back on climate and further modifying vegetation cover.

    In conclusion, I would recommend either reframing the study as an analysis of the effects of land-use and climate change on natural vegetation cover, surface runoff, and carbon storage density, or clarifying the interactions framing and better show the added insights it brings.

Minor comments :

L17 : Why *secondary* effects of human pressures and not just *effects of human pressure* ? I understand the argument of interactions amplifying initial forcing, but to me you are really looking at the effect of climate change and land use change (see also major comment 2)

L42 : climate/flux regimes. Fluxes of what ?

L32-54 : When discussing the different parts of the study, I suggest referring to the appropriate sections in the paper.

L70-75? (problem with line numbering in section 2.1) : This may simply reflect my limited familiarity with land models, but I think it would be helpful to explicitly define what is meant by *natural vegetation cover*. Does it refer to all vegetation types other than

crops? Are areas under silviculture considered part of the natural vegetation cover? If a large-scale reforestation effort were implemented, would that be represented as an increase or a decrease in land use/natural vegetation cover? Clarifying this would also help emphasize that *natural vegetation cover* is distinct from *total vegetation cover*, which is an important distinction for understanding the interactions in the Results sections.

L112-113 : The are some disagreements with Figure 2. How do you get the numbers 20 and 30 ? If you pick 2 different dominant types in 6 possibilities (5 mains types + no veg) you get 15 possible combinations, and if you pick 3 you get 20 possible combinations. In any case, in Figure 2 the numbers are different (24 and 61) and are for 2 main PFTs rather than main types.

L116 and L126 : You say that there are potentially 14 biomes (L116) , that 16 are identified in LPJmL simulations (L126) , and Figure 2 says that there are 15 biomes. Which number is correct ?

L138 : What percentage of tiles are excluded ?

L151 : I would replace *natural partitions* with *top-down partitions* to keep the terminology consistent.

L146-154 : You compare the top-down partitions with the neighborhood-based bottom-up partitions because they look similar, but from what I understood, the distance-based bottom-up partitions,with their more geographically interpretable zones, seem to be the ones most relevant for policymakers and are the intended end-use product. If I were a policymaker or science communicator, I'd want to know how these partitions compare with the more classical top-down ones. Could you explain why this comparison wasn't made directly?

L159 : When using the binary neighborhood relation, it seems that α also ranges from 0.1 to 0.7 in steps of 2

L180 (Section3) : I strongly recommend that the authors consider adding a conceptual diagram illustrating the main biophysical processes discussed in the paper. For example, boxes could represent the different components or processes, with arrows indicating the positive or negative interactions between them. You could also use a different color to show processes that exist in reality but are not represented in the simulations (e.g., carbon release from vegetation contributing to further warming). Such a figure would help readers quickly visualize all the interactions between the different Earth system components.

L200 : Start a new paragraph after *sparse vegetation* and before *Compared*, since you are discussing a different interaction

L216-218 : The sentence "This effect ... precipitation increases" is quite hard to read. Suggestion for rewriting : "This effect can be traced back to enhanced metabolsim and extended growing seasons through warming. The increases in vegetation cover reduces the water runnof, which possibly offsets the effect of precipitation increase "

L225 : *(see Discussion)*. There is no dedicated Discussion section, and I didn't find a place elsewhere in the text where the impact of using different methods to estimate interaction strengths is discussed. I think such a discussion would be very valuable. For instance, how sensitive are the results to the choice of estimation method? Why were different methods chosen for the various interactions instead of using a more consistent approach across them? Finally, if one wanted to apply this framework to study other interactions, which estimation method would you recommend?

L226 (Section 3.1) : Consider adding subsections or paragraph headings, each focusing one key point (eg 3.1.1 Comparison between the top-down and bottom-up approach → top-down partitions are generally worse ; 3.1.2 Top-down partitions can help diagnose the drivers of interactions ; 3.1.3 Clustering can lead to information loss)

L227 : Figure 4 shows results for $\alpha = 0.1, 0.3, 0.5, 0.7$, not $\alpha = 0.1, 0.2$.

L227 : I would replace *within-cluster similarity decreases* by *within-cluster variability increases* to keep terminology consistent with previous definitions. I would also make the the link to RS index explicit : within cluster variability naturally increases, leading to lower between-cluster variability and a reduced R-squared index.

L231 : effect of land use change on climate change → effect of land use change on climate ?

