Response to reviewers

We appreciate the time and effort that the reviewers 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

Comment

Land-use change emissions in CNP are substantially lower compared to independent estimates (Friedlingstein et al., 2022). I assume the main reason is various land-use related processes such as crop and wood harvest or gross transitions not being represented in the model. I am not sure about the implications for the present study, i.e. does this mean total CO2 emissions are likely underestimated? Additionally, nutrient-limited simulations exhibit even lower land-use emissions compared to C-only simulations. Does this mean that while the remaining carbon budget is reduced (due to the smaller land sink), the actual point in time when the temperature threshold is crossed might be the same or even later?

Response

Thank you for your comment. You are correct, the land-use change emission estimates are lower in CNP than the values presented in Friedlingstein et al., 2022. In the UVic ESCM 2.10, as explained in Mengis et al. (2020) "LUC affect the model runs so that when forest or other vegetation is cleared for croplands, range lands or pasture, 50 % of the carbon stored in trees is released directly into the atmosphere, and the remaining 50 % is placed into the short-lived carbon pool" Hence, the reduction of wood biomass in CN and CNP reduced LUC emissions. In CNP, biomass reduction goes beyond CN as tropical regions are subjected to more limitations. In the UVic ESCM 2.10, tropical regions have an overestimation of broadleaf trees in the tropics. When phosphorus is applied, the result is a substantial decrease in land use change emissions compared to the base version of the model, leading to a substantial difference with Friedlingstein et al. (2022). However, CN is still within the range shown in Friedlingstein et al. (2022) study. The nutrient-limited simulations crossed the temperature threshold before the c-only simulations. Despite the decrease in land use change emissions, in nutrient limited simulations there is a net reduction of the carbon flux to land. If you see Appendix B, SSP4-3.4 as an example and take a look at the time when the simulations cross the treshold for the 2 °C, you can notice that CNP and CN reach the temperature around the end of the 2060's while C only in the 2080's.

Comment

There seem to be many different model configurations used for the simulations (emission- vs. concentration-driven, different climate sensitivities, different aerosol forcings). I particularly have difficulties to understand which simulations were emission-driven and which were concentration-driven. A table would help to better understand the simulation setups.

Response

Thank you for your comment. The following table was added to the methodology section:

Table 1. Model simulations set-up with descriptions.

Simulations	Type	Descriptions
C-only	Nutrient-Concentration driven	Carbon only simulation
CN	Nutrient-Concentration driven	Carbon-nitrogen simulation (nitrogen limited)
CNP	Nutrient-Concentration driven	Carbon-nitrogen-phosphorus simulation (nitrogen-phosphorus limited)
SSPs	Future scenarios-Concentration driven	Shared Socioeconomic Pathways
Modified climate sensitivity	Climate sensitivity-Concentration driven	Longwave radiation flow modified to alter equilibrium climate sentivity
TCR and TCRE	1pct CO_2 experiment-Concentration driven	1 percent CO_2 increase experiment.
Effective TCRE	SSP5-8.5-Concentration driven	All forcing SSP5-8.5 scenario.
ZEC	Concentration driven & emission driven	Zero emission commitment experiments

Comment

Related to that, Fig. 2 seems to be based on concentration-driven simulations, with fossil emissions being diagnosed from the other components. Wouldn't it be more logical to conduct emission-driven simulations (as fossil fuel emissions are relatively well-known) and then investigate differences in atmospheric, land and ocean sinks and the airborne fraction? I also don't understand why there are no differences in the ocean sink, shouldn't this also be affected when the land sink diminishes?

Response

Thank you for your comment. It would be more logical if the goal was to assess the nutrient limitation effect on the carbon cycle as a model development effort or if the scenarios used in the model runs were conventionally emission driven. However, we have followed the CMIP6 protocol where the SSPs scenarios are concentration driven. Concentration driven simulations have the advantage of being able to isolate among different scenarios from only the change in model-set-up. In concentration driven simulations the ocean always 'sees' the same CO_2 concentration and hence only temperature feedbacks and other secondary processes will change the rate of ocean carbon uptake.

Comment

More model evaluation would increase confidence into the results. While some evaluation was performed in a previous study, the comparison regarding carbon fluxes seems to be limited to the FLUXCOM product. Why not compare the simulations to other GPP products? I also would like to see a validation of simulated vegetation carbon. In the previous study a simulated vegetation biomass of 456 and 525 PgC was reported but this seemed to be for potential natural vegetation and would be very low compared to other estimates (e.g. Mo et al. 2023; https://doi.org/10.1038/s41586-023-06723-z)

Response

Thank you for your comment. It is a low amount for potential vegetation, but our model does represent human-driven change on vegetation, hence, this amount should be interpreted as the current of vegetation biomass given human action. The estimate for this figure from IPCC AR6 is 450 (380 to 536) PgC (Canadell et al. , 2021), so our simulated values fall within this range. As an intermediate complexity model there is little expectation that UVic ESCM can reproduce regional GPP values at high fidelity (due to climate bias from the simplified atmosphere), for this class of model getting the global value correct is more valuable. The current paper focuses of remaining carbon budgets, comparing GPP in this paper would de-rail the focus on our primary message and story-line. Furthermore, we do present uncertainty ranges in our estimations.

Comment

The introduction lacks clear structure and readability. Many metrics like TCRE, effective TCRE, TCR and ZEC are introduced but the sentences often are not logically well connected and oftentimes terms are repeated at different stages. For instance, several times there is a switch from "nutrients" to "modelling terms" and vice versa. Streamlining this section would enhance clarity.

Response

Thank you for your comment. From the fourth paragraph the introduction has been changed to:

The remaining carbon budget describes how much CO_2 emissions can be allowed to be emitted to stay below global atmospheric temperature target goals, commonly 1.5 and 2 °C (IPCC , 2021). This metric is of utmost importance for policy and emission reduction regulations. Therefore, the estimation of remaining carbon budgets and their uncertainties has led to numerous research efforts in the scientific community (e.g. Matthews et al. (2020); Lamboll et al. (2023)). The cumulative emission of CO_2 has been found to be nearly proportional to the change in global surface atmospheric temperatures (Tokarska et al. , 2018; Matthews et al. , 2020). This almost linear pattern can be conveniently used as a metric, the Transient Climate Response to Cumulative CO_2 Emission (TCRE), to quantify how global surface temperatures change to cumulative CO_2 emissions (Matthews et al. , 2009; MacDougall , 2016; Spafford and MacDougall , 2021). The TCRE can then be applied to estimate remaining budgets, where its inverse represents the allowable carbon emitted for each temperature goal (Matthews et al. , 2020). This metric has been shown to be good for predicting the response of temperature to cumulative CO_2 emissions. However, the TCRE only represents warming from CO_2 emissions, excluding the impacts of non-CO_2 forcing agents. A method to account for this issue is to use the effective TCRE, which includes simulations with all anthropogenic forcings (Tokarska et al. , 2018).

