

General comments

In this manuscript, the authors investigate the effects on mean climate and extremes of biochar, a soil organic carbon enhancement technique, implemented on agricultural land at the global scale. For this purpose, they performed multiple simulations using the CMIP6 version of MPI-ESM with multiple biochar addition scenarios. Through SOC content increase, biochar modifies soil hydrological and thermal properties, which might influence land-atmosphere interactions, especially during extreme events. By looking at differences between a baseline scenario (without biochar) and biochar addition scenarios on the period 2040-2049, they show that the modifications in soil properties has little effect on global mean climate but has rather localised effects on extreme events.

Overall, I found the approach presented in the manuscript original and insightful, providing new elements on the effects on climate of biochar induced soil properties changes. The manuscript is well organised and argued. I have a few questions on the results and discussion part before I would consider the manuscript ready for publication.

R: thanks for the overall positive assessment.

Specific comments

1. I have a few comments on the figures:

1. Could the authors explain why did they choose to standardize the color scales using percentiles in Figures 7 and 9? Could they add this explanation to part 2.5?

4- Reply: Thank you for this comment. In an earlier version of the manuscript, we used a standard linear color scale for these figures. However, we found that the range between minimum and maximum values was very large, causing most spatial signals to be compressed into a narrow color range, while a small fraction of extreme values dominated multiple color bands. To better visualize the spatial patterns, we therefore standardized the color scales using percentiles (5th-95th). We will include this explanation in Section 2.5 as suggested.

2. Concerning the map on Figures 2, 5 and 6, I find it hard to read the values correctly with the chosen spacing between the ticks and the ticks values on the colorbar. For example, on Figure 2a, could the authors choose a range of values between 0 and 120 with equal spacing between the ticks? And maybe they could use the same colormap between low-addition and high-addition scenario to visually see the difference of organic carbon stock increase or bulk density decrease between the scenarios?

2. Reply: thanks for the suggestion. This should be a better presentation of the results for Figure 2, we will adapt the same scheme to Figures 5, and 6 as well in the revision.

2. Why did the authors used a 10-year window period rather than the 20 or 30 years usually used to study mean climate ?

2. Reply: Thank you for this question. In the original study design, we selected three 10-year periods representing the early, middle, and late phases of the future simulations, with the aim of identifying potential temporal trends. However, the simulated signals were relatively weak and showed little variation among these periods. Therefore, we retained only the final 10-year window (2040–2049), which represents near-future conditions. We acknowledge that longer periods (e.g., 20–30 years) are commonly used for mean climate analysis, but given the limited temporal variability in our results, a 10-year window was sufficient to capture the key responses in this study.

3. Line 365-382: The authors discuss the limitation of the method employed, suggesting that “the PTF-based approach oversimplify the complex mechanisms through which biochar alters soil properties” and also that “factors beyond SOC content—such as biochar morphology, particle size distribution, and local soil microstructure—may be critical drivers” but are not well represented by PTFs, but throughout the manuscript the authors speak about “biochar-induced changes”. To be more accurate, the authors must speak about “biochar-driven changes through SOC increase”. The failure to represent different soil types seems to be a major limitation. According to (Acharya et al. 2024), the effects of biochar on soil properties (and therefore on climate effects) depend heavily on soil type. Acharya, B.S., Dodla, S., Wang, J.J. *et al.* Biochar impacts on soil water dynamics: knowns, unknowns, and research directions. *Biochar* 6, 34 (2024). <https://doi.org/10.1007/s42773-024-00323-4>

3. Reply: Thanks for pointing this out. we will clarify this point in the revision.

4. Is there a reason why the authors did not look at albedo changes induced by biochar implementation ? Usowicz et al. (2016) show that albedo decrease after biochar addition, and could therefore induce an increase in temperature. Usowicz, B., Lipiec, J., Łukowski, M., Marczewski, W. & Usowicz, J.: The effect of biochar application on thermal properties and albedo of loess soil under grassland and fallow, *Soil and Tillage Research*, 164, 45– 540 51, <https://doi.org/10.1016/j.still.2016.03.009>, 2016.

Reply: Thank you for this comment. We are aware of this study and have cited it in the context of biochar effects on soil thermal properties. There are two main reasons why albedo changes were not explicitly included in our simulations.

First, studies reporting biochar-induced changes in albedo are still limited, and robust quantitative relationships between biochar application rates and albedo changes are lacking. This makes it difficult to parameterize such effects in a global modeling framework. Second, the influence of SOC on surface albedo is already implicitly represented in the model. As SOC content increases, the model simulates a slightly darker soil surface. Given the uncertainties mentioned above, explicitly prescribing an additional biochar-specific albedo effect would introduce further assumptions beyond the scope of this study.

4. Nevertheless, we agree that this is an important aspect and a promising direction for future research.

5. Lines 45-46 "By improving water retention and moderating soil temperatures, biochar-amended soils can alter surface moisture, temperature, and evapotranspiration rates,": this sentence needs a reference.

5. Reply: Thank you for pointing out this ambiguity. We will revise the sentence to include appropriate references for each component of the statement. Specifically, we will clarify that (1) biochar amendment can improve water retention and moderate soil temperatures (e.g., Edeh et al., 2020; Razzaghi et al., 2020); (2) these changes may influence surface moisture, temperature, and evapotranspiration (e.g., Koster et al., 2004; Seneviratne et al., 2010); and (3) such effects can subsequently impact regional and local climate (e.g., Lorenz and Lal, 2014; Woolf et al., 2010).