L234 : BR index *increases* with increasing spatial constraints

L236 : How can some of the top-down partitions perform even better than unconstrained bottom-up partitions ? Doesn't that reflect flaws in the clustering algorithm ? Without constraints, I would expect the algorithm to provide the optimal clustering, which should be better or equal to any of the top-down partitions. Or maybe it is because the clustering algorithm optimises other metrics than the BR index ? More generally, do you have any hypothesis on why top-down partitions perform so good for the land-climate interaction?

L237 : We want to compare → We compare

L240-241 : I suggest using arrows instead of "-" for interactions (climate→land and land→water), unequivocally specifying the direction of the interactions. Also in lines 272,273.

L242 : If climate-based partitions and PFT-based partitions are best for the effect of land-use on surface run-off, why don't we see climate-PFT partitions in the best performing ones? Also continents-based partitions are more frequent than both climate-based and PFT-based partitions in the highlighted ones in Figure 5A. In short, just looking at Figure 5A, it doesn't strike me that climate and PFT are crucial drivers of land→water interactions (even tough this seems natural).

L246 : (G1A) → (Figure G1A)

L248 : Could also mention that there is a particular strong negative land→water interaction for all rainforests (4 out of the 5 clusters with the lowest mean interaction are rainforests). This strikes me as a good example where a top-down partition can help us understand the drivers of interactions.

L249-251: What do you mean by mismatch ? I assume that you mean that the interaction strength averaged over a cluster doesn't represent well the interaction pattern in that cluster. This could be more explicitly stated. Maybe lines 249-251 can be left out altogether, as the point they make is repeated in more detail in the last paragraph of section 3.1.

L252 : (G2A) → (Figure G2A)

L270-271 : This sentence essentially says that vegetation plays a key role in determining the effect of climate change on vegetation cover. This seems somewhat self-evident, so it might be helpful to clarify what new or unexpected insight the results provides.

L272-273 : natural partitions → top down partitions (see previous comment)

L273 : Do you have some hypothesis on the strong drivers of the climate→land interaction beyond vegetation ?

L287-288 : Which interaction are you talking about ? Given the figures referenced, I assume it is the land→water interaction, but this should be explicitly stated in the text.

L300 : If you choose to keep both the neighborhood-based and distance-based bottom-up partitions (see comment L146-154), then I think it is worth remembering the reader that we are now switching to distance-based bottom-up partitions.

L308 : effect of climate change on land-use → effect of climate change on natural vegetation cover

L311 : In several Figure captions (6,7,I1,J1,J2), it says k=60. Please correct.

L312 : we want to explore → we explore

L320-369 + Figure 8 : You do not explain what you mean by "particularly strong" interaction strengths. Is it an arbitrary appreciation or have you fixed a certain threshold above which interactions are deemed particularly strong ? If you have some quantitative way to judge whether an interaction is particularly strong, how do you select the examples given in the text and in Figure 8? Do they include all the clusters where at least two interactions are considered as "particularly strong" ?

L339 : When I read "we find the exact opposite interaction profile", I thought that you were talking about an interaction profile with positive land→water interaction, negative land→climate interaction AND negative climate→water interaction, which is the exact opposite interaction profile as for cluster 44, the last cluster you mention in the text above. Upon further reading, I understood that you meant an interaction profile with just positive land→water interaction and negative land→climate. interaction. To avoid confusion, you might consider rephrasing this sentence.

L340-341 : effect of climate change on vegetation cover → effect of climate change on natural vegetation cover

L349-351 : Do you have an explanation for this? Is the reduction in surface water runoff due to stronger evaporation over croplands compared to temperate forests mixed with C3 grass, a higher infiltration rate, or another mechanism?

L352-353 : I would replace "particularly low" and "particularly high" by strongly negative and strongly positive. "Particularly low" may be understood as an interaction that has a low absolute strength, irrespective of its sign.

L374-377 : As mentioned in a previous comment (L242), I'm not fully convinced that Figure 5A clearly demonstrates that climate is the main driver of the land→water interaction. Moreover, in Section 3.2, the sign of the land→water interaction is consistently explained as a function of the vegetation type being replaced by cropland, rather than by climatic factors. And this is for a bottom-up partition (k=65, α=0.7) that performs better for the land→water interaction than all the top-down partitions, including the ones based on climate. Of course, vegetation in a given region depends strongly on climate, so I'm not suggesting that the statement is incorrect. However, based on my understanding of the paper, I'm not entirely convinced by the chain of arguments linking these results to the conclusion that climate is the main driver of the land→water interaction.