As a metric, the TCRE has a large uncertainty within published research studies, ranging from 1.0 to 2.3 K EgC^{-1} (IPCC , 2021). Understanding the sources of these uncertainties can improve the estimation of remaining carbon budgets and thereby increase the accuracy of environmental regulations. For idealized experiments, the Transient Climate Response (TCR) can be used to quantify the physical uncertainty in TCRE. TCR is the amount of global warming expected to occur when atmospheric CO_2 concentrations double from their pre-industrial levels, while all other factors remain constant. This corresponds to year 70 in a 1pctCO2 experiment where the annual CO_2 concentration is increased at a rate of 1 % yr^{-1} (Eyring et al. , 2016). In Earth system models, the representation of the carbon cycle is one of the most important sources of uncertainties for the estimation of remaining carbon budgets (Matthews et al. , 2020).

Nutrient limitations play a vital role in the estimations of remaining carbon budgets due to their constrain on the terrestrial carbon cycle. This study assesses how nutrient limitation impacts 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 ESMs, and the unrealized warming from past CO_2 emissions–called the Zero Emissions Commitment (ZEC) (Rojelj et al. , 2018).

N and P are the main nutrients limiting terrestrial systems. Their inclusion of N and P in Earth system models has been shown to decrease the capacity of the land to uptake carbon and affect the vegetation biomass and distribution representation (Wang et al. , 2010; Goll et al. , 2017; Wang and Goll , 2021; De Sisto et al. , 2023). Aside from land sinking changes, terrestrial N and P limitation also impact land use change emissions and albedo due to decreased vegetation biomass (De Sisto et al. , 2023). Isolating the effects of N and P terrestrial limitation gives a novel insight into how underrepresented processes in terrestrial systems contribute to remaining carbon budget uncertainties. Hence, we explore the effect of terrestrial N and P limitation in remaining carbon budget estimates in an intermediate complexity ESM under historical, idealized, and Shared Socioeconomic Pathways projections.

Comment

Fig. 4-8 require a lot of space and the split into different scenario groups does not seem intuitive to me. Why not include everything in one figure? The extra space could be used e.g. to show some maps to check whether spatial patterns make sense. Also reconsider colour choice for the figures. Fig. 3 and 4 both use the same three colours but the meaning is very different (nutrient configuration in Fig. 3 vs. climate sensitivity in Fig. 4).

Response

Thank you for your comment. We think that the space is needed to properly show the difference among the different simulations. Merging them into one figure, will diminish the visibility of changes. The figures colors have been changed to:

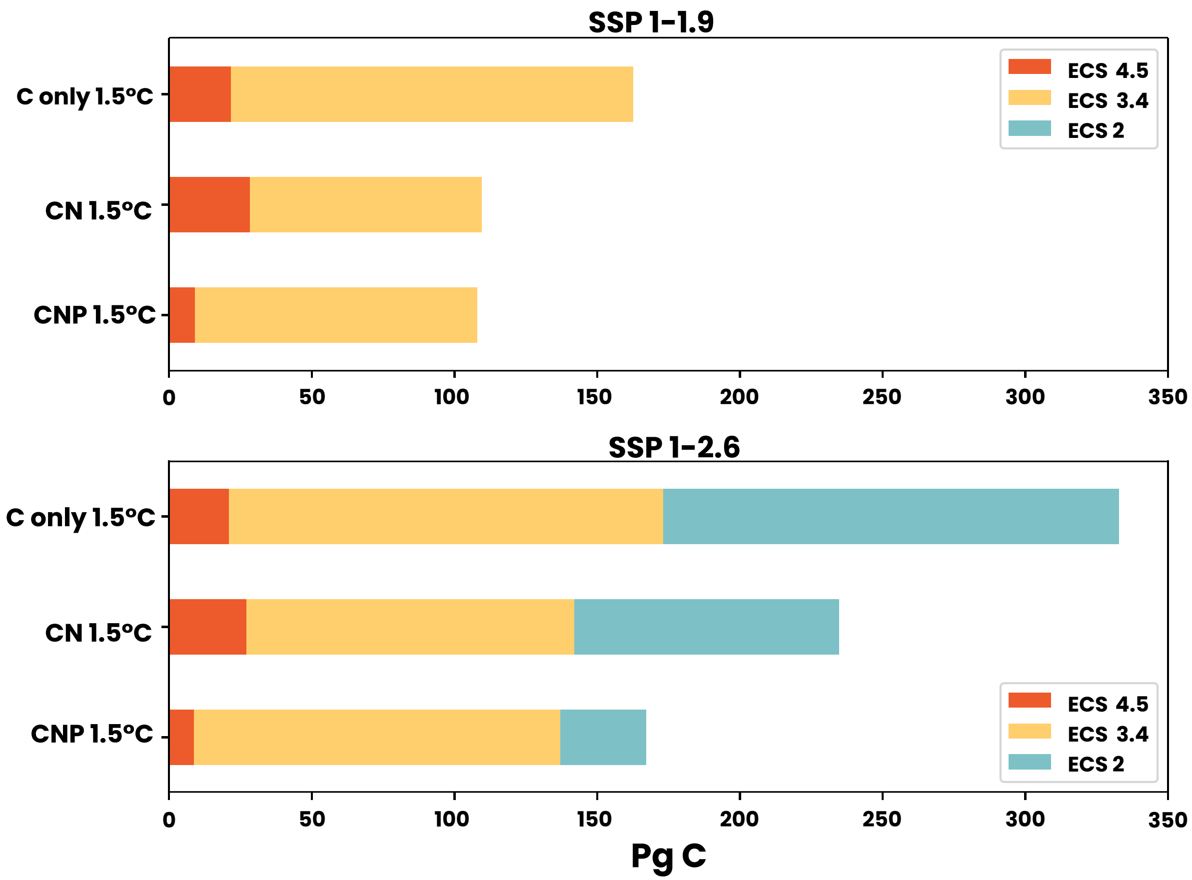

Figure 1. Carbon budgets for the 1.5 °C target for SSP 1-1.9 and 1-2.6. Three model sensitivities are shown as: ECS 4.5 orange, ECS 3.4 yellow and ECS 2 blue.

