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 1

Line 9: Add SSPs between parentheses to introduce the acronym.

Response

Thank you for your comment. As suggested (SSPs) has been added to line 9:

> We use eight Shared Socioeconomic Pathways scenarios (SSPs)

Comment 2

Line 30: Missing reference at the end of the sentence. "Since year 1850, the cumulative CO2 land sink has been estimated to be 210±45 PgC, which represents 31% of all anthropogenic carbon emissions".

Response

Thank you for your comment. A reference has been added to line 30:

Since year 1850, the cumulative CO_2 land sink has been estimated to be 210±45 PgC, which represents 31% of all anthropogenic carbon emissions (Friedlingstein et al. , 2022).

Comment 3

Lines 58: Consider reading Fleischer et al., 2019, which might be a good reference there. Very long first paragraph in the introduction. Consider splitting it.

Response

Thank you for your comment. The first paragraph of the introduction has been split as suggested:

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±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).

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).

Comment 4

Lines 69-70: "The remaining carbon budget framework used in this study follows"... Sounds like a sentence that should be in the methods and could be rephrased.

Response

Thank you for your comment. Line 69-70 has been changed to:

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. , 2019).

Comment 5

Line 94: "budgets budgets" appears repeatedly along the manuscript. Please clarify.

Response

Thank you for your comment. It is a typo, the second "budgets" has been erased.

Comment 6

Line 121: What does the process of biological nitrogen fixation and mineralization of organic nitrogen depend on in the model?

Response

Thank you for your comment. The nitrogen model description has been changed to:

A terrestrial nitrogen and phosphorous model has recently been developed for the UVic ESCM (De Sisto et al. , 2023). The nitrogen cycle module consists of three organic pools (litter, soil organic matter, and vegetation) and two inorganic pools (NH_4^+ and NO_3^-). Nitrogen input is represented by atmospheric nitrogen deposition and biological nitrogen fixation. The latter is dependent on the terrestrial Net Primary Productivity (NPP). Biological nitrogen fixation and mineralization of organic nitrogen produce NH_4^+, which can be absorbed by plants (vegetation), leached, or transformed into NO_3^- via nitrification. NO_3^- is produced through nitrification, can be taken up by plants, leached or denitrified into NO, N_2O or N_2. Inorganic N is distributed between leaf, root, and wood, with wood having a fixed stoichiometric ratio and leaf and root pools having a variable ratio. The partition of carbon, nitrogen and phosphorus among plant structures does not change in when the soil is considered to be nutrient limited. Organic N leaves the living pools via litter-fall into the litter pool which is either mineralized or transferred to the organic soil pool, part of this N can be mineralized into the inorganic N pools. Before litterfall, a constant fraction of the N is reabsorbed. Mineralization of the litter and organic matter pool is dependent on turnover rates, concentration of nitrogen, soil temperature and soil moisture. At the same time N can flow from the inorganic to the soil organic pool via immobilization. A complete description of the nitrogen cycle can be found in Wania et al. (2012) and De Sisto et al. (2023).

Comment 7

Lines 133-134: "The soil litter decomposed is transferred to the soil organic P pool. The dynamics of P organic matter are adapted from Wang et al. (2007)." It would be helpful for the reader to provide a short description of the dynamics. The same is true for line 130, where Goll et al. (2017) are cited. What *do these dynamics depend on? How are N and P together influencing SOM decomposition in the model? Description of the terrestrial model: The methods do not mention leaf nutrient resorption. That's an important aspect of nutrient demand. Although the full description of the model can be found elsewhere, a more complete summary of the terrestrial N and P model would be helpful for the reader.*

Response

Thank you for your comment. The phosphorus model description has been changed to:

The phosphorus module includes three inorganic (labile, sorbed and strongly sorbed) and three organic P pools: Vegetation (leaf, root and wood), litter and soil organic P. The P input is driven by a fixed estimates of P release per global soil types as in Wang et al. (2010). Inorganic P (P_{soil}) in soil follows the dynamics described in Goll et al. (2017) where a fraction of the inorganic soil phosphorus is transfered to the sorbed pool while the remaining fraction is consired to be labile. A portion of the sorbed pool is also transfered to the strong sorbed pool where it is considered a loss of phosphorus from the soil system. After uptake, P is distributed in three vegetation compartments: leaf, root and wood. Leaf and root have a dynamic value that varies between a minimum and a maximum, while wood have a fix C:P ratio. The vegetation P biomass dynamics are determined from the difference between the amount of uptake and the loss from litterfall. Before littefall, a fraction of phosphorus is reabsorbed. The litter P pool is dependent on three terms: the input from litterfall, the decomposition rate and loss from mineralization (Wang et al. , 2007). The soil litter decomposed is transferred to the soil organic P pool. The mineralization of phosphorus is determined from the maximum rate of P mineralization, the N cost of plant root P uptake, a critical value of N cost for root P uptake from where phosphatase production begins and a Michaelis-Menten constant for P mineralization. A complete description of the P cycle can be found in De Sisto et al. (2023).

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 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.

Comment 8

Line 146: The mention of tuning climate sensitivity using an equilibrium climate sensitivity parameter designed by Zickfeld et al. (2009) could benefit from further explanation. Explaining how the tuning process alters the flow of long-wave radiation back to space and how it impacts the climate sensitivity in the model would improve understanding.

Response

Thank you for your comment. The following has been added to line 146:

Furthermore, to capture the uncertainty of the carbon budget estimates, the equilibrium climate sensitivity was tuned by using a parameter designed by Zickfeld et al. (2009) to alter climate sensitivity in the UVic ESCM by altering the flow of long-wave radiation back to space. The dynamics of the alteration is represented in the following equation:

$$L^*_{out} = L_{out} - c(T - T_0), \quad (1)$$

where L^*_{out} is the modified longwave radiation, L_{out} is the unmodified longwave radiation, c is a proportionality constant that corresponds to specific equilibrium climate sensitivities, T is the is the present global average temperature and T_0 is the global average temperature at the initial year of the simulation. The parameter c is use to increase or decrease the net climate feedback by reducing or increasing the outgoing longwave radiation.

Comment 9

Line 160: The mention of "Tokarska et al. (2018) approach" is not explained. It would be helpful to provide a brief description of the approach.

Response

Thank you for your comment. The following has been added to line 160:

Both TCR and TCRE are computed at year 70 of this 1pctCO_2 experiment, when atmospheric CO_2 concentration has doubled. To account for non-CO_2 forcing effect on climate sensitivity, we applied (Tokarska et al. , 2018) approach to compute effective TCRE. This approach computes the change in global temperature over cumulative emissions of CO_2 from fully forced Share Socioeconomic pathways (SSPs) simulations. The SSPs represent different futures that represent a wide array of climate outcomes. For the effective TCRE, SSP 5-8.5 is used to represent a full forced simulation to estimate the response of temperature to cumulative emissions.

Comment 10

Line 161: The acronym in the sentence "SSP 5-8.5 a high emission scenario" is introduced without any prior explanation. It would be helpful to provide a brief description of the SSPs scenarios and what the 5-8.5 scenario represents.

Response

Thank you for your comment. The following has been added to line 161:

This approach uses Share Socioeconomic pathways (SSPs) projections to simulate a full forced simulation. The SSPs represent different futures that represents a wide array of climate outcomes. For the effective TCRE, SSP 5-8.5 is used to represent a full forced simulation to estimate the response of temperature to cumulative emissions.

Comment 11

Line 165: The term "Zero Emission Commitment Model Intercomparison Project (ZECMIP) protocol" is introduced without prior explanation. It would be beneficial to provide a brief description of what the ZECMIP protocol entails.

Response

Thank you for your comment. The following has been added to line 165:

To explore the effects of nutrient limitation on zero emission commitment, an experiment was done following the protocol of the Zero Emission Commitment Model Intercomparison Project (ZECMIP). The objective of ZECMIC is to quantify the amount of unrealized temperature change after CO_2 emissions have ceased and the drivers behind the change. The experimental protocol was applied to C-only, CN and CNP.

Comment 12

Line 166: The statement "the 1pctCO2 experiment is followed until diagnosed cumulative emissions of CO2 reaches 1000 PgC thereafter emissions are set to zero further CO2 emissions" could be clarified. It is not clear what is meant by "diagnosed cumulative emissions". Providing more details on the methodology would improve understanding.