L384: I agree that a natural next step would be to use observational data. However I don't see how this could work with your actual framework. Indeed, to estimate the interactions strengths, you need time series that exclude the effects of land-use

change, which you won't find in observational data. So how would you extend your framework to estimate interactions strengths based on observations?

L 387 : Should it be "all three Earth system" processes instead of "four" ? If not, what is the fourth one ?

Comments on Figures :

Figure 3 : I assume that the plotted values represent the normalized interaction strengths. If so, it would be helpful to mention this explicitly in the legend. In addition, if normalized interactions are used, I would suggest applying the same color scale for all interactions (e.g., blue = –1, red = 1), or briefly explaining why different scales were chosen. For instance, in the land→climate interaction map, the color contrast gives the impression that the interaction in the Sahel region is strongly negative and quite distinct from nearby areas just to the south, where the color is white. However, the color bar indicates that the interaction is only slightly negative and actually quite similar to those southern regions.

Figure 4 : Suggestion : add an arrow on the side indicating the bigger the RS, the better (comment also valid for all other plots which show RS or BR indices). This allows direct interpretation. Other suggestion : change the color (use black?) and/or marker shape of the top-down clustering to emphasize the difference in approaches. Also the y-axis ranges are slightly different for each plot, it would be nice to have the same range for each plot (0 to 1).

Figure 5 : having the same y-axis range for all plots would make it easier to compare visually performance between the different interactions.

Figure 6 : It could help to add arrows in each panel saying in which direction the RS or BR indices represents better clustering quality. For consistency with Figure 4, I would also suggest to use darker color hues for the higher α values.

Figure 7: Same comments as Figure 6 + the y-axis ranges are slightly different for each plot, it would be nice to have the same range for each plot (0 to 1).

Figure 8 : The borders of the 65 clusters are not visible on the map, despite the caption saying it.

Figure C1 : having the same y-axis range for all plots would make it easier to compare visually performance between the different interactions.

Figure E1 : Same comments as figure 4 + the α values in the caption don't correspond to the values in the figure legend.

Figure E2 : Same comments as figure E1

Figure F1 : Never mentionned in the text (?). From what I understand it it the same as panels C and D of figure 3, so it can be-removed.

Figure G1 : Main text says that the figure is for the continent and climate PT partition, but the legend says it is for the realm and climate PT partition. Which one is correct ? I would highlight the same clusters in panel B as in panel A for quicker look-up of interaction values. In panel B, if there are no error bars, is this because there is only one cell in the cluster or because all cells have the same interaction strength ? In panel B, what does the color gradient stand for ? If it is just for aesthetics I would remove it (personal preference). Also, what determines the horizontal order of the clusters in the x-axis? I think you can get more information out of the figure if you order them either by continent either by climate zone (it would also be easier to look up the results for a given cluster). Probably the most interesting would be by climate zone then continent, and order the climate zones by increasing value of mean interaction. In this way you could easily see if there is correlation between climate zones and interaction strength. For example this would directly show that all Rainforests (Af) have a very negative interaction strength.

Figure G2 : Same comments as for Figure G1.

Figure G3 : Same comments as for Figure G1.

Figure G4 : Same comments as for Figure G1.

Figure H1 : Labels on the x-axis are hard to read even when zooming, is it possible to make them slightly larger? I also suggest ordering them in a logical way in order to find information easily (ex by continent then PFT or by PFT then continent). I think it would be nice to highlight the 3 examples given in the text (land→water in temperate Froest North America, climate→water in the tropical Forest of South America, and climate→water in tropical froest of Africa). Similarly to comments on figures in appendix G, I would remove the color gradient if it isn't associated with some information. In the figure caption it says "Aggregations of bottom-up interaction strengths" ; why the bottom-up? This is confusing since we are using a top-down partition. I would just drop the "bottom-up". Also the descriptions of panels C and D are inverted in the figure caption.

Figure I1 : Same comments as for Figure 6 + having the same y-axis range for all plots would make it easier to compare visually performance between the different interactions (as done in the main text).

Typos :

L56 : There is a "1" at the end of the first sentence which can be removed

L334 : The reference to Piao et al is repeated twice. At the end of sentence, it should be surrounded by parenthesis.

Figure J1 : At the end of the caption, should be $\alpha = 0.7$ instead of $\alpha = 0.D$