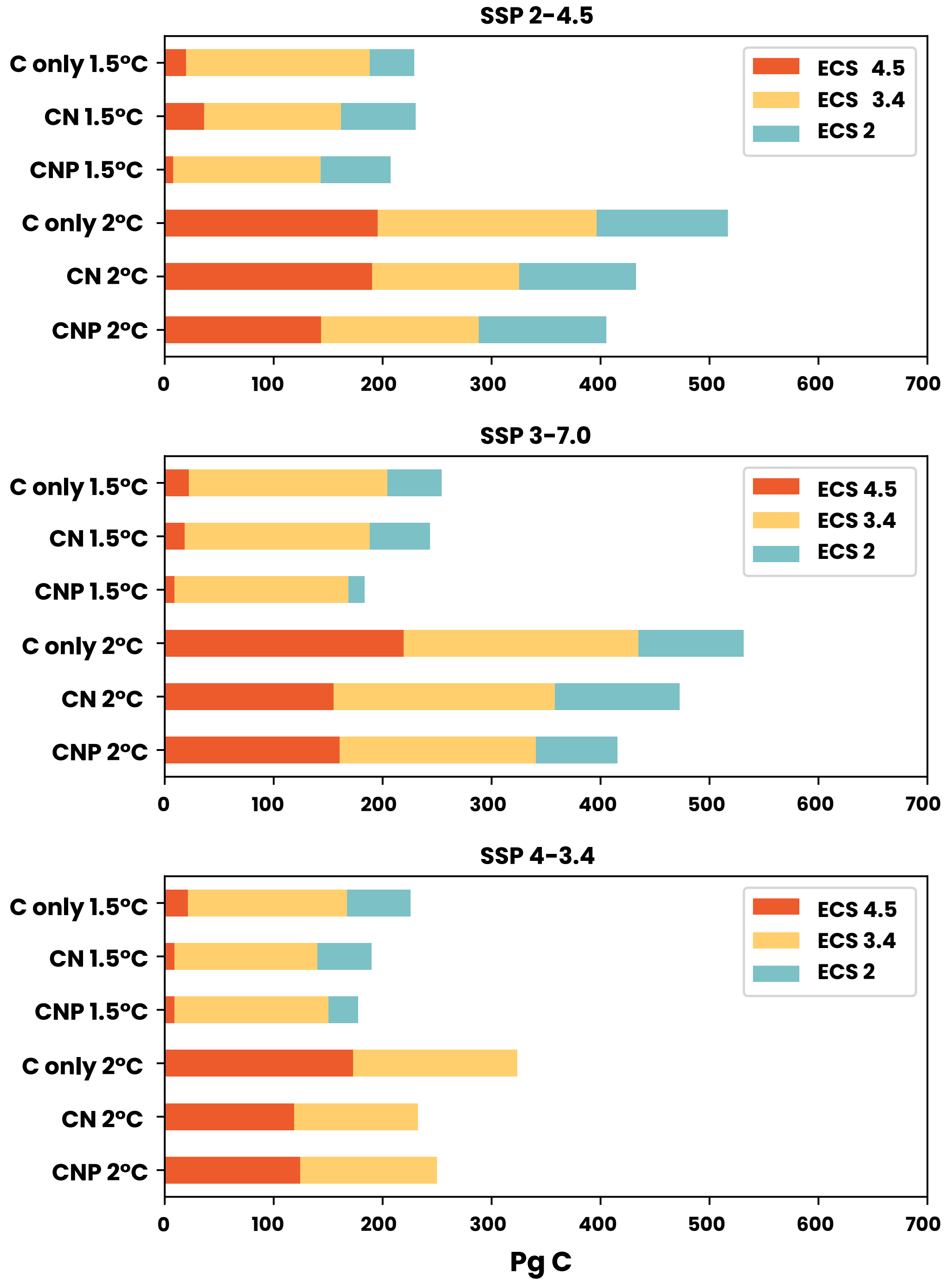

Figure 2. Carbon budgets for the 1.5 and 2 °C targets for SSP 2-4.5, 3-7.0 and 4-3.4. Three model sensitivities are shown as: ECS 4.5 orange, ECS 3.4 yellow and ECS 2 blue.

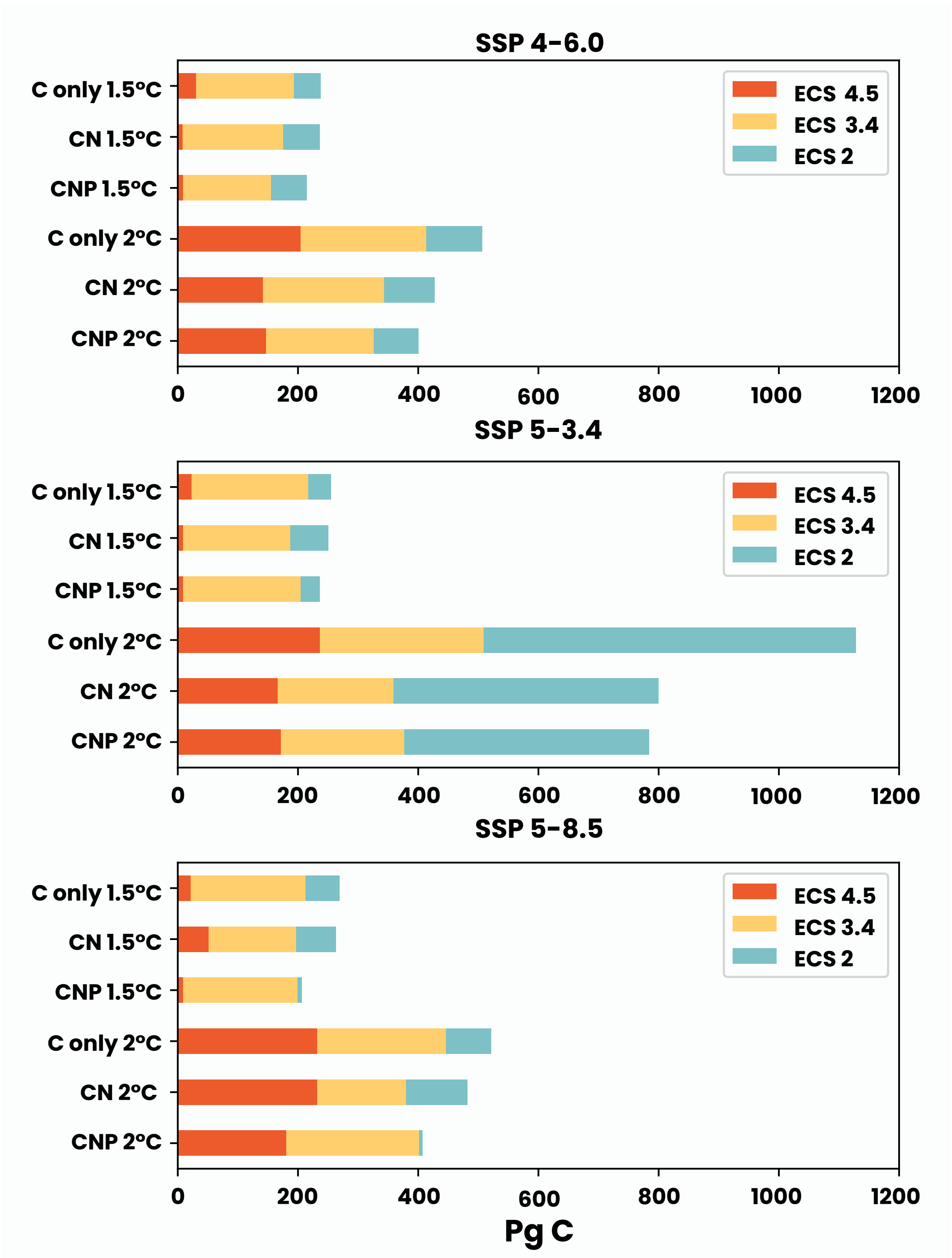

Figure 3. Carbon budgets for the 1.5 and 2 °C targets for SSP 4-6.0, 5-3.4 and 5-8.5. Three model sensitivities are shown as: ECS 4.5 orange, ECS 3.4 yellow and ECS 2 blue.

