Response to reviewers

We appreciate the time and effort that the editors have dedicated to providing your valuable feedback on our manuscript. The reviews are copied verbatim and are italicized. Author responses are in regular font. Changes made to the manuscript are blue.

Comments from reviewer 1

General Comment

The discussion would benefit from a clear structure, making it easier to read, guiding the reader to the conclusions. Try to cut on statements that are repeated several times, and avoid vague/general statements. I suggest subheadings could be used to structure it:(1) summarize all your main findings and interpret them within the context of the current literature. Make sure you're discussing all of your experiments/exercises (for instance, ZEC experiment is not mentioned in the discussion but is mentioned in the conclusion), and follow the same order of your results in the discussion;(2) consider assumptions and limitations, make clear recommendations for future studies;(3) make clear the implications of your work. Your research has meaningful implications, and emphasizing these would strengthen the manuscript's contribution to the field.

Response

Thank you for your comment. We appreciate the constructive feedback. The discussion section has been refined as suggested. A discussion of ZEC has been added. The assumptions and limitations have been added. The implications have been added as suggested. The discussion has been changed to:

The terrestrial carbon cycle in nutrient limiting model structures is suppresed by the capacity of primary producers to uptake carbon, either by controlling photosynthesis or reducing the biomass directly by setting maximum nutrient to carbon ratios. The change in vegetation biomass is dependent on differences among the limitation applied to each PFTs. Therefore, the application of multiple nutrient-limiting stressors such as nitrogen and phosphorus should be applied carefully, as for example, a high phosphorus limitation can easily underestimate the land sink capacity of tropical vegetation.

One of the impacts of terrestrial nutrient limitation on terrestrial systems is that the land surface albedo is increased as the model reduces vegetation due to nutrient limitation and trees are replaced by grasses. The replacement of trees by grasses occurs globally in the model as shown in De Sisto et al. (2023). The land surface albedo increased by 0.04 in nutrient-limited simulations. Conversely, land use changes decrease with the reduction of vegetation biomass. This is due to the land use change emission dynamics in the UVic ESCM where 50 % of the carbon from removed trees is released directly into the atmosphere.

The TCRE shows that nitrogen and phosphorus limitation had a direct effect on the temperature-to-carbon emission proportionality. The nutrient limitation impacts the carbon fluxes, reducing the land carbon sink and increasing the ocean carbon sink, leading ultimately to a net decrease of the carbon taken up from land and ocean. In emission-driven simulations, this will lead to a high buildup of atmospheric CO_2. However, it is clear that better understanding of nutrient distribution in the natural world is necessary to build even more reliable nutrient-limited models.

The impact of terrestrial nitrogen and phosphorus limitation on the ZEC values was expected given the effects of terrestrial nutrient limitation on the carbon cycle. After the cessation of emissions, the uptake of carbon by terrestrial systems is limited by the availability of nutrients, hence, the decrease rate of atmospheric CO_2 redistribution into terrestrial systems leads to an enhanced warming in comparison with the no nutrient simulation values. The ZEC values are within the range of values of -0.36 to 0.29 °C presented by MacDougall et al. (2020). The land carbon sink has been identified as a critical process in ZEC values (MacDougall et al. , 2020; Palazzo et al. , 2023). The study of the redistribution of carbon to land systems after emission have ceassed is then vital to understanding the uncertainties and improving our estimation of ZEC values. Besides nutrient limitation, there are other usually not represented processes that are expected to increase the ZEC outputs in models, these include disturbances in permafrost and peatlands (Palazzo et al. , 2023).

The representation of the carbon cycle in model structures affects the estimation of the remaining carbon budgets. Permafrost thawing for example has been studied for its carbon budget reduction effect in ESMs (e.g. MacDougall and Knutti 2016, MacDougall et al. 2021). In this study, the effect of the terrestrial carbon dynamics has a direct impact on the reduction of the remaining carbon budgets, decreasing the allowable emissions by 19% to 25% in the 1.5 and 2 °C targets. This substantial amount is why terrestrial nitrogen and phosphorus limitation should be considered in the estimation of remaining carbon budgets.

