Reviewer comments

Author responses (**Bold is new text in manuscript**)

RC1

Overall this paper disentangles key drivers of soil carbon dynamics in the CMIP6 model suite. This set of models is fundamental to developing the IPCC reports and thus understanding why the models return the results they do are critical to continual improvement and uncertainty quantifications for policy advising. In general, I think many of the key elements of a strong and insightful analysis are here, but need a bit more connection and stronger caveats.

We are thankful that the reviewer sees the relevance and value of the paper, we feel that including the helpful reviewer comments have now improved the paper.

I would urge the authors to spend more time in their methods section integrating the C4MIP runs with the priming hypothesis. How would we expect false-priming to show or not show up in the various runs and why?

The assertion of false priming as the sole explainer for the correlative increase in NPP and reduction in turnover time is, perhaps, a bit strong. What are alternative explanations for the observed correlations? How are climate drivers delt with in both the NPP and Rh submodels? How does the second order NEP effects integration with this false-priming framework?

Additional text is now included to integrate the false priming hypothesis with the C4MIP simulations, and how these are used with the false priming investigation.

Additional text has been added to the Introduction.
Ln 40:
"***However, the effective soil carbon turnover time can also reduce under increasing litterfall inputs (e.g., due to CO_2 fertilisation of plant growth), because the faster components of the soil increase more quickly than the slower components. The net effect of this is that a higher fraction of the soil carbon is held in the fast pools under increasing litterfall, which reduces the effective soil carbon turnover time - a transient phenomenon known as 'false priming' (Koven et al. 2015).***"
Ln 47:
"***Finally, a simple box model is used to investigate soil carbon change, along with idealised 'C4MIP' simulations which separately model the physiological and climate effects of increasing atmospheric CO_2. Our aim is to distinguish more clearly between the direct and indirect mechanisms of reduced soil carbon turnover times by isolating the effects of false priming in models.***"

Additional text has been added to the Methods.
Ln 76:
"***The use of these experiments allows for a more focused evaluation of soil carbon and related fluxes by isolating sensitivities to CO_2 and associated climate changes, as well as removing additional complications in the SSP simulations.***"

The section '***Section 3.4: Investigating the emergent relationship between $\Delta C_{s,NPP}$ and $\Delta C_{s,\tau}$***' has been split into this section plus an additional section '***Section 3.5: The role of false priming***' (which starts from Line 285). We feel this presents both the C4MIP analysis (Section 3.4) and false priming (Section 3.5) more clearly, and additional text has been added to both sections.

Additional text is added to the start of Section 3.4 to introduce the C4MIP simulations.
Ln 260:
"In this subsection, the emergent relationship between $\Delta C_{s,NPP}$ *and* $\Delta C_{s,\tau}$ *present across the CMIP6 ensemble is* ~~*further*~~ *investigated using the idealised C4MIP simulations (see Methods). T****his enables investigation of the negative correlation without additional complex processes which are included in the SSP simulations. By isolating the sensitivities to*** CO_2 ***and climate, we can more easily identify the processes which results in the apparent coupling between NPP and soil carbon turnover in CMIP6 ESMs.***"

Alternative explanations for the emergent relationship are now discussed in the text and relating to the C4MIP simulations. Additionally, a new figure is included which uses the C4MIP simulations to quantify the fraction of the total change in soil carbon turnover time which is seen in the CO2 only run (i.e. not due to reductions in soil carbon turnover time due to warming), which can be **seen below**, including the new discussion within the text.

Ln 284:
"***The correlation between*** $\Delta C_{s,NPP}$ ***and*** $\Delta C_{s,\tau}$ ***, as seen in the SSP simulations (Fig. 7 and Fig. 8), is also evident in the full 1%*** CO_2 ***C4MIP simulation. This suggests the relationship is not a result of additional processes included in the SSP simulations compared to the C4MIP experiments, such as land use change (Jones et al. 2016). An additional explanation for the coupling could be similarities in the modelled sensitivities of NPP and Rh to changes in climate. For example, if NPP and specific soil respiration rate both increased with warming, a negative correlation between*** $\Delta C_{s,NPP}$ ***and*** $\Delta C_{s,\tau}$ ***would be seen. However, under these circumstances the negative correlation would not be seen in the*** CO_2 ***only C4MIP runs, as there is no global warming in these simulations (see Methods). Instead, a reduction in effective soil carbon turnover time is seen in the BGC runs (Fig. A2), which implies a non-climate response in*** τ_s ***and results in an NPP-***τ_s ***negative correlation (Fig. 9). Fig. NEW shows that the change in the effective soil carbon turnover time in the BGC simulation accounts for at least 50% of the total change in the effective soil carbon turnover time in the full 1% simulation across CMIP6 ESMs.***"