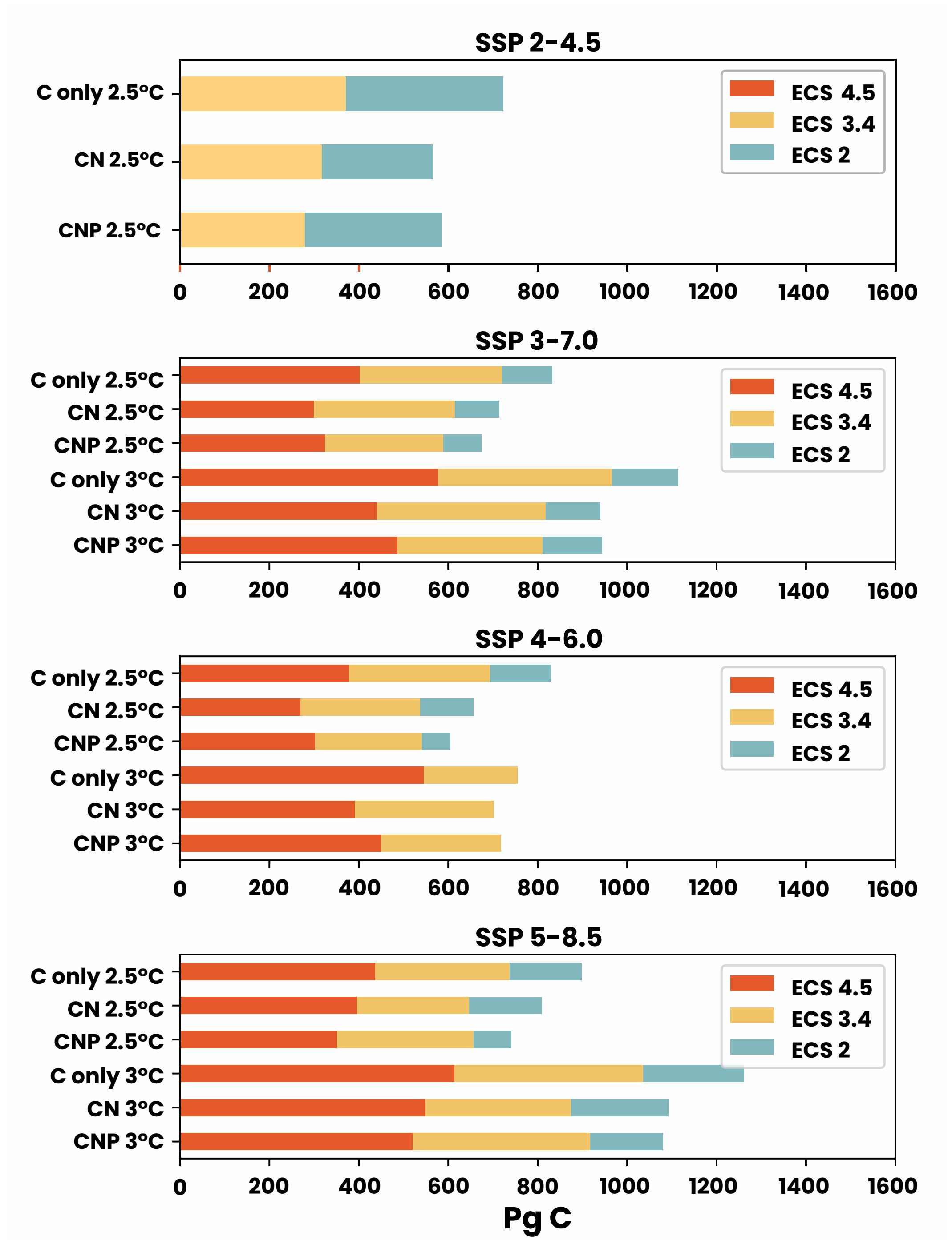

Figure 4. Carbon budgets for the 2.5, 3 °C targets for SSP 3-7.0, 4-6.0 and 5-8.5. These were the only scenarios that reached the threshold. Three model sensitivities are shown as: ECS 4.5 orange, ECS 3.4 yellow and ECS 2 blue.

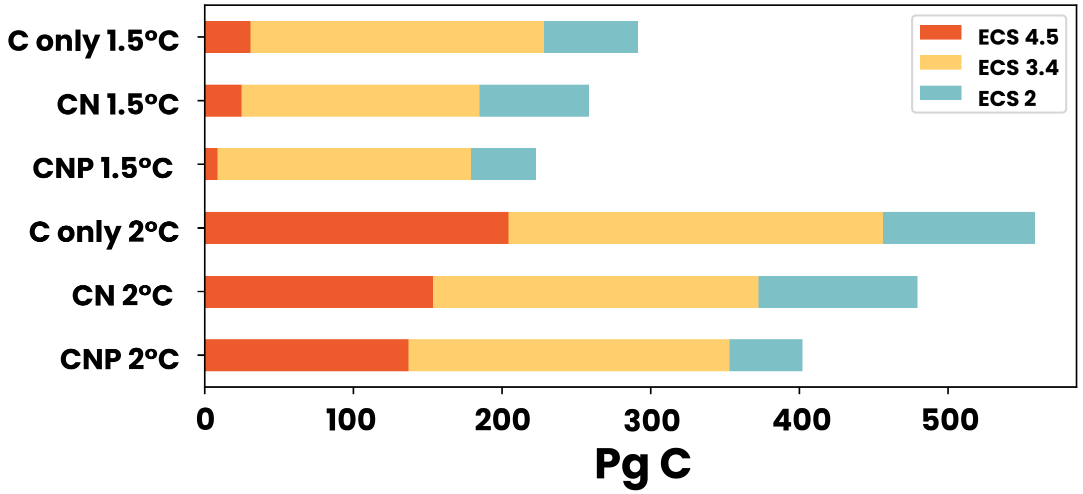

Figure 5. Mean SSP carbon budgets for the 1.5 and 2 °C temperature targets.

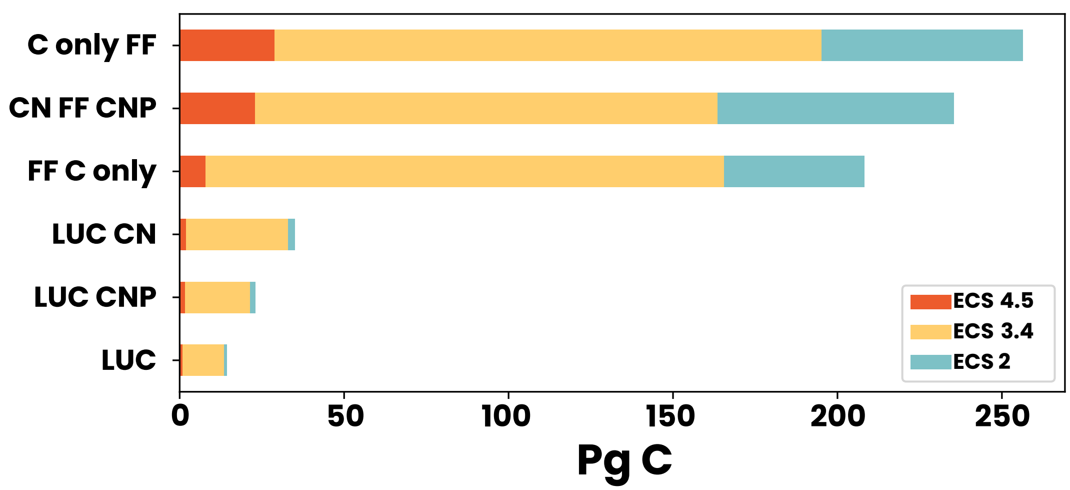

Figure 6. Mean SSP carbon budgets for Fossil Fuel (FF) and LUC emissions for the 1.5 °C temperature target.

