I. Response to comments and suggestions of Reviewer #1

Peer Review, Liu, et. al., 2022: PInc-PanTher estimates of Arctic permafrost soil carbon under the GeoMIP G6solar and G6sulfur experiments

The authors use the PInc-PanTher tool to analyze the simulated effects of solar geoengineering (SG) on permafrost carbon. The authors consider six different Earth system models (ESMs) and four different scenarios: moderate emissions (SSP2-4.5), high emissions (SSP5-8.5), high emissions with dimmed sunlight (G6solar) and high emissions with stratospheric aerosol injection, or SAI (G6sulfur). The authors quantify permafrost area, carbon stocks, and economic impacts in each case, and they find that all six ESMs show statistically significant impacts in both SG scenarios.

I thank the authors for the opportunity to review their work. The permafrost-carbon-climate feedback is a critical yet relatively ill-quantified consequence of global warming, and the possible impacts of SG on permafrost carbon are even less well understood. To my knowledge, there have been very few multi-model analyses of the potential effects of SG on permafrost, and this one is well-designed and well-written. My comments are relatively minor, and they largely address word choice, grammar, and clarity. I recommend the manuscript be accepted for publication with minor revisions, and I do not feel it necessary for me to review it again. Specific comments are included in the attached document.

We would like to thank the Anonymous Referee #1 for the appreciation of the main advances of our work. We would also like to thank for all the constructive comments and valuable suggestions, which have helped us to improve the quality of the manuscript. For each question and comment, we gave point-by-point response and made additions and revisions to the manuscript. Please see the attached response.

Abstract:

- Line 10: I would be cautious of referring to circumpolar permafrost carbon as a "tipping point"; Schuur, et. al., (2015) argues that while such emissions would be a "significant source" of carbon over decades and centuries, there is little evidence that thawing permafrost would release a "catastrophic" or "large and rapid pulse" of carbon. As such, I would lean towards phrasing like "irreversibility," "positive feedback," and "significant" rather than "tipping point," which implies a sudden or catastrophic change.
- We have modified the text: "Circum-Arctic permafrost stores large amounts of frozen carbon that must be maintained to avoid catastrophic climate change."

- Line 15: There are a lot of numbers in this sentence, which makes it hard to read. Rather than just listing numbers, could you order and phrase them in a way that makes them easier to process? For example, "Under SSP2-4.5 and SSP5-8.5, respectively, permafrost area decreases by ____ and ____ by 2100, and carbon stocks decrease by __and ___. In comparison, under G6solar, permafrost area decreases by only ___and carbon stocks decrease by only ___; under G6sulfur, they decrease by only ____ and ___." Alternatively, you could omit the raw numbers altogether, and write something like "we find that G6solar mitigates X % of the permafrost area loss for SSP5-8.5 relative to SSP2-4.5".
- We have made changes as suggested. "By 2100, simulations indicate a loss of 9.2 ± 0.4 (mean ± standard error) million km^2 of permafrost area and 81 ± 8 Pg of soil carbon under the SSP5-8.5 scenario. In comparison, under SSP2-4.5, G6solar and G6sulfur, permafrost area loss would be mitigated by approximately 39%, 37% and 34% and soil carbon loss by 42%, 54% and 47%, respectively, relative to SSP5-8.5."

- Line 18: This sentence is unclear because the subject of the first phrase lacks an object, and it took me several reads to understand the meaning. Either write out the object twice (e.g., "X raises soil C conservation, while Y lowers it, with the net effect of…") or write in the passive voice (e.g., "Soil C conservation is raised by X and lowered by Y, with the net effect of…")
- We have made changes as suggested. "Increased carbon flux from vegetation to soil raises soil C storage, while the priming effects of root exudates lowers it, with a net mitigating effect on

soil C loss."

- Line 21: Here and throughout the paper, "ESM" should be used when referring to only one model, and "ESMs" should be used when referring to more than one.
- Thanks for reminding. We have made changes as suggested.

- Line 24: I talk about this more in my comments on the discussion/conclusions below, but I strongly advise cutting the last part of this sentence. This is a purely technical paper and not a social science one; while using the potential economic benefits of SG as income for Indigenous communities is an interesting idea, without any citations, such discussions are pretty far outside the scope of this paper. The abstract especially is much stronger if you stick to the results of the paper, and I'd recommend stopping after "...$20 trillion in economic losses by 2100," which is a very strong result to end on.
- We have made changes as suggested.

