

## Response to comments from Reviewer 2

### Authors:

We would like to thank the reviewer for the positive and perceptive comments, as well as for the questions, which will help us to improve the paper, specifically by giving more details, information and explanations about our data, methods and results.

This study describes a simple model of soil organic carbon (SOC) turnover that represents the effects of soil physical protection and microbial energy limitation. The paper first describes the model in a soil profile, then tests it using SOC data from a long-term study on agricultural fields with varied C inputs to the soils. Finally, the model's most influential parameters were identified in a sensitivity and uncertainty analysis. Overall, the paper is well written and presents a model of interest and relevance to soil carbon management. Below, please find specific comments intended to help improve the paper.

### Comment 1

L83 – Define the abbreviation USSF.

**Authors:** OK, we will do this in the revised version (it stands for **U**ppsala model of **S**oil **S**tructure and **F**unction)

### Comment 2

L91-95 – I would suggest ending the introduction with a strong thesis statement of what the paper contributes to current knowledge of the subject.

**Authors:** Yes, we will add such a statement at the end of the introduction.

*“The contribution of this study is to demonstrate the utility of a simple soil C turnover model that can account for the nexus of soil management, soil structure and microbial activity that critically determine C mineralization and stabilization at the scale of a soil profile.”*

### Comment 3

L97-101 – I appreciate this overview of the methods, very helpful to have this framework.

**Authors:** Thanks!

### Comment 4

L103 – In section 2.1.1 that starts on this line, it is unclear if the model as described in this section is the work of the authors or if this is describing previously published work. If it has been previously published, I suggest including most of the equations in this section in a supplement rather than in the main document. In the main manuscript, I suggest describing the model in writing and including important equations for the modifications to the model that are new in the current study.

**Authors:** The model is based on a combination of the model described by Meurer et al. (2020) accounting for physical protection in relation to soil properties with the model described in Wutzler and Reichstein (2013) for microbial energy limitation. This combination of the two models was outlined in Coucheney et al. (2024), along with some minor improvements and modifications. However, the description of this SOM model was only included in the supplementary information in Coucheney et al. (2024) as the model itself was not tested at all. So although the main constituent components of the model have been described earlier, this is the first time that the complete model has been *tested*. As the model is quite new and previously untested, we prefer to keep these equations in the main paper, as it makes it easier for the reader. The paper is not too long and including the equations in the main text will ensure that the equations are readily available.

We think this history of the model development is clearly explained at lines 104 to 115.

Additionally, I would encourage the authors to post their full model code online and cite it in the paper.

**Authors:** We built the model using the icon-based modelling software STELLA, which is a commercial product. The model file will be made available on request to the authors – this will be stated in the “data availability statement” at the end of the manuscript.

## Comment 5

L107-109 – It would be helpful to specify the direction of the relationship between these effects (e.g., Do smaller pores get fewer root derived inputs?

**Authors:** Not necessarily, no. It depends on the pore size distribution in the soil, which in turn depends on the soil texture (or more simply clay content in our approach). The pore size distribution determines the partitioning of root-derived inputs of OM between the two pore regions (see Eqs. 10-13). This means that a larger proportion of the root C inputs would enter the micropore region in a clay soil than in a sandy soil, because the porosity of a clay soil predominantly consists of smaller pores. Clay soils therefore have a higher potential for physical protection of soil C. The effect of the physical protection is quantified by the factor  $F_p$  (Eqs. 1-4) that reduces the rate of SOC decomposition in micropores.

We will modify the text at L107-109 to make this clearer:

*“In turn, the pore size distribution determines the partitioning of root-derived inputs of OM between the two pore regions. Compared with a sandy soil, a larger proportion of the root OM input will enter the micropore region in a clay soil, as it predominantly consists of smaller pores. The soil pore size distribution also regulates decomposition rates with slower decomposition rates of OM stored in microporous regions of the soil. Compared with sandy soils, clay soils therefore have a greater potential for physical protection of soil C”.*

Do micropores have lower decomposition rates?).