Comment

The discussion lacks focus and should incorporate more references to existing studies for context and comparison.

Response

Thank you for your comment. The discussion has been re-worked as suggested:

The representation of the carbon cycle in Earth system models has been shown to be a source of uncertainty in the estimation of remaining carbon budgets (Matthews et al. , 2020). In nutrient-limited structures, the capacity of land to uptake atmospheric carbon is a constrainted (Wang et al. , 2010; Wieder et al. , 2015; Wang and Goll , 2021; Wei et al. , 2022; De Sisto et al. , 2023). This study shows a decrease in land carbon sink in nutrient-limited simulations, agreeing with other nutrient-limited model structures in literature (Wang et al. , 2010; Wieder et al. , 2015; Wang and Goll , 2021). In contrast, the reduced carbon uptake by plants is balanced by a decreased of land use change emissions. This reduction comes in the UVic ESCM due to a decrease of vegetation biomass, especially from woody plants (De Sisto et al. , 2023). This is also shown in Wang et al. (2015), where the implementation of nutrient-limited models reduced the carbon emissions from deforestation in RCP8.5 scenarios.

The reduction of vegetation biomass also leads to an increase of albedo due to the replacement of broadleaf trees and needleaf trees with grass or bare soil, as shown in (De Sisto et al. , 2023). The albedo differences among nutrient-model structures have a marginal effect on temperature. It is interesting to note that in nature, there are observations pointing to positive correlations between the concentration of nitrogen in canopies and albedo (Loozen et al. , 2020). This correlation is not reflected in the model structure as high nitrogen concentrations would reduce the leaf "shed" when the model is considered to be under nutrient limitation.

The change of terrestrial carbon fluxes under nutrient limitation is shown in this study to accelerate warming, impacting the time when temperature thresholds are reached in different simulations. Hence, corresponding to an increase of the TCRE. In concentration driven simulations the diagnosed cumulative emissions estimated by the model under nutrient limitation is lower than C-only simulations, as in figure 2. The main reason being the decrease of land carbon flux. The carbon sink in terrestrial systems was noted as one of the most significant sources of uncertainties in TCRE estimated (Jones and Friedlingstein , 2020). Other unrepresented terrestrial processes, such as permafrost thawing, have also been shown to affect the TCRE and remaining carbon budgets (MacDougall et al. , 2015).

After cessation of emissions, the terrestrial nutrient limitation was shown to increase the temperature response after emissions have ceased. The ZEC values are within the range of values of -0.36 to 0.29 °C presented by MacDougall et al. (2020) who analysed model simulations from 9 ESMs and 9 Earth system model of intermediate complexity. The land carbon sink has been identified as a critical process in ZEC values (MacDougall et al. , 2020; Palazzo et al. , 2023). After emissions ceased the reduced rate of carbon sink by terrestrial systems increases the immediate temperature response of the systems in nutrient limited simulations. This decreased sink, leads to an overall reduction of ZEC compared to C-only simulations.

In this study, the effect of terrestrial nutrient limitation on the terrestrial carbon dynamics resulted in 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 N and P 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, N and P 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.

Regarding the uncertainties in the terrestrial nitrogen and phosphorus cycles, 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. Other uncertainties on the representation of terrestrial nutrient limitation in 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 N and P uncertainties can be found in the complete description of the model in (De Sisto et al. , 2023).

Comment

L24: I find the order of the introduction a bit odd. It starts with describing ESMs accounting for nutrient limitation before actually explaining why nutrients are important.

Response

Thank you for your comment. The first two paragraph have been modified as:

Nutrient availability constrains the capacity and rate at which terrestrial plants assimilate carbon (Goll et al. , 2012). Nitrogen and phosphorus are the nutrients that most commonly limit vegetation growth (Filipelli , 2002; Fowler et al. , 2013; Wang et al. , 2010; Du et al. , 2020) and hence have been the subject of most research and large scale modelling efforts. Globally, this effect varies. Most of the terrestrial biosphere is co-limited by both N and P, with N being the dominant nutrient limitation in higher latitudes while phosphorus predominates in lower latitudes (Du et al. , 2020). Earth system models are designed to account for land use change, and biological productivity when estimating the carbon sink on land (Kiwamiya , 2020). The change of nutrient concentration in terrestrial systems in future simulations is an uncertainty for determining the land carbon sink over the next decades (Shibata et al. , 2010, 2015; Menge et al. , 2012). Complicating this problem further, a large portion of nutrients on land are derived from anthropogenic sources, including agricultural fertilization (artificial, compost and manure), atmospheric deposition of N-bearing pollutants, and urban wastewaters (Lu and Tian , 2017; van Puijenbroek et al. , 2019).

Future climate projections have only rarely accounted for nutrient limitation of the land carbon sink (Wang and Goll , 2021). For the sixth phase of the Coupled Model Intercomparison Project (CMIP6) this weakness was partially overcome with more Earth system models (ESMs) embracing nitrogen limitation as a standard for terrestrial system structures. However, the inclusion of phosphorus remains rare and representation of micro-nutrients remains a distant ambition. (Arora et al. , 2020; Spafford and MacDougall , 2021). Thus, the future of the land carbon sink remains uncertain as projecting the interactions between the terrestrial system and atmosphere is a challenge without fully accounting for nutrient limitations (Achad et al. , 2016). Since year 1850, the cumulative CO_2 land sink has been estimated to be 210$\pm$45 PgC, which represents 31% of all anthropogenic carbon emissions (Friedlingstein et al. , 2022). The terrestrial carbon sink has increased historically with increasing CO_2 emission rate, such that the proportion of carbon taken up by land has remained close to constant (Friedlingstein et al. , 2022).

Comment

L44: use ”carbon dioxide” or “CO2” consistently

Response

Thank you for your comment. Carbon dioxide has been changed to CO_2 across the manuscript.

Comment

L57: “has”

Response

Thank you for your comment. Line 57 has been modified:

This metric has been shown to be good for predicting the response of temperature to cumulative CO_2 emissions.

Comment

L58: “represents”

Comment

Thank you for your comment. Line 58 has been changed as suggested.

Comment

L61: In the previous sentence you introduced the effective TCRE. Do you mean effective TCRE?

Response

Thank you for your comment. No, that is not the effective TCRE. The introduction has been changed to:

The TCRE can then be applied to estimate remaining budgets, where its inverse represents the allowable carbon emitted for each temperature goal (Matthews et al. , 2020). This metric has been shown to be good for predicting the response of temperature to cumulative CO_2 emissions. However, the TCRE only represented warming from CO_2 emissions, excluding the impacts of non-CO_2 forcing agents. A method to account for this issue is to use the effective TCRE, which includes simulations with all anthropogenic forcings (Tokarska et al. , 2018).

