Feedback from the reviewer is written in italic face, while our responses are written in normal font in green.

Reviewer 2

We thank the reviewer for taking the time to read our manuscript and for providing constructive feedback. Please find our responses to the feedback below.

Manuscript Title

A microbially-driven and depth-explicit soil organic carbon model constrained by carbon isotopes to reduce equifinality

Recommendation

This paper presents a novel SOC model (SOIL carb), designed to mitigate equifinality by integrating $\delta^{13}C$ and $\Delta^{14}C$ values of soil organic carbon (SOC). Calibration solely based on SOC stock data results in imprecise estimations of subsoil organic carbon (OC) residence times. The inclusion of $\delta^{13}C$ has a minimal effect, whereas the incorporation of $\Delta^{14}C$ accurately captures the SOC turnover rate but only partially alleviates equifinality for certain parameters. Given that all parameters are susceptible to equifinality, additional data is required to establish reliable constraints. Achieving an optimal balance between model complexity and data availability is crucial for accurately predicting soil carbon-climate feedback mechanisms.

The article's topic selection is significant and demonstrates robust logic and academic rigor. Nevertheless, certain sections necessitate further refinement. The subsequent revision recommendations are outlined below

Major revisions

Introduction

1. *Further explanation can be provided on why accurately predicting the reserves and dynamics of Soil Organic Carbon (SOC) is crucial for combating climate change. Additionally, pointing out the problems caused by inaccurate SOC models, it can enhance readers' comprehension of the urgency and significance of this research endeavor.*

Thanks for this suggestion, this was indeed missing in the introduction. At the end of the first paragraph of the introduction (L26-28 in the original manuscript), we added: "*A correct representation of the rate of OC cycling along the soil profile in biogeochemical models is necessary to make accurate predictions about climate – soil carbon feedbacks. When these rates are overestimated, the simulated size of the SOC stock* *will adapt too fast to changes in OC inputs. This leads to an underestimation of the time it takes for soils to increase their OC storage due to increases in, for example, net primary productivity or OC inputs in agroecosystems (He et al., 2016; Wang et al., 2019).".*

To make the potential impact of equifinality in SOC models clear, we added to following to L60 (in the original manuscript): "*In the case of SOC models, models characterised by equifinality are often able to make correct predictions of current SOC stocks, although these stocks can be predicted by different distributions of SOC over the simulated model pools (Braakhekke et al., 2013). The problems (and uncertainty) arise when different behavioural models are used to make predictions of SOC stocks based on changing environmental conditions or OC inputs. In this case, behavioural models starting from an identical initial SOC stock can produce a wide range in predicted values, from which it is generally not possible to identify the correct model (and parameter set) (Luo et al., 2016, 2017).".*

2. *It is suggested that a brief discussion be included at the end of the introduction regarding the potential impacts of this study on soil carbon cycling, climate change prediction, and land management practices, enhancing the practicality and relevance of the research.*

Thanks for this suggestion. We now end the introduction with "*As equifinality in SOC models has received only limited research attention, increasing awareness of, and solving, this problem will increase confidence in simulations of the role soils can play in climate change mitigation or increasing SOC stocks to improve soil health in agroecosystems.".*

Materials and Methods

1. *In Sensitivity Analysis: The authors should provide more details on the parameter sensitivity analysis, particularly for those parameters that have the greatest impact on the model's output.*

The description of the methods for the sensitivity analysis (section 2.5.1) has been updated to make this more clear (see below). The results of this sensitivity analysis are briefly presented in section 2.3.2, and figures showing the results are provided in the supplementary information (Fig. S5). We hope this is sufficient for the reader to understand these results.

Results

1. *At the beginning of each results section paragraph, the key findings of this study can be highlighted using concise and clear language, enabling readers to quickly grasp the main outcomes of the research.*

Thanks for this suggestion, we now start every section of the results with a sentence summarizing the most important findings.

2. *The results should present a sensitivity analysis of the parameters that significantly affect the model output, which aids in understanding which parameters are most critical to the model's outcomes.*

This analysis has been performed, and is described in section 2.5.1. The results are briefly presented in section 2.3.2 and the results shown in Fig. S5. We hope this is sufficient for the reader to visualize and understand the effect the different parameters have on the model outcomes.

[**answer**]

3. *If there are limitations to the results, such as the representativeness of the data or the applicable conditions of the model, they should be clearly stated in the Results section.*

The aim of the developed model for the presented manuscript was not to promote its application to a specific environment. Instead, we developed a model in line with the current knowledge of the SOC cycle similar to other recently developed models, with the aim of showing how equifinality can affect simulations of the turnover rate (through $\Delta^{14}C$) of SOC. To make this more clear to the reader, we added the following sentence to the first paragraph of the methods section: "*We note that the main aim of the developed model for the present manuscript was to show the effect of equifinality on model outcomes, and that the application of SOILcarb to other environments requires further testing.*".