**Authors:** Yes, they do. We will clarify this in the revised text at lines 107-109 (see above text)

## Comment 6

L125 – Is the “(-)” after  $fr_{mic}$  supposed to indicate that it is unitless?

**Authors:** Yes

## Comment 7

L218 – How does this straw addition rate compare to the maize biomass per hectare?

**Authors:** Note that maize was only grown since 2000. Between 2000-2019, the crop fertilized and crop fertilized+straw treatments had on average 6.07 and 7.09 t ha<sup>-1</sup> maize yield, respectively (see Kätterer & Bolinder, 2024). However, above-ground maize and crop residues were removed from the field and it is very speculative how much C is added to the soil system via root inputs (rhizodeposition and exudates) and such C inputs are challenging to quantify and are therefore not included in the present proposed model. For the modelling, we know how much straw was added and this is included in the paper.

## Comment 8

L219 - 220 – Include the scientific names/varieties of the crops.

**Authors:** We will include Latin names in the revised version:

*“Maize (*Zea mays*) has been grown on the cropped plots since 2000. Before 2000, the crop rotation included barley (*Hordeum vulgare*), oats (*Avena sativa*), beets (*Beta vulgaris*) (prior to 1967) and rape (*Brassica napus*).”*

In addition, we propose to include a reference to a newly published data paper which gives a complete description of the experiment, as well as links to all the data (Data in Brief paper. Pold et al. 2025 - Soil and vegetation property data from the Ultuna R3-RAM56 long-term soil amendment experiment, 1956-2023).

## Comment 9

L220 - What is the purpose of hand digging the plots after harvest?

**Authors:** It's to simulate ploughing: the plot size of 4 m<sup>2</sup> is too small to manage in the same way as a farmer's field. We will add this information at L220.

## Comment 10

L 231 – What measurements were used for the calibration? Only OM or additional measurements?

**Authors:** Only SOC. We will state this explicitly in the revised version.

Calibrating to additional variables could help reduce equifinality.

**Authors:** Perhaps, depending on the type of data and its quantity and quality. But we were able to strongly reduce the prior uncertainty ranges for the parameter values anyway, despite parameter correlation.

See also our answer to comment number 7 from reviewer 1.

## Comment 11

L238 – Specify the field bulk density values used for this validation.

**Authors:** OK, yes, we will do so (the numbers are 1.43, 1.28 and 1.21 g/cm<sup>3</sup> in the treatments “Fallow”, “N-fertilized” and “N fertilized+straw” respectively)

## Comment 12

Table 1 – Are there field measurements available for any of these parameters? If so, how similar are they to these fixed values?

**Authors:** Yes, we didn't write it explicitly but these values in table 1 were based (with one exception) on data obtained at the study site. We will add a column to this table with the heading “Source” where we will cite the relevant studies.

See also answer to comment 4 – reviewer 1

## Comment 13

Figure 1 needs a legend to identify what the different colors/patterns of shading indicates.

**Authors:** We will add this information to the caption

*“Figure 1. Map of Sweden (**in white**) showing the location of the Ultuna Long-term Soil Organic Matter Experiment (Uppsala, Sweden) and the extent of the production area PO4 (**shaded area in grey**). Drawn by Anna Lindahl, SLU from Esri, TomTom, Garmin, FAO, NOAA, USGS”*

## Comment 14

Table 1 – Are there data references for these parameter values? If not, how did you come to these values?

**Authors:** Yes, we will give these references. We will add a column to this table with the heading “Source”

Tables – I recommend including captions for tables with relevant details.

**Authors:** We will revise the table captions giving more informative detail. For example:

*“Table 1. List of the 9 model parameters that were fixed at constant values during the calibration based on field measurements or literature data”*

*“Table 2. List of the 6 selected model parameters included in the model calibration to the Ultuna Long-Term Soil Organic Matter Experiment and their initial parameter uncertainty ranges”*

*“Table 3. List of the 15 model parameters and the input distributions used in the sensitivity analysis”*

## Comment 15

L264- What determined if the data support was sufficient?