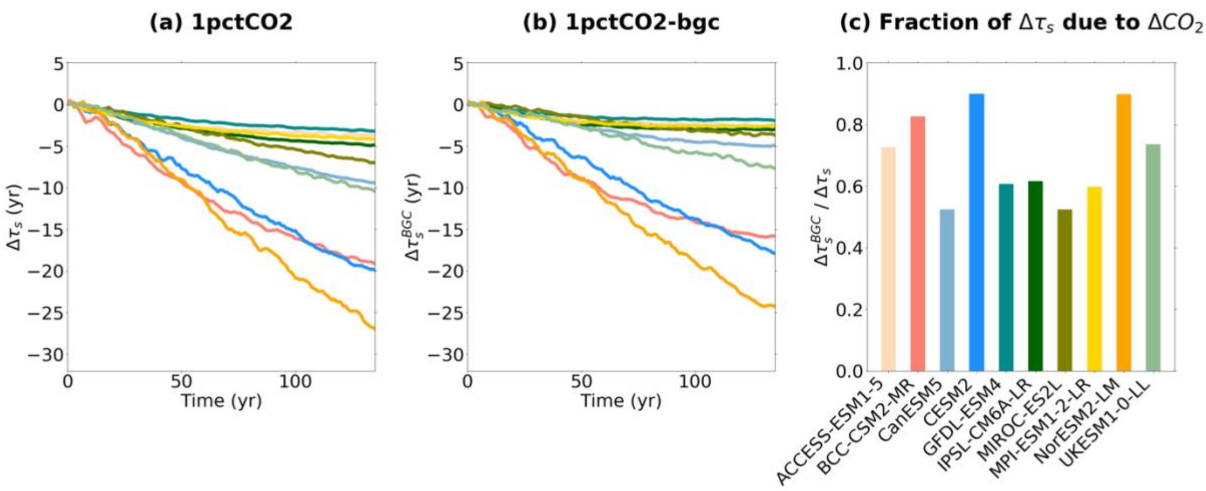

Fig NEW.*: "Changes in soil carbon turnover (*$\Delta\tau_s$***) in C4MIP runs for the CMIP6 ESMs, with and without direct climate effects on*** τ_s***. (a) timeseries of*** $\Delta\tau_s$ ***in full 1% CO2 simulation (climate and*** CO_2 ***changes), (b) timeseries of*** $\Delta\tau_s$ ***in BGC simulation (***CO_2 ***changes only), and (c) bar chart showing the fraction of total*** $\Delta\tau_s$ ***due to the changes in*** CO_2 ***for each model.***"

New text in new false priming section clarifying the role of false priming in ESMs.
Ln 325:
"*It is noted that the influence of false priming was stronger in the full 1% CO_2 and BGC (CO_2 only) simulations, compared to the RAD (climate only) simulation* ***(Fig. 8)****. This is likely due to the RAD simulation not seeing sufficient NPP change****, and therefore sufficient input of soil carbon,*** *for the false priming* ***e****ffect to be significant (see* ***Fig. A2****). Additionally, the direct effect of temperature changes on* $\boldsymbol{\tau_s}$ *in the RAD simulation is likely to dampen the correlation to NPP changes, due to both direct and indirect* $\Delta\boldsymbol{\tau_s}$ *in this case (Varney et al. 2020).* ***False priming is dependent on the structure of the soil carbon model within the ESM. The reduced effective turnover time occurring in a transient system, without any external sensitivities on*** $\boldsymbol{\tau_s}$***, is a consequence of varying turnover times between different soil carbon pools.***"

Additionally, false priming is now presented as a likely contributor to this correlation seen in ESMs, opposed to the sole explainer. The text has been edited throughout accordingly, such as below.