Response

Thank you for your comment. In the 1pctCO_2 experiment, CO_2 concentration is prescribed in the simulation. Hence, the model diagnoses CO_2 emissions based on CO_2 concentration.

Comment 13

Lines 175-178: The SSP scenarios are again mentioned without explanation, a brief general description of what they mean would be helpful for the readers.

Response

Thank you for your comment. The following has been added to line 161:

This approach uses Share Socioeconomic pathways (SSPs) projections to simulate a full forced simulation. The SSPs represent different futures that represents a wide array of climate outcomes. For the effective TCRE, SSP 5-8.5 is used to represent a full forced simulation to estimate the response of temperature to cumulative emissions.

Comment 14

Line 179: Throughout the manuscript, I am confused with how you use the term "land use change." Please, clearly define it. It seems the term is being used to describe natural changes in vegetation cover. But land use change is related to anthropogenic transformations of the natural landscape.

Response

Thank you for your comment. We do explain land use change in line 113 of the methodology as: "The UVic ESCM prescribes anthropogenic land-use changes based on standardized CMIP6 land-use forcing (Ma et al., 2020) regridded to the UVic ESCM grids. Land-use data products have been modified for UVic ESCM use by aggregating cropland and grazing land into one crop type, representing any of the five functional types of crops, and one grazing variable, representing pastures and rangelands. By using this forcing, the model determines the fraction of grid cells that contain crops and grazing areas, and these fractions are assigned to C3 and C4 grasses and excluded from the vegetation competition routine of TRIFFID." Hence, it is not a natural change in vegetation cover. It is stated across the paper that nutrient limitation affects vegetation biomass and therefore, it affects the carbon quantities released during land use change.

The following has been added to line 161:

The dynamics of CO_2 emissions from LUC are designed so that when forest or other vegetation are cleared for crop or pasture, 50 % of the tree carbon is released directly into the atmosphere and the remaining is allocated into the litter pool.

Comment 15

Line 183: punctuation missing

Response

Thank you for your comment. The punctuation has been added.

Comment 16

Line 191: Term GISS introduced without further clarification. Additionally, was this mentioned in the methods?

Response

Thank you for your comment. The following line has been modified in line 152:

Each model structure was calibrated using aerosol scaling so that historical temperatures match observations. We used Goddard Institute for Space Studies (GISS) temperature observations in this study.

Comment 17

Line 204: I believe the correct wording should be "less carbon is taken up from the land." Please, check the rest of the manuscript for the same issue (e.g., line 220, replace uptake for take up).

Response

Thank you for your comment. The suggested change has been applied to all applicable cases.

Comment 18

Line 213: It would be helpful to remind the reader what the TCR means and how to interpret it. For instance: "the amount of global warming expected to occur when atmospheric CO2 concentrations double from their pre-industrial levels, while all other factors remain constant", or what you think is more appropriate.

Response

Thank you for your comment. It was defined in line 62: "For idealized experiments the Transient Climate Response (TCR) can be used to quantify the physical uncertainty in TCRE. TCR is the change of temperature at the time of doubling atmospheric CO_2 concentrations (year 70 in a 1pctCO2 experiment). However unlike TCRE, the TCR is dependent on the scenario used to compute it (e.g. MacDougall (2017)). The other important source of variability among TCRE estimates comes from uncertainties in carbon uptake by the ocean and terrestrial biosphere". Line 62 has been change as suggested to:

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.

Comment 19

Line 218: Sentence could be improved; it is not complete, should be "vegetation uptake of carbon" I believe

Response

Thank you for your comment. Lines 218 has been changed to:

Under a 1% atmospheric CO_2 increase per year experiment, terrestrial nutrient availability limits the capacity of terrestrial vegetation to uptake carbon. Hence, even with a rapid increase of CO_2 concentration in the atmosphere, terrestrial vegetation carbon uptake capacity is limited and the uptake rates are not as high as with an unlimited amount of nutrients readily available for uptake.

Comment 20

Line 222: Replace: "terrestrial vegetation is constrained by nutrient..."

Response

Thank you for your comment. Line 222 has been removed from the text and replaced with:

Under a 1% atmospheric CO_2 increase per year experiment, terrestrial nutrient availability limits the capacity of terrestrial vegetation to uptake carbon. Hence, even with a rapid increase of CO_2 concentration in the atmosphere, terrestrial vegetation carbon uptake capacity is limited and the uptake rates are not as high as with an unlimited amount of nutrients readily available for uptake.

