Reviewer Comments
Author Responses

**Review for by Soil carbon-concentration and carbon-climate feedbacks in CMIP6 Earth system models by Varney et al., submitted to Biogeosciences (EGUsphere)**

The authors present an analysis of soil carbon cycle feedbacks using CMIP6 models forced with the 1pct-CO2 experiment. Feedbacks are quantified using the integrated flux-based feedback framework from Friedlingstein et al. (2006), referred to here as the βγ formulation. Feedback parameters are computed from the biogeochemically and radiatively coupled simulations for the carbon-concentration (β) and carbon-climate (γ) feedbacks respectively. The study concludes that the sensitivity of soil carbon to climate change increases with warming and is more dominant than the vegetation carbon response, underscoring the importance of soil carbon in long-term land carbon storage. The manuscript is generally clear, and the text has a logical flow through introduction to conclusion.

We thank the reviewer for their positive and constructive comments.

However, I have two main issues:

1. While this study is a useful contribution, it would benefit from an expansion of the analysis. For example, the processes driving soil carbon change in each simulation could and it would be interesting to discuss why the soil carbon response differs between models, although I understand this may require a substantial amount of additional work. I also notice that some sections of the discussion read as a literature review, which could be remedied by better linking the spatial analysis results to driving mechanisms.

   The analysis has now been expanded to include a breakdown analysis of the processes driving soil carbon in each simulation. The $\beta_s$ and $\gamma_s$ feedback parameters are broken down into sensitivity components due to changes in Net Primary Productivity (NPP) and changes due to soil carbon turnover time ($\tau_s$), which follows the framework presented in Varney et al. 2023 (Biogeosciences). The manuscript will now include a new Methods section '***Processes driving soil carbon change and relation to the βγ formulation***' describing the formulation and how it relates to the $\beta_s$ $\gamma_s$ formulation presented here, and a results section '***Breakdown of the feedback parameters into soil carbon drivers***', including a new figure (**attached below**). Additionally, the discussion has been rewritten and now links to the new results to back up the discussion throughout, so it is now less like a literature review and more of a discussion of the results.

   *Varney, R. M., Chadburn, S. E., Burke, E. J., Jones, S., Wiltshire, A. J., and Cox, P. M.: Simulated responses of soil carbon to climate change in CMIP6 Earth system models: the role of false priming, Biogeosciences, 20, 3767–3790, https://doi.org/10.5194/bg-20-3767-2023, 2023.*

   The manuscript seems to address two kinds of non-linearities: (1) the non-linearity in the soil carbon responses to CO2 and temperature, and (2) another form of non-linearity which arises from non-additivity in the responses in the BGC and RAD simulations to that in the full simulation. In the results section, both non-linearities are mentioned, but in the discussion, it appears that the two are combined and given

the same explanation.
Agreed. We have added the following text to make this clearer:
*'The βγ formulation has many benefits in allowing the quantification and comparison of land and soil carbon feedbacks amongst ESMs.* ***However, one limitation is due to $\Delta C_s$ not being consistently linear with increasing $CO_2$ and temperature (Fig. 3), so the parameter values depend on the point in time which they are calculated (for example, 2x$CO_2$ or 4x$CO_2$). This has been shown to be due to non-linearities in the processes driving soil carbon feedbacks (Fig. 4), such as the discussed saturation of the $CO_2$ fertilisation effect ($\beta_{NPP}$; Wang et al. (2020)) and additionally a known $Q_{10}$ dependence of heterotrophic (soil) respiration to temperature ($\gamma_T$; Zhou et al. 2009)).***

*Non-linearities between ~~the~~ $CO_2$ and T responses are* ***also*** *known and have previously been shown within ESMs in the future land carbon responses (Schwinger et al., 2014; Zickfeld et al., 2011; Gregory et al., 2009).'*

**Minor comments**
L3: I suggest replacing the word *feedback* with *response.* The soil carbon responses to CO2 and climate change give rise to the feedbacks.
We agree that soil carbon responds to $CO_2$ and climate changes which then leads to feedbacks on the climate system. However, the use of the term 'feedbacks' when referring to beta and gamma factors, is common in this field and we maintain it here for continuity. We have however changed the sentence to address this comment.
"*This paper quantifies the global soil carbon changes* ***due*** *to changes in...*"

L5: Please maintain consistency in the terminology used throughout the manuscript. The feedbacks are mostly referred to as soil carbon-concentration feedbacks (without the word *specific*).
The manuscript has been checked for consistency and now the feedbacks are always referred to as soil feedbacks (without the word specific).

L12: Increases in global temperature are an indicator of climate change, not an impact of climate change. Perhaps, rephrase to "sensitivity to climate change and the associated impacts such as changes in precipitation patterns."
The words "to *climate change*" has been removed here. This means the sentence now refers to global temperature increase as a result of increased atmospheric $CO_2$ concentrations, rather than as a more general impact of climate change.

