

Reviewer Comments (1)

Author Responses

General comments

This manuscript describes an analysis of CMIP6 outputs, specifically presenting a computation of the soil, vegetation, and land carbon sensitivity to CO₂ (beta) and climate (gamma) changes. This follows earlier, similar analyses of previous CMIP generations, and is a useful diagnostic of model behavior and to help understand earth system response to anthropogenic CO₂ emissions. The ms is well written and interesting, focused, and generally clear; I applaud the inclusion of a link to the analytical code.

We thank the reviewer for their positive and constructive comments.

In addition to some minor issues, my overall concern is that the analysis is quite limited, misses some very interesting possibilities, and doesn't always display its results well. Specifically, a comparison of CMIP5 and CMIP6 values—ideally quantitatively in a figure, but at least treated in the discussion—would add a lot of value. In addition, the bar graphs are not particularly illuminating, and consider better visualization options (e.g. #9 below).

In summary, this is an interesting and valuable contribution, but needs moderate revisions for concision and clarity; to improve how it conveys its results; and, ideally, to expand its scope a bit.

This comment has been taken on board and addressed in our manuscript. Firstly, we now include a comparison of the CMIP6 soil carbon beta and gamma values with equivalent values from CMIP5 models, which are presented in a new table and new figure (**see below**) within the appendix. The following text has been added to the Results:

'The β s and γ s values were also calculated for CMIP5 ESMs (Table A3), which can be compared with a subset of generationally related CMIP6 ESMs considered in this study (Fig. A3). The CMIP6 ensemble means for both β s and γ s parameters are found to be lower compared with the CMIP5 ensemble means (Table A3 and Table 2). The relationship of β s and γ s values between CMIP5 and CMIP6 however, is not found to be consistent amongst the ensembles. For β s, reductions are seen in 4 ESMs (GFDL-ESM2M Vs GFDL-ESM4, IPSL-CM5A-LR Vs IPSL-CM6A-LR, MPI-ESM-LR Vs MPI-ESM1-2-LR, and HadGEM2-ES Vs UKESM1-0-LL), compared to increases in the remaining 2 (CanESM2 Vs CanESM5 and NorESM1-ME Vs NorESM2-LM). For γ s, a greater value (closer to 0) is seen in 4 ESMs (CanESM2 Vs CanESM5, GFDL-ESM2M Vs GFDL-ESM4, IPSL-CM5A-LR Vs IPSL-CM6A-LR, and MPI-ESM-LR Vs MPI-ESM1-2-LR), compared to a lower value (greater negative) is seen in the remaining 2 ESMs (NorESM1-ME Vs NorESM2-LM and HadGEM2-ES Vs UKESM1-0-LL).'

Also, see comments to #9 that Fig. 4 has been updated from the bar chart to the suggested scatter graph (**see Fig. attached**).

Additionally, the analysis has now been expanded to include a breakdown analysis of the processes driving soil carbon in each simulation. The β_s and γ_s feedback parameters

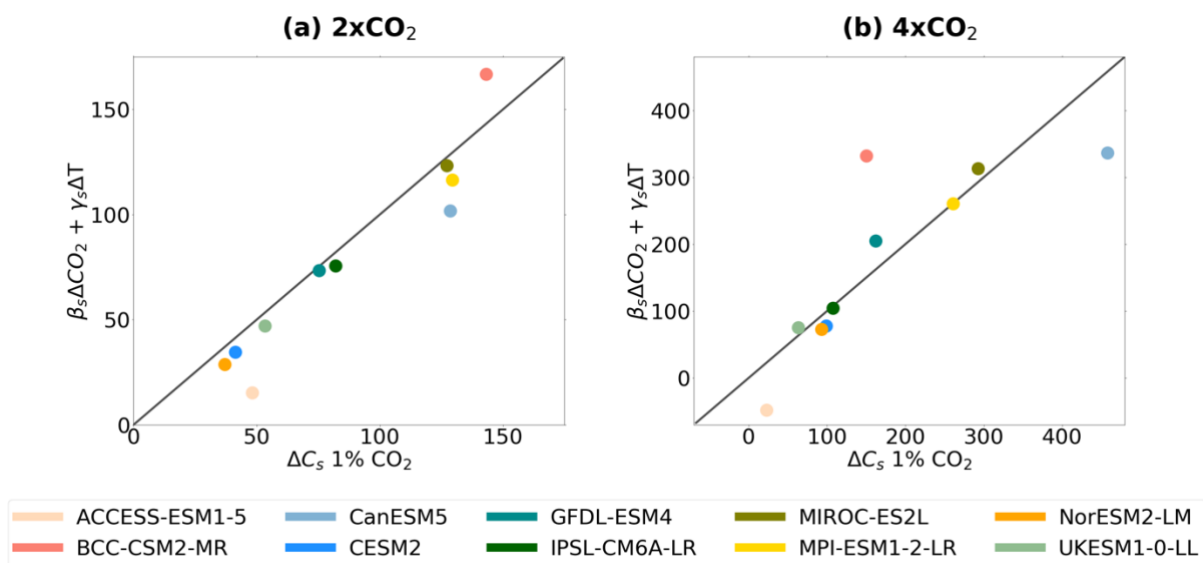
are broken down into sensitivity components due to changes in Net Primary Productivity (NPP) and changes due to soil carbon turnover time (τ_s), which follows the framework presented in Varney et al. 2023 (Biogeosciences). The manuscript will now include a new Methods section '**Processes driving soil carbon change and relation to the β 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**).