Comment 21

Line 235: Remind the reader of what is and how to interpret ZEC values. For instance: "values indicate the estimated temperature increase resulting from the ZEC after 50 years of no further emissions. Higher ZEC value suggest... (continue)."

Response

Thank you for your comment. The following has been added to line 245:

The overall ZEC value is higher in CNP and CN than in C-only. Higher ZEC values indicate a larger increase of temperature after emissions have ceased.

Comment 22

Line 262: Replace "Figures 2-8."

Response

Thank you for your comment. The suggested change has been applied to line 262.

Comment 23

Lines 273-274: "As the model reduces vegetation due to nutrient limitation and trees are replaced by grassed, the land surface albedo is increased." This needs further clarification. In what parts of the world is this happening, and what ecosystems are being replaced by grass? Additionally, replace grassed by grasslands.

Response

Thank you for your comment. The change in vegetation in the model was addressed in detail in De Sisto et al. (2023). Lines 273-274 has been modified to:

As the model reduces vegetation due to nutrient limitation and trees are replaced by grasses, the land surface albedo is increased. The replacement of trees by grasses occurs globally in the model as shown in (De Sisto et al. , 2023)

Comment 24

Lines 272-274: Here, you are talking about land use change, that trees are being replaced by grasses due to nutrient limitation. Is this land use change? I would say anthropogenic activities, not nutrient limitation, drive land use change. Nutrient limitations might cause natural changes in vegetation cover.

Response

Thank you for your comment. Yes, land use change is driven by anthropogenic activites. However, land use change emissions are sensitive to the vegetation biomass of the model. In the model the dynamic of CO_2 emissions from LUC are designed so that when forest or other vegetation are cleared for crop or pasture, 50 % of the tree carbon is released directly into the atmosphere and the remaining is allocated into the litter pool. In line 272 we were referring to land use change emissions: "These changes include: 1) vegetation biomass, 2) vegetation distribution, 3) primary productivity, 4) land use change emissions and 5) terrestrial albedo. In the UVic ESCM version 2.10, the vegetation biomass, distribution and productivity were addressed in (De Sisto et al. , 2023), while land use change emission and albedo remained unexplored"

Comment 25

Lines 282-283: "When the diagnosed C:N or C:P leaf ratios are higher than the set maximum leaf ratio, the vegetation biomass dies so that the leaf ratios decrease back to the maximum ratio threshold."

This sentence needs further explanation. If there's a maximum set, how can it go higher? I don't fully understand what is the assumption here with the biomass dying and the ratios being reset.

Response

Thank you for your comment. They can go higher because it is a dynamic system. The assumption is that with higher C:N or C:P ratios the litterfall rate is high, while in low C:N and C:P ratios the litterfall rate is low. An example of a study showing this dynamic can be found in Vitousek (1984) forest dynamics paper.

Comment 26

Lines 283-284: First time the acronym PFT is used, it is not defined, and no further clarification is given—the relevant differences among PFTs were not summarized in the methods or there. Also, be consistent with the use of all acronyms throughout the text; either use them or not.

Response

Thank you for your comment. PFTs has been changed to plant functional types. The relevant differences were described in a complete paper by Cox (2001).

Comment 27

Lines 284: "nutrient limiting stressors such as nitrogen and phosphorus should be applied carefully as a high limitation of phosphorus can easily underestimate the land sink capacity of tropical vegetation". This needs additional clarification. What in the model's representation of the P cycle could be causing P to be too limiting, causing this underestimation? Considering you do not account for the C costs of P uptake, I would expect the other way around. What are the limitations of the P cycle in the model? Couldn't other assumptions in the model, not related to the P cycle, be the problem in tropical regions?

Response

Thank you for your comment. The suggested clarification was already addressed in detail in De Sisto et al. (2023), we now point to this explanation in the manuscript. Line 284 has been change to:

Therefore, the application of multiple nutrient limiting stressors such as nitrogen and phosphorus should be applied carefully as a high limitation of phosphorus can easily underestimate the land sink capacity of tropical vegetation. 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).