Introduction:

- Line 39: Again, I disagree with the characterization of the permafrost-carbon feedback as a "tipping point". I recommend either using different language, or finding other sources to support this characterization. When describing a tipping point, the author cited here (Linton, et. al., 2019) cites his own work (Linton, et. al., 2008), but in that earlier article, Dr. Linton defines a tipping point as "a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system"; Table 1 of that 2008 article lists the critical threshold of permafrost as "missing", and in Appendix 2, he writes "no studies to date convincingly demonstrate that [permafrost] is a tipping element by our definition". As cited above, more recent research (Schuur et. al., 2015) argues that, while significant and irreversible, the permafrost-carbon feedback will likely scale incrementally over time and with warming, rather than abruptly.
- Agreed. We have replaced the reference to Lenton et al., 2019 with the McKay et al., 2022 paper on tipping points that defines abrupt loss of boreal permafrost as a potential tipping point, but with lower confidence than the gradual decline the referee notes:

  "The large hysteresis in the water/ice phase change, and associated climate feedbacks make this an essentially irreversible change, and a potential "tipping point" (McKay et al., 2022)."

  McKay, D.I.A., Staal, A., Abrams J.F., Winkelmann, R., Sakschewski, B., Loriani,S., Fetzer,I.,

Cornell,S.E., Rockström,J., Lenton, T.M.: Exceeding 1.5°C global warming could trigger multiple climate tipping points, Science, https://doi.org/10.1126/science.abn7950, 2022.

- Lines 51-54: I dislike that a political stance is used in these lines to justify this study's purpose. While the statement "the best option for mitigating climate change is to aggressively cut GHG emissions by switching to clean energy sources" is probably true, and I agree with it, the word "best" is highly unscientific without substantial support. Additionally, the number of other scientists studying SG does not make this study more r less important. There is plenty of justification for this research based on scientific merit alone, and I recommend cutting these lines entirely and sticking to the argument begun in lines 48-50 and continued in lines 54-59: SG is potentially faster, cheaper, and technically easier than mitigation and CO_2 removal, past studies (e.g., Chen, et. al., 2020) find that it might work, and you improve on them here.
- We have removed them as suggested.

- Line 64: Comma between "injection, respectively."
- Thanks for the correction.

- Line 68: Can you add more detail about the simulations you're analyzing from each ESM? Based on the rest of the study, each ESM appears to have one ensemble member for each of the four scenarios run from 2015-2100, but adding a sentence here (or earlier in this paragraph) would help clarify things, rather than having readers guess based on the plots or go and look up the G6 papers.
- We have added the description. "These six ESMs contain simulations for the G6solar, G6sulfur, SSP5-8.5 and SSP2-4.5 scenarios up to 2100, and their first ensemble members were used for analysis."

Materials and Methods:

- Section 2.1 as a whole: I would consider combining this with section 2.2, and possibly even moving Table 2 to supplementary, as discussed below. After reading the entire paper, it seems to me that the initial C stocks are listed and discussed to explain model differences and provide justification as to why bias correction is necessary, but they are not actually needed for the

analysis, as in Lines 149-150, you say that PInc-PanTher only needs TSL, NPP, and RPE, and one of the models also doesn't report initial C stocks. If this is correct, this is good background information and still worth including, but consider consolidating and combining sections 2.1 and 2.2 and moving Table 2 to supplementary. (If this is incorrect, and initial C stocks are used directly by PInc-PanTher, please explain how you can conduct the analysis for the model whose initial C stocks are not reported!)

- Thanks. We have modified it as suggested.

- Line 83: This sentence needs to be split up, e.g. "CMIP6 ESMs have many improvements, including X, Y, and Z. However, estimates still vary across models, which has been associated with deficiencies in the representation of Q and R."
- We have revised it as suggested. "CMIP6 ESMs have many improvements over preceding generations of CMIP models, including better treatment of snow radiative transfer and insulation effects, soil hydrology and vegetation dynamics (Fox-Kemper et al., 2021). However, estimates of permafrost extent and carbon stock changes still vary across models, which has been associated with deficiencies in the representation of soil thermodynamics and carbon dynamics (Burke et al., 2020; Mudryk et al., 2020)."

- Lines 87-88: Not critical, but can you provide any more information on how the other models estimated initial carbon stocks if they didn't use observations? Nothing too detailed, but a few words here would be helpful if you can find them.
- We have added the description. "Of the six CMIP6 models we used (Table 1), only the CESM2-WACCM land surface model (CLM5) adjusted permafrost carbon stocks to the latest observations and included a vertically resolved soil carbon representation, which is important for more consistent modelling of real-world soil carbon (Varney et al., 2022)."
  Varney, R. M., Chadburn, S. E., Burke, E. J., and Cox, P. M.: Evaluation of soil carbon simulation in CMIP6 Earth System Models, Biogeosciences, https://doi.org/10.5194/bg-19-4671-2022, 2022.

- Lines 91-94: "Can be" explained, or "is" explained? According to Table 2, the other models don't underestimate soil C loss; they show no losses at all. I don't understand the cause-and-effect

you're trying to argue in the last two sentences in this paragraph; whatever you're trying to say, please try to explain it more clearly.