As a metric, the TCRE has a large uncertainty within published research studies, ranging from 1.0 to 2.3 K EgC^{-1} (IPCC , 2021). Understanding the sources of these uncertainties can improve the estimation of remaining carbon budgets and thereby increase the accuracy of environmental regulations. For idealized experiments, the Transient Climate Response (TCR) can be used to quantify the physical uncertainty in TCRE. TCR is the amount of global warming expected to occur when atmospheric CO_2 concentrations double from their pre-industrial levels, while all other factors remain constant.This corresponds to year 70 in a 1pctCO2 experiment where the annual CO_2 concentration is increased at a rate of 1 % yr^{-1} (Eyring et al. , 2016). In Earth system models, the representation of the carbon cycle is one of the most important sources of uncertainties for the estimation of remaining carbon budgets.

Comment

L65: Because it depends on baseline CO2 concentration?

Response

Thank you for your comment. The TCR is dependent on rates of CO_2 concentrations represented in the input datasets.

Comment

L81: Unclear. I think what you mean are (biophysical) feedbacks.

Response

Thank you for your comment. Yes, that is why Albedo is mentioned in the line.

Comment

L85: Do you mean N and P limitation? And what is meant by the present simulations? The ones conducted in this study?

Comment

Thank you for your comment. Line 85 has been removed from the manuscript.

Comment

L105: I don't understand why the lower layers are included. What processes take place there? Also I would like to see more information about how the vegetation is actually modelled. For instance, how is mortality implemented?

Response

Thank you for your comment. The deep layers are needed as a heat sink to make the permafrost module work (Avis , 2012). Without deep layers permafrost thaws far too fast. The original TRIFFID paper (Cox , 2001) has the information necessary to understand the basics of vegetation in the UVic ESCM. These mechanisms have not been substantially modified since TRIFFID was incorporated into the model in 2003 (Meissner et al. , 2003).

Comment

L122: "module"?

Response

Thank you for your comment. Yes, a module as in a component of the larger model structure.

Comment

L124: "N deposition". Where does the deposition data come from? Is it different for the different SSPs?

Response

Thank you for your comment. Nitrogen deposition comes from Dentener (2006). It is not different among SSPs.

Comment

L132: How large is this fraction?

Response

Thank you for your comment. 0.5 as in De Sisto et al. 2023. Line L132 has been changed to:

> Before litterfall, a constant 0.5 fraction of the N is reabsorbed.

Comment

L133: What is the relationship between soil temperature/water and mineralization? Warlind et al. (2014, 10.5194/bg-11-6131-2014) might be a good reference for the discussion.

Response

Thank you for your comment. That was addressed in the model description paper De Sisto et al. (2023). The mineralization is dependent on moisture and temperature functions.

Comment

L149: Unclear. So if leaf C:N exceeds a threshold a fraction of the biomass is killed? Or does it just mean no more biomass can be build up?

Response

Thank you for your comment. Leaf will "shed" and added to the litter pool until the maximum C:N ratio is met once again.

Comment

L176: I don't understand. The emissions of CO2? If calibration to observed temperature was done via aerosol forcing then why are CO2 emissions not the same? To get the same CO2 concentration?

Response

Thank you for your comment. Aerosol tuning is imprecise as aerosol optical depth is very spatially and temporally heterogeneous. The model was tuned until the simulations were substantially similar.

Comment

L181: What is the 4xCO2 level used for?

Response

Thank you for your comment. For initial validation to previous model assessments.

Comment

L186: "where", "is"

Comment

Thank you for your comment. The suggested changes has been applied in the manuscript.

Comment

L189: So CO2 is increased by 1% per year but the other forcings are from SSP5-8.5? Also you also need to explain the meaning of the second number.

Response

Thank you for your comment. Effective TCRE is derived from transient scenarios, most previous studies have used RCP 8.5 or SSP 8.5 and we follow this convention Tokarska et al. (2018)

Comment

L199: Why is there a multi-year average for year 50 but not for year 0 and 100 after emission cessation?

Response

Thank you for your comment. The next sentence states that we do use ZEC 100, ZEC_0 is by definition 0.

Comment

L201: I don't think this is a good title as you don't really isolate the non-CO2 forcing. How about "Remaining carbon budgets in SSP scenarios"?

Response

Thank you for your comment. The title has been changed to "Estimated effect of nutrient limitations on SSP scenario simulations"

Comment

L207: So is this for the first year the temperature targets are exceeded? Why not a multi-year average?

Response

Thank you for your comment. The UVic ESCM does not have unforced climate variability, due to its simplified atmosphere. So for our model the usual smoothing techniques are not necessary.

Comment

L208: "on"

Response

Thank you for your comment. The change has been applied as suggested.

Comment

L210: So are the missing land-use emissions added to the fossil emissions to maintain total emissions?

Response

Thank you for your comment. No, in a concentration driven simulation CO_2 is prescribed. Hence, the model diagnoses emissions base on carbon fluxes. As these fluxes are not reflected in the atmospheric CO_2, because it is prescribed, changes in fluxes are thereby reflected in the diagnosed emissions.

Comment

L220: Remove this sentence.

Response

Thank you for your comment. The sentence in question is "The temperature anomalies were plotted against 220 GISS near surface air temperatures anomalies relative to 1951-1980 (GISTEMP Team , 2023)." We do not understand the reason behind this suggestion, the sentence details which temperature reconstruction we are using is basic information needed by the reader.

Comment

L224: Why are total emissions the same when land-use emissions are smaller in CNP?

Response

Thank you for your comment. That is describing the model development paper De Sisto et al. (2023) . It refers to an emission driven simulation, where with the same amount of emissions the temperature response is higher in CNP (less carbon sink).

Comment

L225: Again, consider showing some maps of these results.

Response

Thank you for your comment. Our focus and message is to show the impact of nutrient limitation on the remaining carbon budgets. The full revision was already shown in De Sisto et al. (2023)

Comment

L248: "to take up"

Response

Thank you for your comment. The change has been applied as suggested.

Comment

L260: Is there an explanation for this behaviour?

Response

Thank you for your comment. We believe the behavior is related to sea-ice feedbacks and interruptions to the overturning circulation.

Comment

L271: Figure 2+3 are not about the remaining carbon budget in SSPs.

Response

Thank you for your noticing. The reference to the figures has been changed accordingly.

Comment

L272: It reads as if the target is to exceed these temperature limits. Also the 2° target is actually defined as "well below 2°".

Response

Thank you for your comment. Line 272 has been changed to:

Given the different SSPs forcing and resulting warming, not all experimental simulations crossed the 2, 2.5 and 3 °C thresholds.

Comment

L287: Land-use change in the two 1.5°C-consistent scenarios actually involves net reforestation so I would have expected these numbers to be negative?

Response

Thank you for your comment. That number represents the mean of all the SSPs in different climate sensitivities.

Comment

L300: The whole albedo discussions seems out of place. Why haven't any results been shown when this is so relevant?

Response

Thank you for your comment. Section 3.2: These small differences are driven by albedo changes. Between CNP and CN, the albedo change has a small increase effect of 0.004 °C in CNP compared to CN (note the UVic ESCM lacks internal variability, so this very small difference is computable).

Comment

L303: Do you mean land-use change emissions?

Response

Thank you for your comment. Yes, land-use change emissions. The line has been change to:

In contrast, the reduced carbon uptake by plants is balanced by a decreased of land use change emissions.

Comment

L306: I am confused about the ocean statement, Fig. 2 suggests the ocean sink is unaffected?

Response

Thank you for your comment. Line 306 has been been removed.