Comment 28

Lines 305-306: "These estimations are larger than the rough estimate of 27 PgC reduction of carbon budgets due to unrepresented carbon feedbacks (Rojeli et al., 2018), suggesting that this value may have been underestimated in the IPCC 1.5◦C report." What did Rojeli et al. do differently? Rojeli is not on the reference list; is that Rogelj? Please check the references and reference list for such mistakes. The use of a reference manager is recommended.

Response

Thank you for your comment. Rojeli is indeed Rogelj, thank you for noticing the typo. Rogelj shows values from integrated assessment modelling. The main difference is likely the explicit representation of terrestrial nitrogen and phosphorus cycles. However, within their assessment, Rogelj does account for nutrient limitation.

Comment 29

Line 320: Revise the sentence; it is unclear. "Although, different using ECS might assess some variability shown in other models, there is a clear uncertainty in how variable the impacts is in other model structures."Discussion: the manuscript lacks an important aspect, which is a more robust discussion of the model's limitations. What are the most important limitations and assumptions of the model (Land *surface model or otherwise)? What needs to be improved? You briefly speak of the lack of data, some uncertainties, but what uncertainties, and what data specifically? (Starting on line 315).*

Response

Thank you for your comment. Regarding the discussion, the focus of this study is not to assess the terrestrial nitrogen and phosphorus limitation developed in the model, this was already assessed in De Sisto et al. (2023). Our focus is on understanding how nutrient limitation affects remaining carbon budgets estimations. Line 320 has been changed to:

Although, by varying ECS we may capture some of the range shown in other models, the full range of structural uncertainty is not captured by our experiment design.

Comment 30

Line 315: Not clear, nutrient concentration in what? Soil? Leaf? Biomass?

Response

Thank you for your comment. That would be in all aspects. Line 315 has been changed to:

In ESMs, nutrient simulations could be improved with further global observations. The current available data have large ranges and make difficult to assess how reliable are the nutrient values given by ESMs simulations. Theses uncertainties are present in most aspects of the global nitrogen and phosphorus cycles.

Comment 31

Line 325: "If the objective is to improve the carbon cycle accuracy, the inclusion of P is advisable for its limiting role in tropical regions. From a carbon budget estimations view, we observed similar results for CN and CNP." I find this to be a very overstated conclusion. There are several studies pointing to the very uncertain representation, particularly of the P cycle in land-surface/vegetation models. Several C costs *of acquiring N and P are not accounted for in these models (e.g., C allocation to mycorrhizas, enzymes, and other root exudates). These could highly impact projections of biomass growth in tropical forests (e.g., Fleischer et al., 2019; Braghiere et al., 2022). Additionally, the vegetation models poorly represent the links between N and P cycles (e.g., N cost for phosphatase enzyme production for P acquisition from leaves and soil, or a P cost for N fixation), which could also affect global projections. Moreover, there are several uncertainties about P pool dynamics in models and their fixed ratios. This is to say biomass growth in some vegetation models could be overestimated, particularly in tropical regions, especially in future scenarios. Based on your CNP vegetation/terrestrial model, could such limitations, if overcome, change your results and affect the remaining C budget, for instance? In other words, is it true the P cycle does not make a difference, or the problem is that it is loosely represented due to a lack of data? This should be discussed.*

Response

Thank you for your comment. The focus of this study is not to assess the terrestrial nitrogen and phosphorus cycle structure within the model nor to compare it to other Earth system models structures. You are correct that the terrestrial nitrogen and phosphorus cycles are highly uncertain, but are a work in progress for the Earth system modelling community. However the full complexity of the N and P cycles are not captured by our model and further development of such modules may reverse this result.

Comments from reviewer 2

Comment 1

Throughout the manuscript, it is not very clear how convincing those numbers presented regarding the remaining carbon budget are. It would be beneficial if the authors could show some validation after incorporating the dynamics of the N and P cycles. Additionally, providing more information about the underlying mechanisms within the model would enhance the depth of understanding of the findings. For instance, how does the model deal with carbon partitioning between growth, respiration, and storage in response to nutrient availability and other meteorological factors? Are seasonal variations in nutrient concentrations or in the C:N:P ratio in plants implemented in the model? Is there resorption after tissue senescence? And to what extent these assumptions in the model will affect the results?

