Response to reviewers for BG-2022-92: "Controls of intermodel uncertainty in land carbon sink projections"

Referee #1:

Padrón et al report an analysis of drivers of the terrestrial carbon sink in the CMIP6 ensemble scenario SSP126 where warming is limited to 2 oC. This is a useful study of the latest CMIP model results in a policy relevant scenario, showing that terrestrial carbon sink projections by 2100 (cumulative NBP) in the ensemble vary from 56 to 207 Pg C, mean 144 and standard deviation 47 Pg C. Using linear regression Padrón et al partition this variability among sensitivity to CO2, temperature (T), soil moisture (SM), and differences in baseline temperature and soil moisture. Their methods show that the greatest proportion of this variance is explained by sensitivity to T and SM combined, with sensitivity to CO2 as the second most important driver of variability. Based on these results, they conclude that the gamma feedback (climate) is greater than the beta feedback (physiological) under this policy-relevant scenario and thus climate sensitivities require the greatest attention. They also show compensating drivers of cumulative NBP variability such that reduction of uncertainty in response to one driver would not greatly reduce overall NBP variability. Overall this is a well written and executed study. The analysis of the relatively low- warming SSP126 scenario is timely and to my knowledge has not been done before. I have several comments and criticisms that I hope will help to make the analysis and conclusions more robust and impactful. First, I think that for a number of reasons the method has low-biased the estimation of the impact of CO2 sensitivity on NBP variability. Second, I encourage a little more quantification and thought into exactly what is quantified and communicated

We appreciate the overall positive evaluation of our manuscript.

To clarify, we do not conclude that the gamma feedback is greater than the beta feedback, but rather that model differences in the sensitivities of NBP to climate (related to gamma) contribute more to the land carbon sink intermodel spread than what model differences in the sensitivity of GPP to CO_2 (related to beta) do.

First: underestimation of the impact of CO2 sensitivity on NBP variability. CO2 sensitivity is estimated as the sensitivity of GPP to CO2 in the 1 % per year increases in CO2 simulations (1pctCO2-bgc) in which CO2 ranges from 350 to 800 ppm. This method assumes 1) the CO2 sensitivity of NBP is the same as that for GPP, 2) that CO2 sensitivity is linear across the range 350 to 800 ppm, and 3) that there are no interactions between CO2 sensitivity and either T or SM. It is likely that all three of these assumptions will low- bias the estimate of the impact of model CO2 sensitivity on cross-model NBP variability.

While GPP sensitivity to CO2 is likely the main driver of NBP sensitivity to CO2, as asserted in the current ms, the assumption ignores potential changes in turnover rates that can also occur in response to CO2, which can be substantial. Using cross-model GPP sensitivity to CO2 will result in a lower correlation with NBP variability than using NBP sensitivity to CO2. Further, for T and SM sensitivity, NBP is used, biasing results in favor of T and SM sensitivity. Comparing the sensitivities of GPP to CO2 to NBP to T and SM is not a like-for-like comparison. Sensitivity of NBP to CO2 should be estimated and used in the regression analysis.

We appreciate the insight, and now expanded the text to include this point. We also include in the supplement figures like Fig. 8 when using the sensitivity of NBP and NPP to CO_2 instead of the sensitivity of GPP for the analysis.

When using the sensitivity of NBP to CO_2, it is important to note that model differences can arise from (i) differences in the sensitivity of GPP to CO_2, (ii) differences in the sensitivities of RA, RH and DIS to CO_2 (i.e., the point of the reviewer), but also from (iii) differences across models in their sensitivities of RA, RH and DIS to temperature and soil moisture.

GPP generally increases with increasing CO_2 in the 1pctCO2-bgc simulations. This increase in GPP results in indirect effects of CO_2 on RA due to enhanced root respiration associated with greater belowground plant biomass, and on RH due to enhanced microbial decomposition of fresh carbon due to greater supply of foliar and root-derived labile soil carbon, and to increased microbial priming of old soil organic matter fueled by this increased supply of labile soil carbon (Gao et al., 2020). On the other hand, the magnitude of the changes in RA, RH and DIS in each model following the increase in GPP also strongly depend on the models' sensitivity of these fluxes to temperature and soil moisture (Todd-Brown et al., 2013; Varney et al., 2020).

The indirect effects of CO_2 on RA, RH and DIS are ignored when using sCO_2 as the sensitivity of GPP to CO_2, whereas the contribution of model differences in their sensitivity to climate are partially attributed to differences in sCO_2 when using the sensitivity of NBP of CO_2. To be comprehensive we now show the results of our analysis when using both the sensitivity of GPP and of NBP to CO_2.

Gao, Q., Wang, G., Xue, K., Yang, Y., Xie, J., Yu, H., Bai, S., Liu, F., He, Z., Ning, D., Hobbie, S. E., Reich, P. B. and Zhou, J.: Stimulation of soil respiration by elevated CO_2 is enhanced under nitrogen limitation in a decade-long grassland study, Proc. Natl. Acad. Sci., 117(52), 33317–33324, doi:10.1073/pnas.2002780117, 2020.

Todd-Brown, K. E. O., Randerson, J. T., Post, W. M., Hoffman, F. M., Tarnocai, C., Schuur, E. A. G. and Allison, S. D.: Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations, Biogeosciences, 10(3), 1717–1736, doi:10.5194/bg-10-1717-2013, 2013.