Ln 8:
"*We show* ***that the concept of 'false priming' is likely to be contributing to this emergent relationship*** ~~*this emergent relationship is the result of `false priming'*~~*, which leads to a decrease in the effective soil carbon turnover time as a direct result of NPP increase and occurs when the rate of increase of NPP is relatively fast compared to the slower timescales of a multipool soil carbon model.* ***This finding suggests that the structure of soil carbon models within ESMs in CMIP6*** ~~*The inclusion of more soil carbon models with multiple pools in CMIP6 compared to CMIP5, therefore seems to have*~~ ***has likely*** *contributed towards the reduction in the overall model spread in future soil carbon projections* ***since CMIP5****.*"

Ln 323:
"*… suggesting that* ***false priming and the structure of the soil carbon models within the ESMs is likely contributing to*** *these correlations in CMIP6 (and to a lesser extent in CMIP5).* ~~*are predominantly due to false priming.*~~"

Ln 348:
"***False priming was found to likely be contributing to the apparent emergent relationship between*** $\Delta \boldsymbol{C_{s,NPP}}$ ***and*** $\Delta \boldsymbol{C_{s,\tau}}$ ***in CMIP6 ESMs****, …* ~~*The apparent emergent relationship between* $\Delta C_{s,NPP}$ *and* $\Delta C_{s,\tau}$ *in CMIP6 ESMs was found to be a result of false priming*~~,"

The 'false priming framework' is used to explain the concept of a reduced effective turnover in a box model with multiple pools of differing turnover times. Under increasing NPP, the fast turnover pool gets a greater weighting when calculating an effective turnover of the system compared to the slow turnover pool, but the respiration values Rh do not change. Therefore, false priming is an artifact of the transient nature of the system, with NPP and Rh differing in the transient. NEP is used to define the difference between NPP and Rh (by definition). The 'NEP integration' is used to account for the subsequent change in ΔC_s due to our isolation of above and below ground soil carbon controls during a transient climate.

See line comments below:

Ln 35: Should probably mention expected limitations on the nutrient fertilization effect and colimitation of water and other factors on the turnover time.

The paragraph has been updated to include additional discussion.
Line 32:
"*This study assumes Net Primary Productivity (NPP) represents the input flux of carbon to the* ***system*** ~~*soil*~~ *and is defined as the net rate of accumulation of carbon by vegetation arising from photosynthesis minus the loss from plant respiratory fluxes (Todd-Brown et al. 2013, 2014).* ***In the absence of nutrient and moisture limitations (Wieder et al. 2015; Green et al. 2019),*** *NPP is projected to increase under increased atmospheric CO_2 due to the CO_2 fertilisation effect, which can result in an increased soil carbon storage* ***through increased litter*** *(Schimel et al. 2015). Heterotrophic respiration (R_h) is assumed to represent the output flux of carbon from the soil and is defined as the carbon losses due to decomposition from microbes in the soil. Rh is projected to increase under global warming,* ***due to an increased rate of microbial decomposition under warming*** *(Varney et al. 2020),* ***in the absence of very significant increase in soil moisture or nutrient limitations (Sierra et al., 2015; Schmidt et al., 2011).*** *Soil carbon turnover time (τ_s) is defined as the ratio of soil carbon stocks to the output flux of carbon (Rh)* **.**~~*, where*~~ ***Global*** *warming alone generally reduces tau resulting in* ***carbon residing in the soil for less time and*** *a release of carbon from the soil into the atmosphere (Crowther et al. 2016).*"

1. Wieder, W. R., Cleveland, C. C., Smith, W. K., and Todd-Brown, K. (2015). Future productivity and carbon storage limited by terrestrial nutrient availability. *Nature Geoscience*, 8(6):441–444.
2. Green, J., Seneviratne, S., Berg, A., Findell, K., Hagemann, S., Lawrence, D., and Gentine, P. (2019). Large influence of soil moisture on long-term terrestrial carbon uptake. Nature, 565(7740):476–479.
3. Sierra, C. A., Trumbore, S. E., Davidson, E. A., Vicca, S., and Janssens, I. (2015). Sensitivity of decomposition rates of soil organic matter with respect to simultaneous changes in temperature and moisture. *Journal of Advances in Modeling Earth Systems*, 7(1):335–356.
4. Schmidt, M. W., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D. A., et al. (2011). Persistence of soil organic matter as an ecosystem property. *Nature*, 478(7367):49–56.