Comment

L313: "no nutrient limitation"?

Response

Thank you for your comment. Line 313 has been removed.

Comment

L314: More context is needed. Remind the reader what the ZEC values of the present study are. And what kind of models were included in MacDougall et al.?

Response

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

After cessation of emissions, the terrestrial nutrient limitation was shown to increase the temperature response after emissions have ceased. The ZEC values are within the range of values of -0.36 to 0.29 °C presented by MacDougall et al. (2020) who analysed model simulations from 9 ESMs and 9 Earth system model of intermediate complexity. The land carbon sink has been identified as a critical process in ZEC values (MacDougall et al. , 2020; Palazzo et al. , 2023). After emissions ceased the reduced rate of carbon sink by terrestrial systems increases the immediate temperature response of the systems in nutrient limited simulations. This decreased sink, leads to an overall reduction of ZEC compared to C-only simulations.

Comment

L326: But still much higher than the IPCC number even though the IPCC presumably does not include P limitation? What could be the reasons for that?

Response

Thank you for your comment. Yes, compared to the 50% likelihood but are close to the 67%.

Comment

L331: Typo in Rojelj. This error occurs multiple times in the manuscript.

Response

Thank you for your comment. The suggested changes has been applied across the manuscript.

Comment

L332: "where"

Response

Thank you for your comment. Line 332 had been removed.

References

Achad, D., Gallet-Budynek, A. and Loustau, D: Future challenges in coupled C–N–P cycle models for terrestrial ecosystems under global change: a review. Biogeochemistry, 131, 10.1007/s10533-016-0274-9, 2016.

Arora, V. K., Katavouta, A., Williams, R. G., Jones, C. D., Brovkin, V., Friedlingstein, P., Schwinger, J., Bopp, L., Boucher, O., Cadule, P., Chamberlain, M. A., Christian, J. R., Delire, C., Fisher, R. A., Hajima, T., Ilyina, T., Joetzjer, E., Kawamiya, M., Koven, C. D., Krasting, J. P., Law, R. M., Lawrence, D. M., Lenton, A., Lindsay, K., Pongratz, J., Raddatz, T., Séférian, R., Tachiiri, K., Tjiputra, J. F., Wiltshire, A., Wu, T., and Ziehn, T.: Carbon–concentration and carbon–climate feedbacks in CMIP6 models and their comparison to CMIP5 models, Biogeosciences, 17, 4173–4222, https://doi.org/10.5194/bg-17-4173-2020, 2020.

Avis, C. A.: Simulating the Present-Day and Future Distribution of Permafrost in the UVic Earth System Climate Model, PhD thesis, University of Victoria, 2012.

Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi: 10.1017/9781009157896.007.

Cox, P. M.: Description of the TRIFFID dynamic global vegetation model, Tech. Rep. 24, Hadley Centre, Met office, London Road, Bracknell, Berks, RG122SY, UK, 2001.

De Sisto, M. L., MacDougall, A. H., Mengis, N., and Antoniello, S.: Modelling the terrestrial nitrogen and phosphorus cycle in the UVic ESCM, Geosci. Model Dev., 16, 4113–4136, https://doi.org/10.5194/gmd-16-4113-2023, 2023.

Dentener, F. J.: Global maps of atmospheric nitrogen deposition, 1860, 1993, 2050., Data set., Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A., http://daac.ornl.gov/, 2006.

Du, E., Terrer, C., Pellegrini, A., Ahlstrom, A., Van Lissa, C., Zhao, X., Xia, N., Wu, X. and Jackson, R.: Global patterns of terrestrial nitrogen and phosphorus limitation, Nat. Geosci. 13, 221–226, https://doi.org/10.1038/s41561-019-0530-4, 2020.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016.

Filippelli, G.: The global phosphorus cycle, in phosphates: Geochemical, geobiological, and materials importance, Reviews in Mineralogy and Geochemistry, 391-425. 2002.

Fowler, D., Coyle, M., Skiba, U., Sutton, M. A., Cape, J. N., Reis, S., Sheppard, L. J., Jenkins, A., Grizzetti, B., Galloway, J. N., Vitousek, P., Leach, A., Bouwman, A. F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M., and Voss, M.: The global nitrogen cycle in the twenty-first century, Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 368(1621), https://doi.org/10.1098/rstb.2013.0164, 2013.

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C. E., et al.: Global Carbon Budget 2021, Earth Syst. Sci. Data, 14, 1917–2005, https://doi.org/10.5194/essd-14-1917-2022, 2022.

Goll, D., Brovkin, V., Parida, B., Reick, C., Kattge, J., Reich, P., van Bodegom, P., and Niinemets, Ü.: Nutrient limitation reduces land carbon uptake in simulations with a model of combined carbon, nitrogen and phosphorus cycling, Biogeosciences 9, 3547–3569, https://doi.org/10.5194/bg-9-3547-2012, 2012.

Goll, D., Vuichard, N., Maignan, F., Jornet-Puig, A., Sardans, J., Violette, A., Peng, S., Sun, Y., Kvakic, M., Guimberteau, M., Guenet, B., Zaehle, S., Penuelas, J., Janssens, I. and Ciais, P.: A representation of the phosphorus cycle for ORCHIDEE. Geoscientific Model Development 10, 3745-3770, doi.org/10.5194/gmd-10-3745-2017, 2017.

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. In Press.

Jones, C. D., Frölicher, T. L., Koven, C., MacDougall, A. H., Matthews, H. D., Zickfeld, K., Rogelj, J., Tokarska, K. B., Gillett, N. P., Ilyina, T., Meinshausen, M., Mengis, N., Séférian, R., Eby, M., and Burger, F. A.: The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions, Geosci. Model Dev., 12, 4375–4385, https://doi.org/10.5194/gmd-12-4375-2019, 2019.

Jones, C. and Friedlingstein, P. Quantifying process-level uncertainty contributions to TCRE and Carbon Budgets for meeting Paris Agreement climate targets. Environmental Research Letters. 15. 10.1088/1748-9326/ab858a, 2020.

Kawamiya, M., Hajima, T., Tachiiri, K., Watanabe, S. and Yokohata, T.: Two decades of Earth system modeling with an emphasis on Model for Interdisciplinary Research on Climate (MIROC), Prog Earth Planet Sci 7, 64, https://doi.org/10.1186/s40645-020-00369-5, 2020.

Lamboll, R.D., Nicholls, Z.R.J., Smith, C.J. et al. Assessing the size and uncertainty of remaining carbon budgets. Nat. Clim. Chang. 13, 1360–1367, https://doi.org/10.1038/s41558-023-01848-5, 2023.

Loozen, Y., Rebel, K., De Jong, S., Lu, M., Ollinger, S., Wassen, M. and Karssenberg, D. Mapping canopy nitrogen in European forests using remote sensing and environmental variables with the random forests method. Remote Sensing of Environment. 247. 111933. 10.1016/j.rse.2020.111933, 2020.

Lu, C., and Tian, H.: Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: Shifted hot spots and nutrient imbalance, Earth System Science Data, 9, 181-192. https://doi.org/10.5194/essd-9-181-2017, 2017.