Response

Thank you for your comment. The terrestrial nitrogen and phosphorus cycles were extensively assessed in De Sisto et al. (2023). We thought that showing the full details of the model description would be repetitive. To address these concerns the terrestrial nitrogen and phosphorus cycles description in the methodology has been expanded:

A terrestrial nitrogen and phosphorous model has recently been developed for the UVic ESCM (De Sisto et al. , 2023). The nitrogen cycle module consists of three organic pools (litter, soil organic matter, and vegetation) and two inorganic pools (NH_4^+ and NO_3^-). Nitrogen input is represented by atmospheric nitrogen deposition and biological nitrogen fixation. The latter is dependent on the terrestrial Net Primary Productivity (NPP). Biological nitrogen fixation and mineralization of organic nitrogen produce NH_4^+, which can be absorbed by plants (vegetation), leached, or transformed into NO_3^- via nitrification. NO_3^- is produced through nitrification, can be taken up by plants, leached or denitrified into NO, N_2O or N_2. Inorganic N is distributed between leaf, root, and wood, with wood having a fixed stoichiometric ratio and leaf and root pools having a variable ratio. The partition of carbon, nitrogen and phosphorus among plant structures does not change in when the soil is considered to be nutrient limited. Organic N leaves the living pools via litter-fall into the litter pool which is either mineralized or transferred to the organic soil pool, part of this N can be mineralized into the inorganic N pools. Before litterfall, a constant fraction of the N is reabsorbed. Mineralization of the litter and organic matter pool is dependent on turnover rates, concentration of nitrogen, soil temperature and soil moisture. At the same time N can flow from the inorganic to the soil organic pool via immobilization. A complete description of the nitrogen cycle can be found in Wania et al. (2012) and De Sisto et al. (2023).

The phosphorus module includes three inorganic (labile, sorbed and strongly sorbed) and three organic P pools: Vegetation (leaf, root and wood), litter and soil organic P. The P input is driven by a fixed estimates of P release per global soil types as in Wang et al. (2010). Inorganic P (P_{soil}) in soil follows the dynamics described in Goll et al. (2017) where a fraction of the inorganic soil phosphorus is transfered to the sorbed pool while the remaining fraction is consired to be labile. A portion of the sorbed pool is also transfered to the strong sorbed pool where it is considered a loss of phosphorus from the soil system. After uptake, P is distributed in three vegetation compartments: leaf, root and wood. Leaf and root have a dynamic value that varies between a minimum and a maximum, while wood have a fix C:P ratio. The vegetation P biomass dynamics is determined from the difference between the amount of uptake and the loss from litterfall. Before littefall, a fraction of phosphorus is reabsorbed. The litter pool is dependent on three terms: the input from litterfall, the decomposition rate and loss from mineralization Wang et al. (2007). The soil litter decomposed is transferred to the soil organic P pool. The mineralization of phosphorus is determined from the maximum rate of P mineralization, the N cost of plant root P uptake, a critical value of N cost for root P uptake from where phosphatase production begins and a Michaelis-Menten constant for P mineralization. A complete description of the P cycle can be found in De Sisto et al. (2023). 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 biomass. 2) A stoichiometric reduction of biomass when N and P are considered to be limiting terrestrial plants. If C:N ratios are too above a 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.

Comment 2

In the introduction, the authors emphasized the limitation of P is crucial when modeling vegetation carbon uptake at low latitude regions (L67-69). However, in the discussion, the major impact of P limitation was concluded to be on the land use change emissions (L327-328). Is this conclusion consistent with the initial emphasis? If available, the authors could present data or analysis that demonstrates the specific regions with land use changes under P limitation.

Response

Thank you for your comment. We do not state that the major impact of P limitation is on the land use change emissions: "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." One of the main differences is indeed land use changes emissions changes. Terrestrial P limitation impact plant productivity and biomass. In the model land use change emissions are designed so that when forest or other vegetation are cleared for crop or pasture, 50 % of the tree carbon is released directly into the atmosphere and the remaining is allocated into a short-lived carbon pool. This information has been added to line 161 of the paper as suggested by another reviewer. Hence, it is consistent with the first emphasis. Less forest biomass result in lower land use change emission values. Data supporting this statements are found in the extensive review of the terrestrial nitrogen and phosphorus cycle in De Sisto et al. (2023). The following has been added to line 161:

The dynamics of CO_2 emissions from LUC are designed so that when forest or other vegetation are cleared for crop or pasture, 50 % of the tree carbon is released directly into the atmosphere and the remaining is allocated into the litter pool.