Ln 60: repeat information about the ESMs as needed to understand the results of this study. Citation hunts interrupt reading of the study.

Firstly, we now have included a new table in the manuscript (which has been adapted from Tables 1 and 2 from Varney et al. 2022), which includes information on the soil carbon components of the ESMs in both CMIP5 and CMIP6. Specifically, the no. of dead soil carbon pools within the ESMs **(see below)**.

Earth System Model	Nitrogen cycle	No. of live carbon pools	No. of dead carbon pools	References
BNU-ESM	No	-	-	Ji et al. (2014); Dai et al. (2003)
CanESM2	No	3	2	Arora et al. (2009); Arora and Boer (2010)
GFDL-ESM2G	No	8	2	Dunne et al. (2012, 2013); Shevliakova et al. (2009)
GISS-E2-R	No	7	5	Schmidt et al. (2014); Yue and Unger (2015)
HadGEM2-ES	No	3	4	Jones et al. (2011); Best et al. (2011): Clark et al. (2011)
IPSL-CM5A-LR	No	-	7	Dufresne et al. (2013); Krinner et al. (2005)
MIROC-ESM	No	4	2	Watanabe et al. (2011); Ito and Oikawa (2002); Sato et al. (2007)
MPI-ESM-LR	No	4	2	Raddatz et al. (2007); Knorr (2000)
NorESM1-M	Yes	13	7	Bentsen et al. (2013); Iversen et al. (2013); Lawrence et al. (2011)
ACCESS-ESM1.5	Yes	3	6	Ziehn et al. (2020); Haverd et al. (2018);
BCC-CSM2-MR	No	3	8	Wu et al. (2019); Ji et al. (2008)
CanESM5	No	3	2	Swart et al. (2019); Melton et al. (2020); Seiler et al. (2021)
CESM2	Yes	22	7	Danabasoglu et al. (2020); Lawrence et al. (2019)
CNRM-ESM2-1	No	6	7	Séférian et al. (2019); Delire et al. (2020)
GFDL-ESM4	No	6	4	Dunne et al. (2020); Zhao et al. (2018)
IPSL-CM6A-LR	No	8	3	Boucher et al. (2020); Cheruy et al. (2020); Guimberteau et al. (2018)
MIROC-ES2L	Yes	3	6	Hajima et al. (2020); Ito and Oikawa (2002)
MPI-ESM1.2-LR	Yes	3	18	Mauritsen et al. (2019); Goll et al. (2017); Goll et al. (2015)
NorESM2-LM	Yes	22	7	Seland et al. (2020); Lawrence et al. (2019)
UKESM1-0-LL	Yes	3	4	Sellar et al. (2020); Wiltshire et al. (2021)

Table NEW: "***The CMIP5 and CMIP6 Earth system models included in this study and the relevant features of associated land carbon cycle components: simulation of interactive nitrogen, number of live carbon pools and the number of dead soil carbon pools (Varney et. al 2022; Arora et al. 2013; 2020).***"

Secondly, we have included extra text in the Methods.

Ln 57:

"~~Specific soil carbon related updates within ESMs from CMIP5 to CMIP6 are included in Varney et al. 2022 within the 'Earth system models' section of the Methods, and more general model updates are presented within the 'Model descriptions' section of the Arora et al. 2020 Appendix.~~

The use of CMIP allows for comparison between ESMs in the different ensemble generations. Table 1 presents key soil carbon ESM information from both CMIP6 and CMIP5 (adapted from Tables 1 and 2 in Varney et al. 2022). The Table can be used to identify key ESM updates between CMIP6 and CMIP5, such as: the simulation of interactive nitrogen in CMIP6 (ACCESS-ESM1.5, CESM2, MIROC-ES2L, MPI-ESM1.2-LR, NorESM2-LM and UKESM1-0-LL) compared to CMIP5 (NorESM1-M) and the number of soil carbon pools (dead carbon pools). The ESMs where both CMIP5 and CMIP6 generations are included in our analysis are: CanESM2 and CanESM5, GFDL-ESM2G and GDFL-ESM4, IPSL-CM5A-LR and IPSL-CM6A-LR, MIROC-ESM and MIROC-ES2L, MPI-ESM-LR and MPI-ESM1.2-LR, NorESM1-M and NorESM2-LM, and HadGEM2-ES and UKESM1-0-LL, respectively, where direct comparisons can be made. It is noted that some Land Surface Models within ESMs

share similarities (e.g. CESM2 and NorESM2-LM both use the Community Land Model version 5; Arora et al. 2020)."