- We have revised it as suggested. "This is explained by the underestimation of initial permafrost CSoil which then leads to an underestimation of future soil C decomposition. CSoil flux from surface vegetation increases due to GHG-driven increases in productivity, and this input flux exceeds soil C decomposition in those models with little initial soil carbon."

- Table 2: As mentioned above, consider moving this table to supplementary - the differences between initial carbon stocks are interesting, and mentioning them is important to explain why bias correction is necessary. However, since PInc-PanTher doesn't appear to use them (the numbers are missing for one of the models, and you're still able to conduct your analysis!), they're probably not necessary to include in the main body of the paper.
- We have moved this table to the supplementary section as suggested.

Results:

- Line 205: The comparison of your results in 2100 to those of McGuire, et. al. (2018) in 2300 raises an eyebrow. You mention that McGuire simulates faster rates of warming, but do the differences between RCP4.5/RCP8.5 and SSP2-4.5/SSP5-8.5 really justify comparing periods 200 years apart? If it does, you should include some more numbers to explain why (what are the rates of warming, exactly?), because otherwise there's a bit of comparing apples to oranges going on here. McGuire finds that, in their study, significant losses of carbon wouldn't occur until after 2100; perhaps digging into that would be a more apt comparison here or in the next subsection.
- Agreed, we have removed the comparison here as suggested, leaving it for the Discussion.

- Table 3 (and other tables, where applicable): Putting a description of the whole table - "Cooled TSL (℃)" - as the header of the first column is confusing. That information is already in the table description, so I recommend writing "scenario" or similar as the header of the first column.
- We have modified Table 3.

- Figure 5: What defines the boundaries of the "permafrost region" in this figure? In the paper as

a whole, the term appears to refer generally to the area at high latitudes where permafrost can be found, but in this figure, every panel seems to have exactly the same region outlined in color. More specifically, does the red color indicate regions that qualified as permafrost in 2015, or some other period, according to PInc-PanTher, but are no longer permafrost as of 2100?

- We have added the description to the caption. "The initial permafrost extent was derived from the boundary of the permafrost soil C maps (Hugelius et al., 2014)."

- Line 237: It's a bit picky, but I'm not sure I would qualify 81 ± 8 vs. 92 ± 17 as "close"... maybe "similar to," "the same order of magnitude" or "within the bounds of uncertainty"?
- We have revised it as suggested. "Our estimated permafrost C losses for the SSP5-8.5 projection are within the uncertainty range of the 92±17 Pg C estimate based on a literature compilation"

- Line 249: "the spatial distribution is controlled by latitude and initial C stocks" - I thought all of the PInc-PanTher simulations used identical initial C stocks? This is implied by Lines 149-150, which says that only TSL, NPP, and RPE from each ESM are used; by Lines 154-155, which describes initial C stocks for PInc-PanTher; and by the fact that initial C stocks for one of the models are missing. If this is correct, then consider revising this statement slightly, perhaps saying that distribution is related to initial C stocks and controlled by the initial distributions of the variables actually fed into PInc-PanTher.
- Thanks, we have revised it as suggested. "the spatial distribution is related to initial C stocks and controlled by the distributions of TSL, NPP, and RPE."

- Section 3.3 in general: Lee, et. al. (2022, https://doi.org/10.1002/essoar.10512047.1) examined high-latitude stratospheric aerosol injection and its effect on permafrost in CESM2-WACCM. That study only used one climate model, but they also looked at the effects on soil carbon vs. vegetation carbon; it may be worth comparing your results here, or in the first or third paragraph of the conclusions.
- As suggested, we have added citation and comparison. "Lee et al. (2022) studied two Arctic-only stratospheric aerosol injection strategies using CESM2-WACCM and found that the reduction in vegetation carbon gains due to SG outweighed the increase in permafrost soil carbon."

Discussion and Conclusions:

- Lines 344-345: Can you qualify this statement from McGuire a bit more? Gains in vegetation C might outweigh losses in soil C in the near future, but is that true for any scenario, over any period of time?
- We have revised it as suggested. “Gains in vegetation C are expected to partially, or even over-compensate, for losses in soil C in the permafrost region over the century (McGuire et al., 2018).”

- Line 359: Need an “and” after the comma
- Thanks. Corrected.

- Lines 360-end: I’m extremely nervous about telling historically marginalized communities what they “should” do, especially in a purely technical paper. You make some good points here, but as this is an earth science paper and not a social science one, I would strongly recommend leaving most of this implied, but unsaid - you’ve laid out the evidence for the economic benefits of SG; best leave it up to the social scientists to ponder what to do with them. I would cut this entire block, but if you do want to leave part of it in, I advise sticking to objective sentences that would be very difficult to disagree with.
- We have removed this sentence as suggested.

References:

- Line 467: There’s a typo in the DOI for McGuire, et. al. (2018): the DOI has a space before the last two numbers, which makes it a bit harder to follow the link.
- Checked, the DOI can be linked correctly.