**Authors:** This is partially a subjective decision. However, we can revise the sentence to be a bit more specific:

*“We assumed normal distributions when the **literature or measured** data was considered sufficient to support such a distribution, while uniform distributions were used otherwise (Table 3).”*

## Comment 16

Table 3 – The source “SCB Statistics Sweden” needs to be more specific. Same comment for source listed as “site data” - where are site data accessible? Year, dataset name, authors etc.

**Authors:** Yes, we will add these details

## Comment 17

L304 - 306 – Is this distinction of straw going into only mesopores and root OM going partially into micropores supported by empirical data?

**Authors:** No, it’s more a model hypothesis, although based on process understanding. We can’t see how digging or ploughing down above-ground crop residues could possibly incorporate these residues into the microporous regions of the soil where pore diameters are less than 5 microns (in this study). In contrast, roots can grow through microporous soil regions supplying both POM (on root death) and root exudates.

This hypothesis could be tested experimentally in future work with for example, the help of X-ray tomography on samples taken soon after harvest and ploughing-down of above-ground crop residues). This is however way beyond the scope of the present study.

## Comment 18

L308 – What is meant by “export of residues?” Does that mean the removal of residues by land managers?

**Authors:** Yes. In this treatment, most of the above-ground crop residues are removed. This was explained at line 217. We will replace this phrase by ... “**near total** removal of above-ground crop residues from the field”

## Comment 19

Figure 3 – This panel figure needs letters for each panel and a description of each panel and the definition of the X axes in the figure caption.

**Authors:** We feel that letters for the panels are not needed but we will give further details in the figure caption instead:

*“Figure 3. Mean model efficiencies for each simulation (i.e. parameter set) in the GLUE analysis that gave values larger than zero, plotted against the values of the six parameters included in the analysis (refer to Table 2 for parameter definitions and descriptions).”*

Figure 4 – This panel figure also needs to have the individual panels labeled/described and the axes defined in the caption.

**Authors:** We feel that letters for the panels are not needed because we don't refer to individual subfigures in the text, but we will give further details in the figure caption instead:

*"Figure 4. Inter-relationships among four (out of six) of the targeted model parameters in the calibration. Relationships are shown for the 30 best parameter sets identified in the GLUE analysis (refer to Table 2 for parameter definitions and descriptions)".*

## Comment 20

L314 – In the introduction, large mechanistic models are criticized for having uncertainty and equifinality. That was provided as justification for a simpler parsimonious model. How does that criticism relate to your finding that the simple/parsimonious model presented here has the same issue of equifinality and parameter uncertainty as the more complex models? How does this affect the usefulness of the model or its applicability compared to the larger models? Or, should this model's parameters be further simplified?

**Authors:** Please see our answer to comment 2 of reviewer 1 (also copied here)

Yes, this is a good point. It's true that even the simplest models of organic matter turnover in soil can show equifinality, depending on the type, quantity and quality of the data used to constrain them. This has been demonstrated for models that are even simpler than the one we developed and tested in our study (see e.g. Juston et al., 2010; Luo et al., 2017). We were therefore expecting to encounter the issue, as we wrote at line 233. This is also why we wrote "may" on line 48.

However, in contrast to more complex models, we can clearly see why and where the equifinality arises in our relatively simple model: it depends on the model structure, with correlations among only a few parameters, which makes the problem of parameter uncertainty more manageable. This was the case for the model application to the data at the Ultuna long-term soil organic matter experiment presented in the paper: here, simultaneous calibration to data was sufficient to effectively constrain the model parameters in three treatments with strongly contrasting inputs of OM with respect to both type and amount. This is what we concluded at lines 317-318: *"These strong correlations of  $k_0$ ,  $A_0$  and  $k_{till}$  with  $\varepsilon$  mean that, in practice, all four parameters are well constrained by the calibration"*.