MacDougall, A. H. and Knutti, R.: Projecting the release of carbon from permafrost soils using a perturbed parameter ensemble modelling approach, Biogeosciences, 13, 2123–2136, https://doi.org/10.5194/bg-13-2123-2016, 2016.

MacDougall, A. H., Zickfeld, K., Knutti, R. and Matthews, D. Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO2 forcings. Environ. Res. Lett. 11 019501, http://dx.doi.org/10.1088/1748-9326/11/1/019501, 2015.

MacDougall, A.H. The Transient Response to Cumulative CO2 Emissions: a Review. Curr Clim Change Rep 2, 39–47, https://doi.org/10.1007/s40641-015-0030-6, 2016.

MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., Arora, V. K., Barrett, N. J., Brovkin, V., Burger, F. A., Eby, M., Eliseev, A. V., Hajima, T., Holden, P. B., Jeltsch-Thömmes, A., Koven, C., Mengis, N., Menviel, L., Michou, M., Mokhov, I. I., Oka, A., Schwinger, J., Séférian, R., Shaffer, G., Sokolov, A., Tachiiri, K., Tjiputra , J., Wiltshire, A., and Ziehn, T.: Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2, Biogeosciences, 17, 2987–3016, https://doi.org/10.5194/bg-17-2987-2020, 2020.

MacDougall, A. H.: Estimated effect of the permafrost carbon feedback on the zero emissions commitment to climate change, Biogeosciences, 18, 4937–4952, https://doi.org/10.5194/bg-18-4937-2021, 2021.

Matthews, H. D., Gillett, N., Stott, P., and Zickfeld, K.: The proportionality of global warming to cumulative carbon emissions, Nature, 459, 829-832. https://doi.org/10.1038/nature08047, 2009.

Matthews, H. D., Tokarska, K., Nicholls, Z.R.J., Rogelj, J., Canadell, Josep, Friedlingstein, P., Frölicher, Thomas, Forster, Piers, Gillett, Nathan, Ilyina, T., Jackson, R., Jones, Chris, Koven, C., Knutti, R., MacDougall, A.H., Meinshausen, M., Mengis, N., Séférian, R., and Zickfeld, K.: Opportunities and challenges in using remaining carbon budgets to guide climate policy, Nature Geoscience, 13. https://doi.org/10.1038/s41561-020-00663-3, 2020.

Meissner, K. J., Weaver, A. J., Matthews, H. D., and Cox, P. M.: The role of land surface dynamics in glacial inception: a study with the UVic Earth System Model, Clim. Dynam., 21, 515–537, https://doi.org/10.1007/s00382-003-0352-2, 2003.

Menge D., Hedin, L., Pacala S.: Nitrogen and Phosphorus Limitation over Long-Term Ecosystem Development in Terrestrial Ecosystems, PLOS ONE 7(8), https://doi.org/10.1371/journal.pone.0042045, 2012.

Mengis, N., Keller, D. P., MacDougall, A. H., Eby, M., Wright, N., Meissner, K. J., Oschlies, A., Schmittner, A., MacIsaac, A. J., Matthews, H. D., and Zickfeld, K.: Evaluation of the University of Victoria Earth System Climate Model version 2.10 (UVic ESCM 2.10), Geosci. Model Dev., 13, 4183–4204, https://doi.org/10.5194/gmd-13-4183-2020, 2020.

Palazzo-Corner, S., Siegert, M., Ceppi, P., Fox-Kemper, B., Frölicher, T.L., Gallego-Sala, A., Haigh, J., Hegerl, G.C., Jones, C.D., Knutti, R., Koven, C.D., MacDougall, A.H., Meinshausen, M., Nicholls, Z., Salle´ e, J.B., Sanderson, B.M., Se´ fe´ rian, R., Turetsky, M., Williams, R.G., Zaehle, S. and Rogelj, J. The Zero Emissions Commitment and climate stabilization, Front Sci, 1:117074, doi: 10.3389/fsci.2023.1170744. 2023.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., and Vilariño, M.V. (In Press): Mitigation pathways compatible with 1.5°C in the context of sustainable development. In Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)], 2018.

Seitzinger, S. P., Mayorga, E., Bouwman, A. F., Kroeze, C., Beusen, A. H. W., Billen, G., Van Drecht, G., Dumont, E., Fekete, B. M., Garnier, J., and Harrison, J. A.: Global river nutrient export: A scenario analysis of past and future trends, Global Biogeochem. Cy., 24, GB0A08, doi:10.1029/2009GB003587, 2010.

Shibata, H., Branquinho, C., McDowell, W. H., Mitchell, M. J., Monteith, D. T., Tang, J., Arvola, L., Cruz, C., Cusack, D. F., Halada, L., Kopáček, J., Máguas, C., Sajidu, S., Schubert, H., Tokuchi, N., and Záhora, J.: Consequence of altered nitrogen cycles in the coupled human and ecological system under changing climate: The need for long-term and site-based research. Ambio, 44(3), 178–193, https://doi.org/10.1007/s13280-014-0545-4, 2015.

Spafford, L., and Macdougall, A.H.: Quantifying the probability distribution function of the transient climate response to cumulative CO2 emissions, Environmental Research Letters, 15. https://doi.org/10.1088/1748-9326/ab6d7b, 2020.

Tokarska, K., Gillett, N., Arora, V., Lee, W., and Zickfeld, K. (2018). The influence of non-CO2 forcings on cumulative carbon emissions budgets. Environmental Research Letters, 13. https://doi.org/10.1088/1748-9326/aaafdd, 2018.

van Puijenbroek, P., Beusen, A. and Bouwman, A.: Global nitrogen and phosphorus in urban waste water based on the Shared Socio-economic pathways, Journal of Environmental Management, 231: 446-456, https://doi.org/10.1016/j.jenvman.2018.10.048, 2019.

Wang, Y., Law, R., Pak, B.: A global model of carbon,nitrogen and phosphorus cycles for the terrestrial biosphere, Bio-geosciences 7, 2261–2282,doi:10.5194/bg-7-2261-2010, 2010.

Wang, Y., Zhang, Q., Pitman, A. and Dai, Y. Nitrogen and phosphorous limitation reduces the effects of land use change on land carbon uptake or emission. Environmental research letters, 10 (2015) 014001, http://dx.doi.org/10.1088/1748-9326/10/1/014001, 2015.

Wang, Y. and Goll, D.: Modelling of land nutrient cycles: recent progress and future development, Faculty Reviews. 10. 10.12703/r/10-53.

Wei, N., Xia, J., Wang, Y. P., Zhang, X., Zhou, J., Bian, C., and Luo, Y. Nutrient limitations lead to a reducedmagnitude of disequilibrium in theglobal terrestrial carbon cycle. Journal ofGeophysical Research: Biogeosciences,127, e2021JG006764. https://doi.org/10.1029/2021JG006764, 2022.

Wieder, W., Cleveland, C., Smith, W. and Todd, K.: Future productivity and carbon storage limited by terrestrial nutrient availability, Nature Geosci 8, 441–444, https://doi.org/10.1038/ngeo2413, 2015.

van Puijenbroek, P., Beusen, A. and Bouwman, A.: Global nitrogen and phosphorus in urban waste water based on the Shared Socio-economic pathways, Journal of Environmental Management, 231: 446-456, https://doi.org/10.1016/j.jenvman.2018.10.048, 2019.