Discussion

1. *The discussion should be expanded to address the generalizability of the model results, specifically whether the model is applicable to other soil types or environmental conditions, with further explanation provided in the discussion.*

As explained in the previous response, our aim was not to develop a SOC model that is widely applicable (although it has the potential to be, given that certain changes are made, for example, to apply it to agroecosystems). Therefore, a discussion on this is beyond the scope of our discussion.

To make the general application of our results more clear to the reader, the first sentences of section 4.2 ("Overparameterisation and equifinality in soil biogeochemical models") has been changed to "*Our result show that overparameterisation, which arises when a numerical model has too many parameters compared to the data available to constrain parameter values, has important consequences for the correct simulation of SOC dynamics. As many of the recently developed SOC model have a similar structure and use similar equations, it is likely that this is a general issue for such models, as has previously been shown for conventional turnover-based pool models (Braakhekke et al., 2013; Luo et al., 2016, 2017).*".

2. *The relative importance of different mechanisms at different soil depths can be further explored regarding its causes and potential influencing factors.*

It is not exactly clear which mechanisms at different soil depth could be more explored. In section 3.4 we discuss how different model aspects affect the $\delta^{13}C$ depth profile in the top and subsoil. We hope this provides sufficient information to the reader about how this novel aspect in the model (the simulation of $\delta^{13}C$ depth profiles) is affected by different model parameters.

3. *Although the article mentions the importance of accurately simulating the turnover time of SOC for predicting changes in the global carbon cycle, it can further expand the discussion on the specific significance of the research results in practical applications, such as the potential impacts and inspirations on soil management, climate change response strategies, and other aspects.*

To make the practical applications of the results more clear to the reader, we have added the following to section 4.3 ("Ways forward to identify and reduce equifinality in microbially-driven SOC models"): "*This is particularly important as these models are incorporated in Earth system models to make predictions of the response of the SOC stock to changes in the Earth's climate (e.g., Wieder et al., 2024), or to assess how changes in agricultural management practices can increase the amount of SOC to mitigate climate change and assign carbon credits (e.g., Mathers et al., 2023).*".

4. *Although the author mentioned that the model does not include the effects of temperature and soil moisture, it is suggested to further discuss the specific impacts of these limitations on the model's predictive ability.*

As noted above, the aim of the study was not to develop a model that can be used for predictions under changing environmental conditions, or can be readily applied to a wide range of environments. We do believe that this is possible, after certain modifications are made to the model structure (for example, the simulation of the soil N cycle and a coupling to a plant growth moducle). Therefore, it is beyond the scope of the discussion to provide information on this model limitation.

Minor revisions

1. *In Figure 3, the "calibrated for C" section is in italic format; please consistent formatting.*

Thanks for noticing, all similar labels have been changed to italic format.

2. *There are several sentences in the article that are rather cumbersome, such as the following ones:*

- *The model first calculates fluxes of 12C between pools and subsequently uses the ratio of 12C leaving every pool to the total amount of 12C of the respective pools to calculate how much 13C and 14C leave every pool, based on the respective 13C/12C and 14C/12C values of the pools. The model parameters are thus defined based on the 12C content of every pool.(Line 135)*

Thanks for pointing this out. We rephrased this sentence and provided an equation to show what we mean.

- *The parameter sets to calculate the conditional and unconditional CDFs were obtained using the Matlab® version of SAFE toolbox (Pianosi et al., 2015), which was also used to post-process the results and calculate the sensitivity of the tested parameters using the Kolmogorov - Smirnov (KS) statistic. (Line 282)*

To make this sentence more comprehensible to the reader, we added the following to the first part of this paragraph: "[...] *This is a density-based global sensitivity analysis that quantifies the model sensitivity related to uncertainties of input parameters based on the cumulative distribution function (CDF) of the output distribution. This is done for the CDF when all parameters are varied (the unconditional CDF) and when one parameter is kept constant (the conditional CDF). The distance between both cumulative distributions is used to quantify the sensitivity of model to different parameters, and is calculated using the Kolmogorov-Smirnov (KS) statistic.*".

- *Similarly for the soil, after parameters are optimised using measurements of depth profiles of OC, δ13C and Δ14C of the POC and MAOC pools, simulated depth profiles of these fractions closely reproduce measurements. (Line 307).*

We rephrased this as follows: "*Similarly for the soil, after parameters are optimised using measurements of depth profiles of OC, $\delta^{13}C$ and $\Delta^{14}C$ of the POC and MAOC pools, the measurements of both pools are simulated very well by the model (Fig. 2).*".