Ln 125: Can you pull these ratios from the model to justify this assumption?

The common mathematical assumption (products of deltas are negligible, $\Delta * \Delta \approx 0$) is not made here as we include the $\Delta\Delta$ terms in our analysis. The sentence has therefore been changed to make this clearer.
Ln 124:
"*Equation 7 is exact for given time-varying values of NPP, NEP and τ_{s}. ~~but in this form it does not cleanly separate into contributions due to changes in each of these factors. A linear approximation is therefore made (assuming $\Delta \rm{NPP}/\rm{NPP} << 1$ and $\Delta \tau_{s}/\tau_{s} <<1$), which allows for the cross-terms to be neglected ($\Delta \rm{NPP} \Delta \tau_{s}$ and $\Delta \rm{NEP} \Delta \tau_{s}$).~~ The ~~resultant~~* ***individual*** *terms in Equation 8*

Ln 241: If this term was non-negligible then I would suggest dropping this framing from the introduction and maybe including a comment like "We thought this would be negatable but were surprised to find it was not."

Similarly (**see above**), the text has been changed as follows.
Ln 241:
"*~~The non-linear $\Delta \rm{NPP} \Delta \tau_{s}$ term having non-negligible contributions to future ΔC_{s} means the initial $\Delta \rm{NPP}/\rm{NPP} << 1$ and $\Delta \tau_{s}/\tau_{s} <<1$ assumptions were not valid in this case.~~* ***A linear assumption is commonly used which would allow these cross-terms to be neglected (****$\Delta \rm{NPP}/\rm{NPP} << 1$ and $\Delta \tau_{s}/\tau_{s} <<1$****; Koven et al. 2015). However, the*** *ESM projected … "*

How are the different model runs going to be used in the analysis? How would you expect each scenario to behave given their driving conditions within the framework developed in Eqn 8? I suspect that key to the argument that this is a false-priming effect is going to be the C4MIP runs. Setting this up explicating in the methods section makes a lot of sense.

As above, see main comments 1 and 2. Additional text has been added to explain why each model run is used and explaining false priming in the context of the C4MIP runs.

This false priming analysis feels very tacked on and needs to be introduced before the discussion section more clearly. How was this three box model parameterized? It appears that you are claiming that because you see similar patterns in this 3 pool model that you confirm that this is what is happening in the CMIP models. Maybe but there are other alternatives.

False priming is now introduced within the Introduction (**see response given to comment 1 on Ln. 40**).

A new section '***Section 3.5: The role of false priming***' has been added to present false priming more clearly. It comes at the end because it is used to explain results which were found during the analysis. The 3-box model was taken from Koven et al. 2015 and the same parametrisation was followed. The presence of false priming will not be dependent on the parameterisation assuming the 3-box model has carbon pools with a fast, medium and slow turnover time, and carbon is able to flow between the carbon pools. This has been made clearer in the text (including the additional detail that the carbon pools are initialised at 0).

As above, false priming is now presented as a likely contributor to this correlation due to the structure of the soil carbon models within ESMs producing the same relationship. We feel the additional information on possible alternatives and more details on false priming in the different C4MIP runs will have improved this point.

1. Koven, C. D., Chambers, J. Q., Georgiou, K., Knox, R., Negron-Juarez, R., Riley, W. J., Arora, V. K., Brovkin, V., Friedlingstein, P., and Jones, C. D.: Controls on terrestrial carbon feedbacks by productivity versus turnover in the CMIP5 Earth System Models, Biogeosciences, 12, 5211–5228, https://doi.org/10.5194/bg-12-5211-2015, 2015.