The IPCC AR6 (IPCC 2021) reports remaining carbon budgets estimates from 2020 of 245, 177, 136, 108 and 82 PgC for the 1.5 °C target with a probability of 17, 33, 50, 67 and 83% respectively. Compared to the 50% of probability of 136 PgC our nutrient-limited model simulations, CN 185 PgC and CNP 175 PgC estimated a closer value than the C-only 228 PgC. Hence, nutrient-limited simulations estimates from the UVic ESCM closer to the multi-model mean.

As unrepresented processes in other models, nitrogen and phosphorus limitation reduced the estimated remaining carbon budget in CN and CNP by 43 and 53 PgC for the 1.5 °C target and 98 and 120 PgC for the 2 °C target when compared to the C-only simulation. These estimations are larger than the roughly estimate of 27 PgC reduction of carbon budgets due to unrepresented carbon feedbacks (Rojelj et al. , 2018), suggesting that this value may have been underestimated in the IPCC 1.5°C report.

Overall, our results show that remaining carbon budgets estimated in CNP simulations were lower than CN. In SSPs were this was not the case, a medium or high land use regulation was implicit in the scenario. Hence, one of the main difference between CN and CNP models is how the model response to land use change management in different future projections scenarios. The inclusion of P in ESMs has been shown to improve the terrestrial model performance and hence, we believe that the addition of P limitation should be thought in the development plans of different model working groups.

The main limitation of terrestrial N and P cycles is the lack of global observational data that can be used to refine and validate ESMs. The lack of data includes most of the N and P cycle processes. The uncertainties in the representation of the terrestrial nutrient limitation of the UVic ESCM include the lack of a dynamic leaf nutrient resorption representation, lack of root uptake constraints, simplified sorption-resorption dynamics of phosphorus in soils, and a simplified wetland representation. A detailed description of the terrestrial nitrogen and phosphorus uncertainties can be found in the complete description of the model in (De Sisto et al. , 2023).

General Comment

I also believe the manuscript would benefit from all your research questions being explicitly and clearly listed at the end of the introduction instead of stating you're exploring X, Y, and Z, which is somewhat vague. That way, you can clearly answer the questions in the discussion.

Response

Thank you for your comment. It is explicitly listed in the introduction: "This study assesses how nutrient limitation affects several uncertainties in remaining carbon budget estimates, including uncertainty in the TCRE, the estimated contribution of non-CO_2 climate forcings to future warming, the correction for the feedback processes presently unrepresented by Earth System Models, and the unrealized warming from past CO_2 emissions–called the zero emissions commitment (ZEC) (Rojelj et al. , 2018)."

General Comment

Once you define an acronym/abbreviation, e.g., SSPs, PFT, C, N, P, be consistent with the use throughout the manuscript, either use them or not.

Response

Thank you for your comment. All acronyms inconsistencies has been checked.

General comments

Although the SSPs are an integral part of the work, they are not mentioned in the introduction or were ever explained, except generally. Not all readers will know/remember what the difference between the SSPs are (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, SSP5-3.4-OS and SSP5-8.5). You can easily group them, add a brief description of each, with the differences.

Response

Thank you for your comment. The following has been added to the methodology:

The SSPs represent a range of possible futures, with each scenario defined by key characteristics. SSP1 reflects a sustainable and policy effective scenario were emissions are low and climate impact is minimized. SSP2 in a scenario with medium challenges for mitigation and adaptation. SSP3 is a high challenge for mitigation and adaption scenario. SSP4 is a low challenge for mitigation high challenge for adaption scenario. Finally, SSP5 is a high challenge for mitigation and low challenge for adaptaton scenario.

Comment

About (reviewer 1) comment 28 and response. Citations are still wrong.

Response

Thank you for the comment. They were changed in the revised manuscript.