In the revised version, we will clarify these issues by revising and adding to the text at lines 50 to 55:

*".... their reliability in extrapolation (i.e. prediction of independent data) has not yet been convincingly demonstrated (Garsia et al., 2023; Le Noë et al., 2023). This is because these models have often been tested against insufficient datasets (i.e. observations of topsoil C dynamics at a single site and treatment) which increases the likelihood of equifinality despite the small number of parameters (e.g. Juston et al., 2010; Luo et al., 2017). This may be overcome by simultaneous calibration of the model against data for two or more contrasting treatments, for example with respect to the type and quantity of organic matter inputs (e.g. Meurer et al., 2020) or by multi-site calibration at larger scales using data from long-term field trials at locations with contrasting soils and management practices (e.g. Juston et al., 2010; Dechow et al., 2019). Testing model predictions for entire soil profiles remains however difficult and is therefore rarely done, because fewer measurements are made in subsoils and the turnover of organic C in subsoil is very slow, so datasets will rarely be long enough to detect any changes. Additional data sources may also help to alleviate problems arising from equifinality. One possibility is to make use of ... "*

## Comment 21

L317 – What is the evidence of strong correlation? This statement needs statistical support.

**Authors:** Yes, we will add  $R^2$  and p-values in a revised version of figure 4. All four relationships are highly significant ( $p < 0.002$ ) with  $R^2$  values varying between 0.30 and 0.76.

## Comment 22

L341 – Temperate, not temperature.

**Authors:** Thanks, we will fix this

## Comment 23

Figure 5 – Can you provide a quantitative comparison of the means to support the conclusions?

**Authors:** This is a good point. We didn't attempt any statistics, simply writing that the model “*gives reasonably realistic predictions*”. In fact, statistical tests for differences between the two distributions (not just the means) show that they are significantly different, which is almost entirely due to the much larger spread in the measurements compared to the calculations, especially the occurrence of a number of outliers with large values of organic carbon contents and correspondingly small values of bulk density. This is not really surprising because the calculations do not include the effects of all factors affecting SOC and bulk density. Our guess is that the large values of organic carbon content (and small values of bulk density) correspond to locations with wet soils due to topography (i.e. flood plains, depressions). The model, as it is formulated here, does not include the effects of excess soil moisture on decomposition rates.

We will add some new text in the revised version at line 338 to explain the above.

*“A qualitative comparison with soil survey data for agricultural land in east-central Sweden (production area PO4) suggests that despite its simplicity the model estimates of steady-state SOC and bulk density in the soil profile lie mostly within the range of variation encountered in the region (Fig. 5 and Fig.6). Nevertheless, statistical tests (Z-test) show that the distributions of simulated and measured values of SOC and bulk density are different, which is almost entirely due to the much larger spread in the measurements compared to the calculations and especially the occurrence of a number of outliers with large values of organic carbon contents and correspondingly small values of bulk density. This is not really surprising because the calculations do not include the effects of all factors affecting SOC and bulk density. The large values of organic carbon content (and small values of bulk density) almost certainly correspond to locations with wet soils due to topography (i.e. flood plains, depressions). The model, as it is formulated here, does not include the effects of excess soil moisture on decomposition rates.”*

We will avoid using the word “*predictions*”, because these are the aggregated outputs of a sensitivity analysis and not model predictions that can be compared with measurements at specific locations.

## Comment 24

Figure 6 – Why are only two depths shown in this figure? (there are 3 depths in the previous figure)

**Authors:** Because we only have bulk density data at two depths, i.e. between 0-20 cm depth and 40-60 cm depth, whereas SOC was measured between 0-20, 20-40 and 40-60 cm depth (see line 281)

L357 – What are the cutoffs for NRC values to determine if they are strongly, moderately, or minimally sensitive in this analysis? I think that information should be included in the methods. In the discussion, it would be helpful to more quantitatively compare/describe the model sensitivity to these various parameters.

**Authors:** We prefer to discuss these results in relative terms and therefore we choose to present all values ordered decreasingly in Table 5 without any use of defining cut off values that may be judged to be arbitrary (the readers can also see all of the figures and apply their own criteria if wanted)

## Comment 25

L359 – The fraction of aboveground residues incorporated is roughly as important as the clay content yet it is not mentioned here.