6. I don't understand how the authors build up to the first hypothesis, I feel that references are needed to support it. Why would enhanced soil porosity lead to enhanced evapotranspiration? If soil porosity increases but saturated hydraulic conductivity decreases, I don't expect increased soil evaporation. I would rather expect increased transpiration if more water is available to plant roots. One or multiple references for the second hypothesis would be welcomed too, in line 68: "stronger modifications to soil hydrology and surface energy balance are expected with increasing biochar additions".

Reply: Thank you for this important comment. We agree that the rationale for the first hypothesis requires clearer justification and appropriate references, as we did not specifically separate evaporation from evapotranspiration in this study. We will revise the text to better distinguish the mechanisms involved. In particular, we will clarify that increased soil porosity does not necessarily imply higher soil evaporation, especially when saturated hydraulic conductivity decreases. Instead, the expected increase in evapotranspiration is primarily associated with enhanced soil water retention and greater water availability to plant roots, which can promote transpiration. We will support this with relevant literature, including the review by Dayoub et al. (2023), which reports cases of increased evapotranspiration following biochar application.

For the second hypothesis, we will strengthen the justification by explicitly citing studies that report a positive relationship between biochar application rates and changes in soil hydrological and thermal properties, as summarized in Table 1. These studies provide empirical support for the assumption that higher biochar additions lead to stronger modifications in soil properties and, consequently, in surface energy balance.

6. We will incorporate these clarifications and references in the revised manuscript.

7. Could the authors comment on the influence of internal variability on the results? It seems internal variability has little influence because the patterns of precipitation and temperature differences are consistent between the different biochar scenarios (Figure S4) but it could explain why net top-of-atmosphere radiation and net freshwater flux (Table 3) are of opposite sign for sce2 compared to the others scenarios. It could also explain why the effects on climate are not linear with increasing biochar implementation (lines 474-481).

Reply: Thank you for this constructive comment. Following a similar suggestion from Reviewer 1, we will include an additional figure illustrating internal variability in the revised manuscript (see also the response to RC1: <https://egusphere.copernicus.org/preprints/egusphere-2025-4648#AC1>).

We agree with your interpretation that internal variability has a limited influence on the overall spatial patterns of the climate response to biochar addition, which remain consistent across scenarios. However, internal variability likely contributes to the lack of a clear dose-dependent response and may explain why some variables, such as net top-of-atmosphere radiation and net freshwater flux, show differing signs in the Sce2 scenario compared to others. As a result, the relationship between biochar application rates and climate responses appears non-linear.

7. We will clarify this point in the revised manuscript.

8. Line 401 "While these interactions are generally well-represented in climate models" This sentence is not correct. There is an ongoing debate on whether soil moisture - precipitation coupling is well represented in climate models. Km-scale simulations suggest that the sign of the coupling (generally negative) could be wrong and too large in global climate models (e.g. Lee and Hohenegger 2024). Lee, J. & Hohenegger, C. Weaker land-atmosphere coupling in global storm-resolving simulation. *Proc. Natl Acad. Sci. USA* 121, e2314265121 (2024).

Reply: thanks for the correct, we will revise the statement and include the reference.

Technical corrections

1. The values stated in the text in lines 196-211, referring to table 1, does not correspond with the values given in table 1.

1. Reply: thanks, we will correct it in the revision.

2. Could the authors make sure that everytime they give a result, they refer to the appropriate figure? Including in the discussion part.

2. Reply: we will go through the text carefully in the revision to make sure all the information are correctly associated.

3. Line 282 "Between 2040 and 2049": I don't understand, isn't Table 2 showing the mean climate and the difference between the biochar addition scenario and the base scenario on the period 2040-2049?

3. Reply: Table 2 specifically present the response of sce2, i.e. the difference between Base scenario and the Medium biochar addition scenario. We will clarify it in the caption in the revision.

4. Figure S1: The figure is taken from Iturbide et al. (2020), the authors should give the reference. And the quality of the figure is very low, it would be nice if the authors could increase it. Iturbide, M., Gutiérrez, J. M., Alves, L. M., Bedia, J., Cerezo-Mota, R., Gimadevilla, E., Cofiño, A. S., Di Luca, A., Faria, S. H., Gorodetskaya, I. V., Hauser, M., Herrera, S., Hennessy, K., Hewitt, H. T., Jones, R. G., Krakovska, S., Manzanar, R., Martínez-Castro, D., Narisma, G. T., Nurhati, I. S., Pinto, I., Seneviratne, S. I., van den Hurk, B., and Vera, C. S.: An update of IPCC climate reference regions for subcontinental analysis of climate model data: definition and aggregated datasets, Earth Syst. Sci. Data, 12, 2959–2970, <https://doi.org/10.5194/essd-12-2959-2020>, 2020.

4. Reply: Thanks for the comment. we will improve the quality of the figure and include the reference in the revision.

5. Figure S5 and S6 are not easy to read. The colorbar must be the same for every scenario. And it would be of greater consistency to show the differences with the base scenario for every biochar addition scenario, as for the "mid-addition response" in figure 7.

Reply: we will remake the two figures to show the responses instead of the absolute values in the revision.