Comment

About comment 26 and response. The comment was not addressed. PFT in the text is still not defined, and the sentence is still unclear: "The nutrient limitation is also different for plant functional types and hence, the change in vegetation biomass is depended on differences among the limitation applied to each PFTs." The reader shouldn't have to go to Cox (2001) to understand the sentence; the sentence should be clear and well-structured. What do you mean by differences in limitation applied to each PFT? It sounds like a prescribed trait differing among PFTs. Are you still talking about stoichiometry, which causes them to be affected differently? Or is it just a repetition that PFTs are affected differently by nutrient limitation? The following sentences are also hard to interpret with the "application of nutrient limitation". How does one apply nutrient limitation in the model? Please, be more specific.

Response

Thank you for you comment. You are right PFTs is still missing in the manuscript it was defined in its first mention. However, PFTs are described in the text: "TRIFFID (top-down representation of interactive foliage and flora including dynamics) represents vegetation interaction between 5 functional plant types within the terrestrial vegetation. Based on the Lotka-Volterra equations (Cox , 2001), broadleaf trees, needleleaf trees, shrubs, C3 grasses, and C4 grasses compete for space in the grid." It is usual in ESMs to have different parameter values for PFTs, as they have unique plant characteristics. The nutrient limitation was explained in the text: "Nitrogen and phosphorus limit terrestrial vegetation growth in the model in two different ways: 1) Nitrogen limits the photosynthetical activity (by regulating the maximun carboxilation rate of RuBISCO) and directly by reducing biomass. This reduction is controlled by the maximum C:N leaf ratio, where reducing this value corresponds to a larger reduction of vegetation 150 biomass. 2) A stoichiometric reduction of biomass when N and P are considered to be limiting terrestrial plants. If C:N ratios are above a set ratio threshold, wood and root carbon biomass are then transferred to the litter pool (reassembling decaying vegetation when in nutrient limiting environments) until the "normal" set C:N ratio is reached. There is no direct inclusion of P limitation in photosynthesis-related equations. Past model development efforts tested different approaches such as Walker et al. (2014) but the concepts were incompatible with the current version of land vegetation model structure."

Comment

About comment 31 and response. You said that further developments in the terrestrial CNP model could change your results, so how is that not relevant to the discussion? This might not be the aim of the paper, but if it might change, your results should be discussed, even briefly (although not vaguely). In your response to a comment made by reviewer 3 (comment 2), you said that line 325 (old manuscript), the same sentence in question in my comment 31, would be erased from the manuscript as it has conveyed the wrong message. However, the sentence is still there.

Response

Thank you for your comment. Comment 31 response was a bit over stated at the end. Further improving and refining the nutrient limitation might change the results simply because the limitation of vegetation would be stronger on weaker on those hypothetical model structures. But it is very likely that the remaining carbon budgets are still going to be reduced. With the new revisions suggested in this phase of reviews, the line was erased.

Comment

The paragraph around line 365 could be made more informative and less vague by adding specific details. For instance, when stating "models would improve with more observations," which observations? Similarly, when stating "data have large ranges", which data specifically are you talking about? "N and P cycle are uncertain" is too vague for a statement. While acknowledging uncertainties in your model is important, providing context or referencing existing literature on nutrient cycle implementations in models (you could easily list a couple of examples) could lend more credibility and usefulness to your discussion. Additionally, some of the sentences in this paragraph are not needed (e.g., you're showing results for your model structure, and others will differ).

Response

Thank you for your comment. The paragraph has been changed to:

The main limitation of terrestrial N and P cycles is the lack of global observational data that can be used to refine and validate ESMs. The lack of data includes most of the N and P cycle processes. The uncertainties in the representation of the terrestrial nutrient limitation of the UVic ESCM include the lack of a dynamic leaf nutrient resorption representation, lack of root uptake constraints, simplified sorption-resorption dynamics of phosphorus in soils, and a simplified wetland representation. A detailed description of the terrestrial nitrogen and phosphorus uncertainties can be found in the complete description of the model in (De Sisto et al. , 2023).

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