L23: Yes, the βγ formulation can be used for calculating feedbacks from both concentration-driven and emissions-driven simulations, but there are issues with using the latter. Land-ocean compensation due to differing timescales of carbon uptake and loss between the land and ocean affects the magnitude of feedback parameters, so to ensure that both land and ocean see the same atmospheric CO2 concentrations, concentration-driven simulations are used more widely.
Good point. This sentence has been removed to avoid confusion.

L30: Does the first research question also explore the sensitivity of soil carbon to atmospheric CO2? If so, please clarify.
Changed to avoid confusion:
'*… sensitivity of soil carbon to* ***increased atmospheric $CO_2$ concentrations and associated climate impacts*** *by …*'.

L32: In the third research question, I suggest changing "land surface response" to "land carbon response". This appears to be more consistent with the results presented, which focus on carbon.
Changed as suggested: '~~*surface*~~ ***carbon***'.

L43: Quick clarification on the length of your simulations: are they 140 or 150 years long? L99 refers to 140 years. Please clarify.
C4MIP simulations for the 1% experiments are 150 years long. However, in this case we are considering 2x$CO_2$ (approximately 70 years) and 4x$CO_2$ (approximately 140 years).

L64-66: In equations 2-4, I suggest using the 'approximately equal to' signs between the integrated flux term and the linearization as in Equation 1.
Equations changed as suggested.

L67-68: The change in atmospheric CO2 concentration is consistent in all three simulations, correct? Omitting the RAD simulation from Line 67 implies otherwise. Please address. With that said, I do understand that the point you want to make here is that the carbon cycle in the RAD simulation sees preindustrial CO2 concentration (no CO2 change) unlike that in the full and BGC simulations.
That is a fair comment, the paragraph will be changed so the distinction between the 3 experiments is clear. The paragraph now starts:
"*In these equations, $\Delta CO_2(t)$ (ppm)* ***is consistent between all scenarios. However, within the RAD simulation …***".

L76: Accidental *S* added to the Fig. A1 reference in brackets.
This has been removed.

L117-120: According to Figure 1, ΔCs continues to increase in the GFDL model, whereas in IPSL, the ΔCs saturates. The sentence here states the opposite. Perhaps the positions of the two models were switched in this sentence or the labels on the figure were switched. Please review.
These models have been switched within the text.

L121: ΔCs is used to refer to any simulation (full, BGC, or RAD) in the results section. However, in equations 2 - 4, ΔCs (with no superscript) is denoted as soil carbon change for the full simulation, and superscripts BGC and RAD are added for the BGC and RAD simulations. It would make the results easier to follow if this is maintained in the results section.
The manuscript has been changed to be consistent throughout, where now ΔCs is used for the full simulation and the superscripts BGC and RAD are used for the BGC and RAD simulations respectively.

I also suggest using the phrasing “can be approximated by” rather than “is the net effect of” here because responses in the BGC and RAD simulations are not always additive to the response in the full simulation.
This sentence has been changed as suggested.

L134: Did you mean to say “the *spatial distribution* of ΔCs seen in the full 1% simulation ...”? Please clarify.
Yes, change made as suggested.

L152: I suggest changing the phrase to “increasing range with increased *global temperature*” because, in the RAD simulation, where γ is quantified from, the carbon cycle sees no change in atmospheric CO2.
Sentence changed as suggested.