Comment 3

L63: The 1pctCO2 experiment was not introduced.

Response

Thank you for your comment. The following line has been added to line 63:

TCR is the change of temperature at the time of doubling atmospheric CO_2 concentrations. 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).

Comment 4

L80-81: What are the non-CO2 forcings considered in the study? The impact on land use change emissions was shown in section 3.4, but the carbon cycle feedback was not fully addressed.

Response

Thank you for your comment. Solar, volcanic, aerosol and the aggregate forcing from the halocarbons, CH_4, and N_2O were considered. The full carbon cycle was addressed in De Sisto et al. (2023). The following has been added to line 152:

The non-CO_2 forcing included solar, volcanic, aerosol and the aggregate forcing from halocarbons, CH_4, and N_2O.

Comment 5

L85: The last paragraph in the introduction appears somewhat redundant with the first two paragraphs. Please consider consolidating or simplifying it.

Response

Thank you for your comment. the last paragraphs of the introduction has been modified:

Isolating the effects of N and P terrestrial limitation give a novel insight on how underrepresented process in terrestrial systems contribute to remaining carbon budgets uncertainties. It is therefore important to understand how ESMs carbon cycle sensitivity to nutrient limitation constrain of the land carbon sink in future simulations. Hence, we explore the effect of terrestrial nitrogen and phosphorus limitation in remaining carbon budget estimates in an intermediate complexity Earth system model under historical, idealized, and Shared Socioeconomic Pathways projections.

Comment 6

L107-109: Are there distinct representations of tropical and temperate trees among the five PFTs in the model, particularly concerning their response to variations in nutrient availability and climate?

Response

Thank you for your comment. No, there is no difference between tropical and temperate PFTs in terms of how PFTs-dependent parameters are set. However, PFT growth and fitness are sensitive to temperature. There is active model development underway to add distinct tropical and temperate PFTs to the UVic ESCM.

Comment 7

L170-171: It is not clear why the 50th and the mean ZEC for 100 years after emissions have ceased are considered. Please clarify or add references.

Response

We do have a reference for that in the text (MacDougall et al. , 2020). The main reason we used the metrics is that they are comparable with multimodel assessment studies such as (MacDougall et al. , 2020).

Comment 8

L182: Please clarify what the missing forcing means.

Response

Thank you for your comment. Line 182 has been modified:

The model adjusts its diagnosed CO_2 emissions to account for the missing land use change forcing.

Comment 9

L184-185: Is the albedo change only considered as a byproduct of land use change in this study? How about the change of albedo due to the change of LAI?

Response

Thank you for your comment. The albedo change was considered as a byproduct of terrestrial vegetation cover change, which included changes of LAI and land use change.

Comment 10

L195-196: This result has not been presented in the manuscript.

Response

Thank you for your comment line 195-196 has been erased.

Comment 11

L232-234: Why the temperature exhibits a decline and subsequent increase around the 70-80th year in Figure 3 has not been explained.

Response

Thank you for your comment. It was briefly explained in the figure description. "The rapid changes in global temperature seen in the top panel are due to disruptions to the ocean meridional overturing circulation"

Comment 12

L248: There are no B2 and B3 in the Appendix. In some scenarios, C-only shows a higher temperature increase than the other two experiments (Figure B1). Could you please explain that?

Response

Thank you for your comment. You are right, B2 and B3 mention were erased from the line. The temperature increase is higher in some long-term values of high emission scenarios due to the aerosol scaling calibration used in CN and CNP to improve historical temperature representation. In our case, given the temperature targets, it only really affected SSP3-7.0 3°C target.

Comment 13

L276: It was not shown in the result where and how much the land surface albedo changes due to the nutrient limitation.

Response

Thank you for your comment. The following line has been added:

The land surface albedo increased by 0.04 in nutrient-limited simulations.

Comment 14

L282: What does "the vegetation biomass dies" mean?

Response

Thank you for your comment. The following has been added to line 135:

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 biomass. 2) A stoichiometrica reduction of biomass when N and P are considered to be limiting terrestrial plants. If C:N ratios are too above a 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.