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.

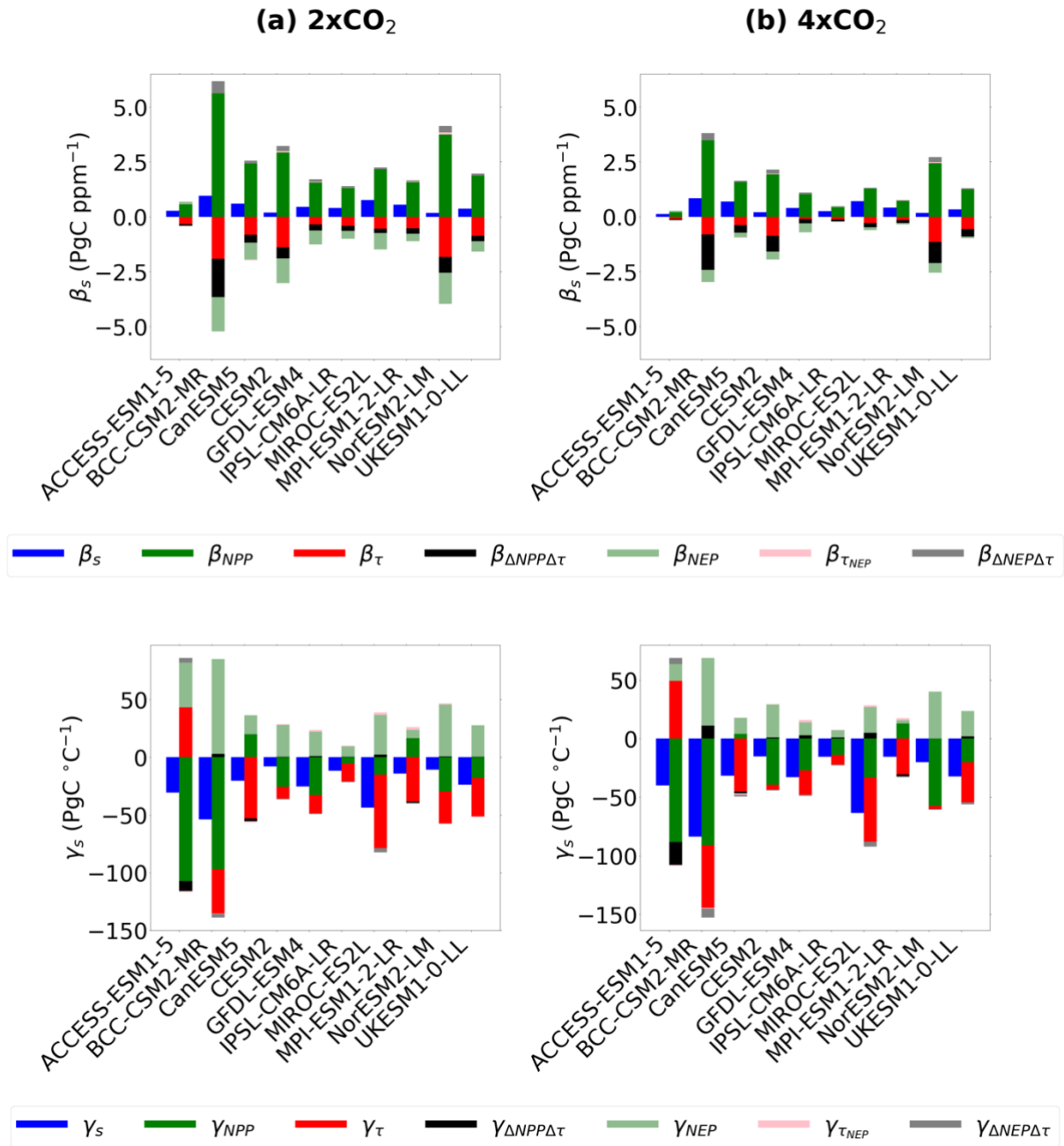
Specific comments

1. Line 11: Jones et al. 2018 <http://dx.doi.org/10.1029/2018GL079350> might be a good citation here
This citation will be added to line 11.
2. 37: “has been”
This sentence will be changed as stated.
3. 52: This is a long time ago! If any models have been added since then, would it be possible to include them on revision? That said, I’m not trying to make a huge amount of new work for the authors
Sorry for the confusion here, it has been checked multiple times and there are no more CMIP6 models which provide the required data (<https://esgf-index1.ceda.ac.uk/projects/cmip6-ceda/>).
4. 141-142: the results section has a certain amount of restating things that have already been defined/said in the introduction and methods; consider trimming. This is one example
Thank you for pointing this out, the results section can be trimmed to be more precise.
5. 239: do you mean “explicit” here?
Indeed. Has been changed to “**explicit**”.
6. 256: missing word? “that beta and gamma linearity is a valid assumption”?
Sentence has been changed to include the word “**linearity**”.
7. 264: thanks for the code transparency. Adding a README to this repo would be useful, and I suggest permanently archiving it (i.e., generating a DOI) using Zenodo