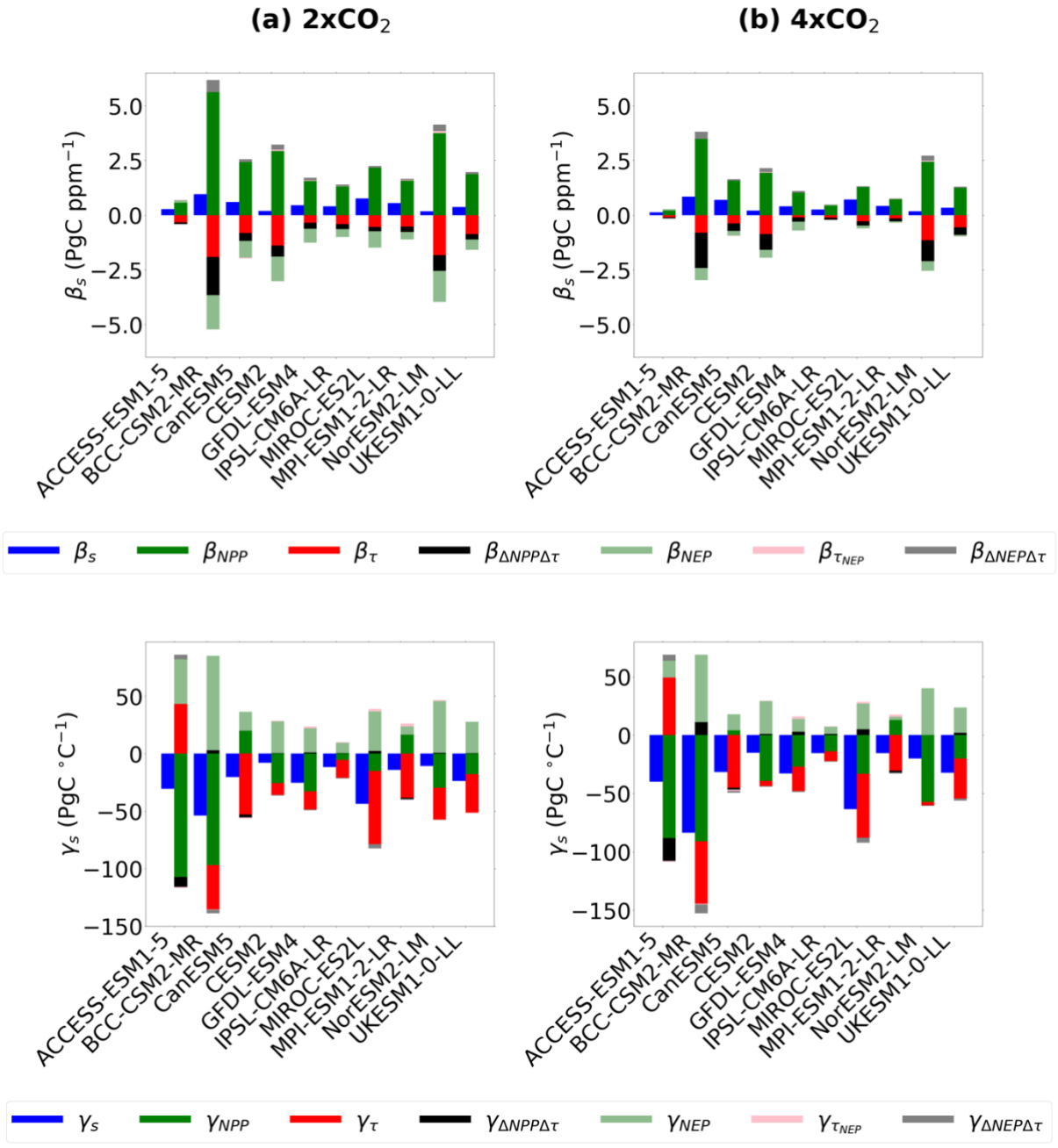
L154: Figure 3 is confusing. Please explain how the 2xCO2 and 4xCO2 β and γ lines were plotted? Could these results be presented differently to improve clarity?
The figure has been updated to improve the clarity.

L229: On the other hand, nitrogen mineralization - the temperature-dependent process by which nitrogen in organic matter is converted into inorganic forms that can be taken up by plants – fertilizes soils, countering the limit on productivity.
We have added the following to the discussion:
‘***However, it is noted that warming within the soil could accelerate nutrient mineralisation, which could result in a liberation of nitrogen due to increased microbial breakdown of plant litter, alleviating the nutrient limitation in plants (Todd-Brown et al. 2014).***’

*Todd-Brown, K. E. O., Randerson, J. T., Hopkins, F., Arora, V., Hajima, T., Jones, C., Shevliakova, E., Tjiputra, J., Volodin, E., Wu, T., Zhang, Q., and Allison, S. D.: Changes in soil organic carbon storage predicted by Earth system models during the 21st century, Biogeosciences, 11, 2341–2356, https://doi.org/10.5194/bg-11-2341-2014, 2014.*

L259: Missing word *carbon* in “the sensitivity of soil **^** to changes in global temperature”
Word “*carbon*” has been added to sentence.

L262: This could be more concise by phrasing as either “long-term land carbon response under ...” OR “long-term land carbon storage under ...”
Changed to “*long-term **land carbon** response under…*”.




**New Fig caption**: '*Investigating the contribution of individual soil carbon drivers to the soil carbon-concentration ($\beta_s$, top row) and carbon-climate ($\gamma_s$, bottom row) feedback parameters, for each CMIP6 ESM, for (a) 2xCO2 and (b) 4xCO2. The figure shows soil carbon feedback parameter contributions from NPP ($\beta_{NPP}$ and $\gamma_{NPP}$), $\tau_s$ ($\beta_\tau$ and $\gamma_\tau$), the non-linearity in NPP and $\tau_s$ ($\beta_{\Delta NPP\Delta\tau}$ and $\gamma_{\Delta NPP\Delta\tau}$), and the effect from the non-equilibrium term NEP ($\beta_{NEP}$, $\beta_{\tau NEP}$ , $\beta_{\Delta NEP\Delta\tau}$ and $\gamma_{NEP}$ , $\gamma_{\tau NEP}$, $\gamma_{\Delta NEP\Delta\tau}$).*'.