Comment 15

L50: Closing punctuation is missing after "... two perspectives".

Response

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

Comment 16

L84: "source" instead of "sources"; "accounted" instead of "account"

Response

Thank you for your comment. The suggested changes have been applied.

Comment 17

L145: Please add a comma after "... carbon budget estimates".

Response

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

Comment 18

L213-214: Incomplete sentence.

Response

Thank you for your comment. Line 213-214 has been modified:

The TCR for doubling CO2 concentrations was 1.78, 1.79 and 1.79 °C in C-only, CN and CNP. 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 19

L222: "…is constrained…"

Response

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

Comment 20

L224: "affect" instead of "effect". Please also check other cases in the text."

Response

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

Comment 21

L226: "…fluxes change…"

Response

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

Comment 22

L227-228: "a more sensitive model"

Response

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

Comment 23

L241: Two "budgets" in a sentence. There are also several cases elsewhere.

Response

Thank you for your comment. The suggested changes have been applied.

Comment 24

L261: "…clearly sensitive…"

Response

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

Comment 25

L303: Add a comma after "…in other models".

Response

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

Comment 26

L307-309: Can the first two sentences be combined?

Response

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

Comment 27

L309-310: "Mainly impacting…from land and ocean" is an incomplete sentence.

Response

Thank you for your comment. Line 309 has been changed to:

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.

Comment 28

L320-321: The last sentence could be more fluid.

Response

Thank you for your comment. Line 320-321 has been modified:

The response of Earth system models to nutrient limitation varies amongst each other depending on how terrestrial nitrogen and phosphorus limitations are applied.

Comments from reviewer 3

Comment 1

The study is well described with regards to the estimations of the carbon budget, the process of vegetation limitation due to nutrients, and recent metrics of carbon accounting, such as transient climate response. The study however lacked the inclusion of references which show the effect of P in modelled ecosystem carbon responses, such as those in Dynamic Global Vegetation Models (DGVMs) (Fleischer et al., 2019; Jiang et al., 2020). The methods were clear and understandable.

Response

Thank you for the positive feedback. We did not add references of P in modelled ecosystem carbon responses because it was already extensively done in De Sisto et al. (2023), where the model is first described, and our focus was more on remaining carbon budget estimates. We do have a reference for an Earth system model containing P in its structure. Rojelj et al. (2019) multimodel carbon budget includes one model with N and P in their model structure.

Comment 2

My main concern was with the analysis and interpretation of results, as well as the implementation of phosphorus limitation. As far as I understood, there is no direct impact of P in photosynthesis, only N, contrary to what is described in the body of knowledge of plant physiology (Ghannoum et al., 2008; Hidaka and Kitayama, 2013; Walker et al., 2014). This may have unrealistically led the CN simulation results close to the CNP ones, and led to the conclusion that these were similar (L325). Related to this another major concern is the lack of statistical error estimations (in the case of the comparisons with the GISS temperature dataset in Figure 1), and statistical tests. While it seems clear that the CN and CNP versions were distinct from the C-only, only a formal comparison of the former would allow to reach a conclusion that CN differed or not from CNP. With such a comparison, and the effect of P in photosynthesis, it would become much clear if adding P to the model is relevant or not for the estimation of the carbon budget.

Response

Thank you for your comment. Correct, there is no direct inclusion of P limitation in photosynthesis-related equations. We did try to apply Walker et al. (2014) concept in the first iterations of the model, but it was incompatible with the previous model structure and led to an extreme overestimation of the effect of phosphorus on terrestrial vegetation. Thereby, it only impacts vegetation biomass. That might be modified in future iterations of the model, and we are grateful for the suggestion. CN and CNP are different, this is extensively shown in De Sisto et al. (2023). Line 325 will be erased as it has conveyed the wrong message. In Fig 8. it is shown that they are in fact different, but among each other are more similar than compared to C-only. In regards to the error estimation for the GISS temperature, that figure is only there to show how close our results are to observations. It does not really require any statistical test to show readers how close our values are, and the UVic ESCM is a fully deterministic model. CN and CNP clearly differ from each other (e.g. figure 8). Again, it is the bad wording in line 325. We do emphasize the importance of P in terms of tropical vegetation and show differences between CN and CNP. The following has been added to line 138:

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.

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