Varney, R. M., Chadburn, S. E., Friedlingstein, P., Burke, E. J., Koven, C. D., Hugelius, G. and Cox, P. M.: A spatial emergent constraint on the sensitivity of soil carbon turnover to global warming, Nat. Commun., 11(1), 5544, doi:10.1038/s41467-020-19208-8, 2020

The CO2 response over 350 to 800 ppm is likely not linear in these models, it almost certainly is not at the leaf scale which drives model CO2 responses. The SPP126 simulations max out at 446 ppm. There is likely saturation in the CO2 response for many models somewhere between 450 and 800 ppm. CO2 sensitivities should be estimated over the range of CO2 concentrations that preserve linearity over the range 350 – 446 (i.e. concentrations can be higher but responses must be linear over the range). A supplemental figure showing NBP against CO2 for the 1pctCO2-bgc simulations would be useful.

We agree with this point. We expanded the text and now include the suggested figure in the supplement. We now use a range approximately between 375 and 500 ppm (the SSP126 range is 400 to 471 ppm) within which the response is relatively linear, while still counting with a sample size of 30 annual values to estimate sCO_2 without being overly affected by internal climate variability. If we were to take fewer annual values from the single simulation for each model, particularly dry/wet and hot/cold anomalies during those years resulting from natural variability could lead to a biased estimate of sCO_2.

There are interactions between CO2 and T and SM. Interactions with T are likely the most important for this discussion. At high T it is well known that CO2 can alleviate some of the reductions in photosynthesis due to interactive effects on photo- respiration. This could alleviate GPP reductions in high T years that I'm not sure would be removed by detrending NBP. I'm not sure there is an easy way to account for this, and that is OK. But some acknowledgment of this effect and some attempt to quantify it would help make results more robust.

Interesting point. We now acknowledge it in the manuscript as another process that is only indirectly represented when trying to explain differences across models in their land C sink projections. Potential model differences in the alleviating effect of CO_2 at high temperatures are implicitly captured within differences in sT.

We additionally compute sT and sSM from the 1pctCO2-rad simulations to exclude the alleviating effect of CO_2 given that vegetation experiences constant CO_2 at pre-industrial level in these simulations. However, in this case we expect differences in sT and sSM compared to those derived from the SSP126 simulations, given that the background CO_2 concentration and climate conditions are different. We now also include in the supplement a Figure like Fig. 8 when using sT and sSM derived from the 1pctCO2-rad simulations.

Second: encourage more thought into exactly what is quantified and communicated. I suggest quantifying statement in the abstract, cumulative NBP variability etc. Also, as well as putting these numbers in the context of current annual emissions, I think it might also be useful to present them as a proportion of the assumed emissions in the SSP126 scenario (if someone has calculated those).

Thanks for the suggestions. We now include more quantitative statements in the abstract. We also indicate that the intermodel spread of ~150 PgC corresponds to approximately 40% of the remaining carbon budget to limit global warming below 2°C (with a 50% likelihood) according to Table SPM.2 of IPCC (2021).

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.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

Why is the proportion of variance in NBP variability to CO2 sensitivity not quantified on ln 354?

We now rephrased the sentence to include this.

I encourage the authors to think about what is best to present given this is a study of the global carbon cycle. Most figures are presented in the units per meter squared. When aggregating to broad zonal regions I suggest it is more informative to present results as the absolute sum across the whole area – this would make it easier to relate the regions and sensitivities directly to the global aggregate numbers. Finally, have differences in grid-square area been taken into account when presenting the global aggregate drivers of NBP variability?

Thanks for the suggestions. We modified Fig. 8 to express the units in carbon mass for the whole land area. For Figs. 6 and 7 expressing the data in gC m^2 y^{-1} helps the visualization, and our goal of comparing models and drivers rather than comparing across regions. Nonetheless, we now make it more visible in the figures what percentage of the land area corresponds to each region instead of only mentioning this in the caption. Finally, we do consider differences in grid cell area according to latitude.

Technical Comments:

Title: suggest switching "controls" for "drivers" as control suggests some degree of intention.

We incorporated this suggestion.

While I see some of the benefits of the narrative style with the methods spread throughout the results (e.g. lns 157-164, 179-189, 263-283, etc), I think it is more practical to have the methods all in one place where they can be found easily and assessed side by side.

Thanks for the suggestion. We consider this to be a matter of style and given that typically papers in *Biogeosciences* do not have a specific "Methods section", we would prefer to keep the original narrative style.

Fig 6: can probably go into the supplement.

We appreciate the suggestion, but nonetheless consider it is useful to keep Fig. 6 in the manuscript to convey the message that the regression estimates can represent well intermodel differences in regional projected NBP.

Fig 7: A little hard to read, I think the sensitivities could be presented more clearly if they were presented as in Fig 8. I recognise that would necessitate removal of uncertainties from the figure and I appreciate the effort made to quantify uncertainty but is clarity of communication is the trade off.

We now also present the results from Fig. 7 as stacked bars in the supplement.

Fig 8 as is could go to the supplement. Fig 8: Suggest adding a dot for the actual cumulative NBP. Also I really think this would be better off expressed in global sums rather than per meter squared. The white dot could be a little larger.

We included the suggestions.

Ln 30: There are several commentaries explaining why Wang et al 2020 is not a reliable analysis.

We decided to remove this reference from the text.

Ln 37: Are there other disturbances that release C directly back to the atmosphere?

Not directly, but other disturbances can include changes in land cover like deforestation.

Ln 61: Note the editor's note for Keenan 2021

Thanks for pointing this out. We removed this reference, as the article has been retracted.

Ln 69: can delete "consider it important to instead"

We rephrased the sentence.