**Authors:** Yes, we agree that it should also be mentioned. We will include a mention of  $f_{inc}$  at lines 361 to 363, alongside the other two parameters that determine the input of above-ground residues.

I'm also unclear why the clay content is mentioned before the other more sensitive parameters in the table.

**Authors:** Yes, we see your point. We mentioned the clay content here because it belongs together with  $F_p$  in that taken together they determine the extent of physical protection. We did try to explain this at line 360, but we will make this connection much clearer in the revised version:

*“The soil clay content, which **together with  $F_p$** , determines the extent to which physical protection is expressed in soils of contrasting texture, is also a relatively sensitive model parameter, **albeit to a lesser extent (Table 5).**”*

## Comment 26

L367-370 – I would be interested to see this idea expanded upon – how does this USSF model result relate back to your model result of an 8% increase in SOM?

**Authors:** It's really mostly just a consequence of the fact that it takes a lot longer than 30 years to reach steady-state after a change in OM inputs. We can add some text to explain this.

And what are the larger implications of these increases for climate change mitigation as you mention? For example, how does a 1.4% increase over the course of 30 years compare to targeted goals for mitigation?

**Authors:** This is discussed in Coucheney et al. (2024) and we refer to this study in the text. We don't think this is the right place to discuss the results from a previous paper.

## Comment 27

L379 – Here, the authors seem to consider a 4-5% reduction in SOM to be minor. But on lines 374 - 377 they seem to indicate that a 3-5% increase is significant. Some benchmarks for the relevance of these changes would be helpful for interpretation of the results.

**Authors:** Thanks for pointing this out. It is only an apparent inconsistency, because the 3-5% increase mentioned at lines 374-377 was after 30 years, whereas at line 379 we are referring to steady-state values. We will make this clearer by slightly modifying the sentence at L377-378:

*“Table 5 suggests that tillage is one of the least sensitive factors affecting **steady-state** SOM stocks “*



## Comment 28

L381 – Haddaway et al. found a difference by tillage intensity in the topsoil, as opposed to what is stated here. Intermediate intensity tillage resulted in greater SOC stocks than the high intensity tillage in that metanalysis.

**Authors:** This seems to be a misunderstanding. We did write that Haddaway et al. found greater stocks of C in the topsoil under no-till. However, we also wrote that they did not find any difference in total C stocks in the profile between no-till and intensive or intermediate tillage systems, which is also true. We will slightly revise the sentence:

*“... Haddaway et al. (2017) and Meurer et al. (2018) found larger SOC stocks under no-till compared with conventional tillage in the topsoil, but no overall difference in total SOC stocks in the soil profile down to 60 cm depth.”*

## Comment 29

L385 – It would be helpful to include empirical data supporting these model data on the figure for comparison with the model data. Or include the empirical data in a table caption.

**Authors:** We would prefer not to modify the actual figure to show data from other studies. This is partly because a direct comparison of predictions for a region in east-central Sweden with measurements from a highly diverse global dataset like Chen et al. (2020) could give readers a misleading impression. In addition, the raw data on MRT from the study by Poeplau et al. (2021) are not available to us. The value quoted in the paper at line 339, “ca. 20 years” was taken from a table in the paper (table 1). In the revised version of the paper, we will also add the values reported by Chen et al. (2020) for cropland to this text, as this data is available. In doing so, we will also slightly modify the text at lines 341 to 342: *“... and they also lie at the high end of the range reported by Chen et al. (2020) for cropland (mean = 9.5 years, standard deviation = 6 years; n = 217).* We feel this is better than adding these numbers to the figure caption.

## Comment 30

Table 5 – It looks like this table was color coded according to the colors of the groups in table 3. That information and the meaning of the colors should be included in the caption.

**Authors:** Yes, that’s right. However, we have been advised by the editor that we must remove this colour coding in the revised version of the paper.



## References cited (in answers to both reviewer 1 and 2)

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