A “README” file has been added to the GitHub repository. If the paper is accepted for publication, we will do as suggested using Zenodo.

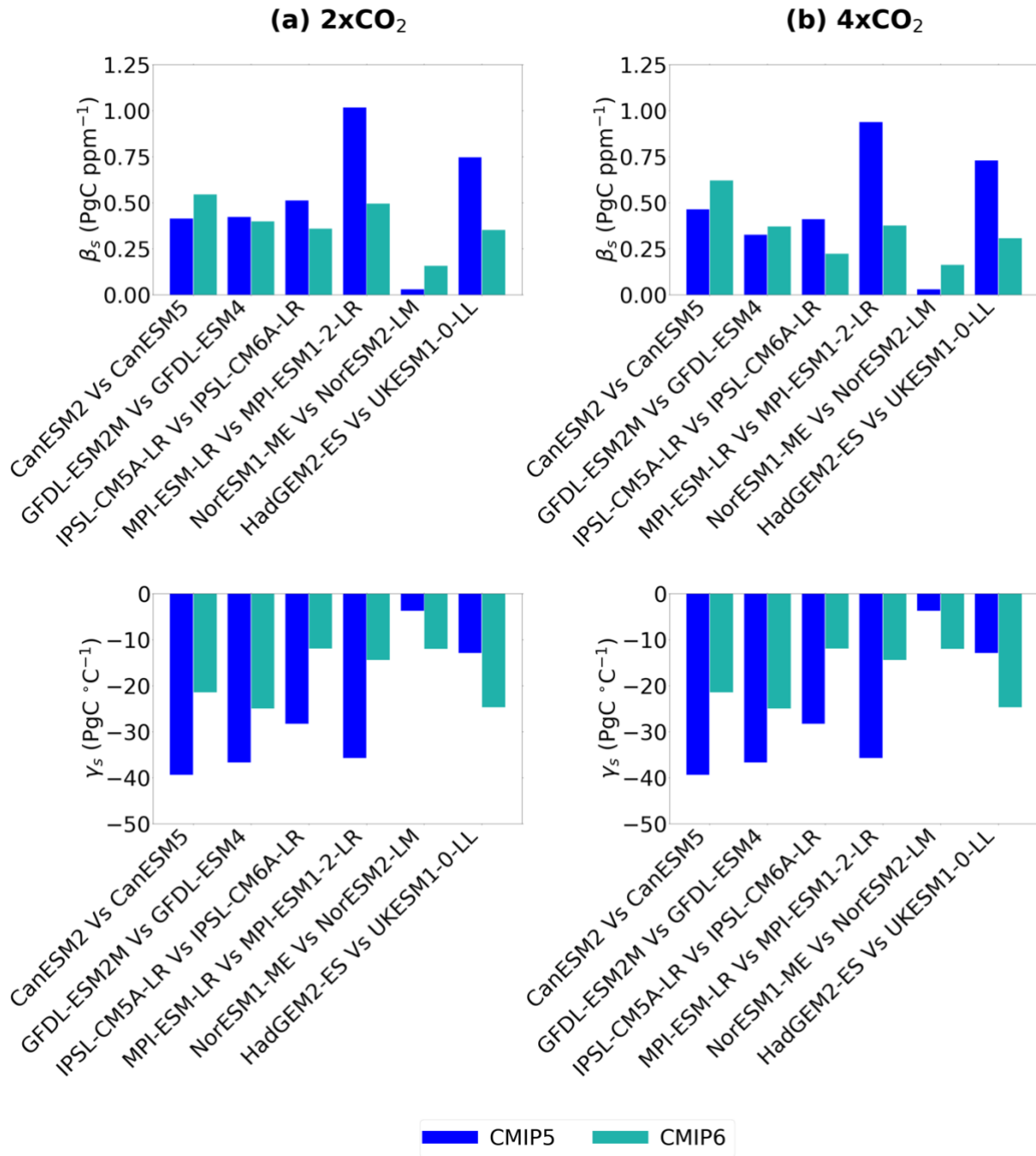
8. Figure 2: move to SI? Not sure how useful this is; maps are very small
 We feel the maps are useful to show the patterns of change in the different experiments and across the CMIP6 Earth system models so have kept in the main manuscript, and given that this is an online journal, they can be expanded by the viewer to see greater detail.
9. Consider whether Figure 4 could be re-thought for clarity and impact. For example, what about plotting deltaCs (x) versus beta+gamma (y) with a 1:1 line, coloring points by 2xCO2 or 4x? That might be a better way to visualize for readers
 Figure 4 has been remade to follow the suggestion of plotting deltaCs (x) versus beta+gamma (y) with a 1:1 line (see Figure below). Though a colour has been used for each ESM (as in Figure 1) so the reader can identify ESMs when comparing to the 1:1 line, therefore a panel is included for 2xCO2 and 4xCO2.
10. You don't need to say "Bar chart", "Maps", etc. in the figure captions. Readers can see what type of plot it is
 The figure captions will be changed to avoid unnecessary information, such as 'bar chart' and 'table'.



New Fig. 4 caption: 'Comparison of ΔC_s (PgC) in the full 1% CO₂ simulation (x-axis) against the estimated ΔC_s using the calculated β_s and γ_s feedback parameters (y-axis), where estimated $\Delta C_s \approx \beta_s \Delta CO_2 + \gamma_s \Delta T$, for each CMIP6 ESM at (a) 2xCO₂ and (b) 4xCO₂.'



New Fig caption: ‘Investigating the contribution of individual soil carbon drivers to the soil carbon-concentration (β_s , top row) and carbon-climate (γ_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 (β_{NPP} and γ_{NPP}), τ_s (β_τ and γ_τ), the non-linearity in NPP and τ_s ($\beta_{\Delta NPP\Delta\tau}$ and $\gamma_{\Delta NPP\Delta\tau}$), and the effect from the non-equilibrium term NEP (β_{NEP} , $\beta_{\tau_{NEP}}$, $\beta_{\Delta NEP\Delta\tau}$ and γ_{NEP} , $\gamma_{\tau_{NEP}}$, $\gamma_{\Delta NEP\Delta\tau}$).



CMIP5 New Appendix Fig: ‘Comparison of the soil carbon-concentration (β_s) feedback parameters (top row) and the soil carbon-climate (γ_s) feedback parameters (bottom row) from generationally related ESMS from CMIP5 and CMIP6, for (a) $2x\text{CO}_2$ and (b) $4x\text{CO}_2$ ’.

Reviewer Comments (2)

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 $\beta\gamma$ 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 β_s and γ_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 (τ_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 $\beta\gamma$ 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 β formulation has many benefits in allowing the quantification and comparison of land and soil carbon feedbacks amongst ESMs. **However, one limitation is due to ΔC_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, $2xCO_2$ or $4xCO_2$). 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 (β_{NPP} ; Wang et al. (2020)) and additionally a known Q_{10} dependence of heterotrophic (soil) respiration to temperature (γ_r ; 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 CO_2 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 β 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 CO_2 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 CO₂ 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 2xCO₂ (approximately 70 years) and 4xCO₂ (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, ΔC_s continues to increase in the GFDL model, whereas in IPSL, the ΔC_s 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: ΔC_s is used to refer to any simulation (full, BGC, or RAD) in the results section. However, in equations 2 - 4, ΔC_s (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 ΔC_s 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 ΔC_s 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).’

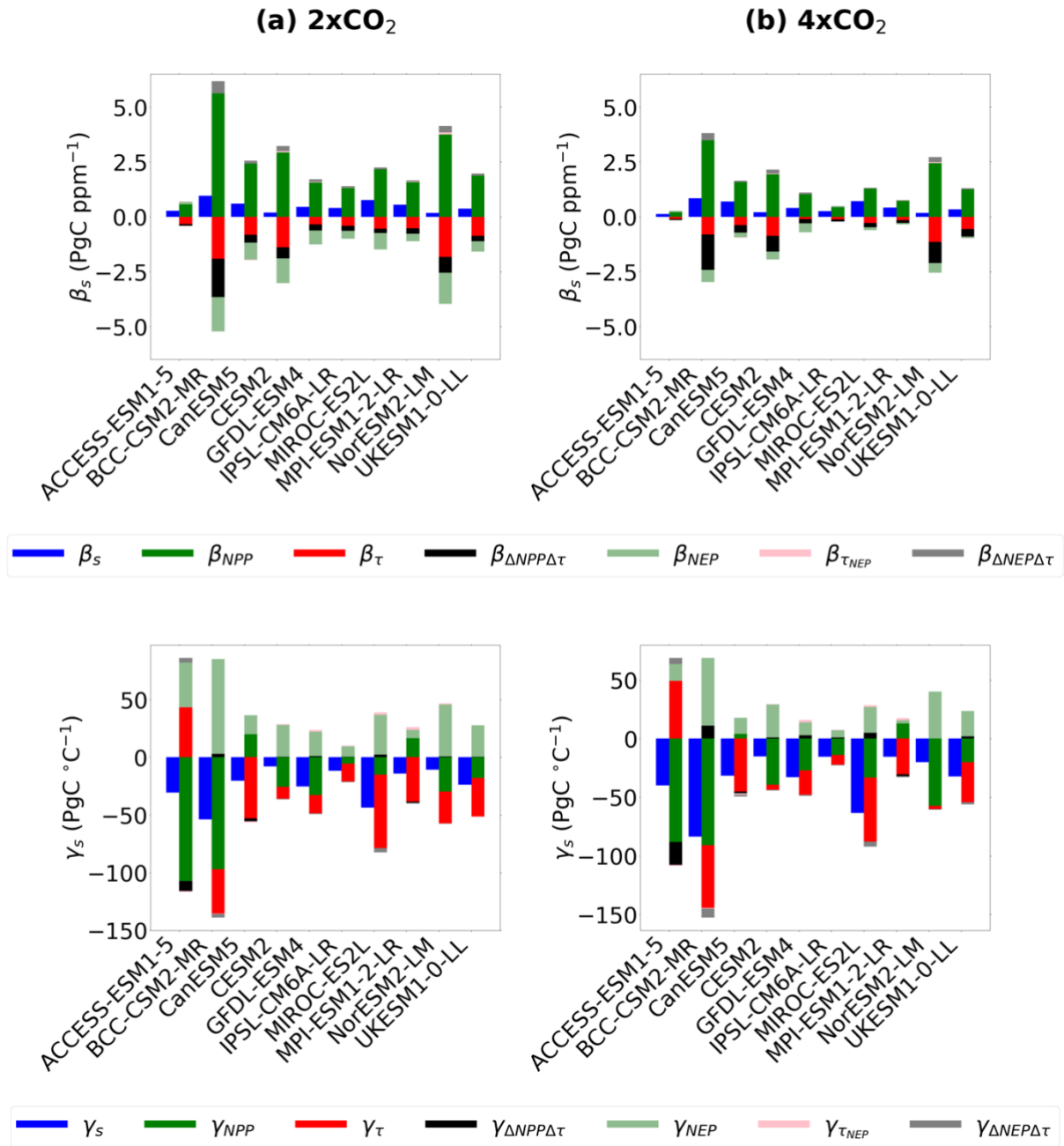
Todd-Brown, K. E. O., Randerson, J. T., Hopkins, F., Arora, V., Hajima, T., Jones, C., Shevliakova, E., Tjiputra, J., Volodin, E., Wu, T., Zhang, Q., and Allison, S. D.: Changes in soil organic carbon storage predicted by Earth system models during the 21st century, Biogeosciences, 11, 2341–2356, <https://doi.org/10.5194/bg-11-2341-2014>,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

L259: Missing word *carbon* in “the sensitivity of soil ΔC_s 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 (β_s , top row) and carbon-climate (γ_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 (β_{NPP} and γ_{NPP}), τ_s (β_τ and γ_τ), the non-linearity in NPP and τ_s ($\beta_{\Delta NPP\Delta\tau}$ and $\gamma_{\Delta NPP\Delta\tau}$), and the effect from the non-equilibrium term NEP (β_{NEP} , $\beta_{\tau_{NEP}}$, $\beta_{\Delta NEP\Delta\tau}$ and γ_{NEP} , $\gamma_{\tau_{NEP}}$, $\gamma_{\Delta NEP\Delta\tau}$).’