Response to Anonymous referee #1

The authors have incorporated most of the suggestions in this review. However, after reviewing the tracked changes and the responses, several items still need further clarification.

We thank the reviewer for their comments and acknowledging our efforts to improve the manuscript during the previous round of revisions. We have carefully reviewed and responded to the reviewer's additional feedback, summarized item-by-item below. We hope our responses and manuscript improvements will meet the reviewer's expectations.

- The comment on lack of the model comparison against the observational data has not been addressed. Although the authors state that model experiments are based on laboratory studies, they do not include these studies.

We would like to clarify that only the Q_{10} values for the Km of depolymerization are based on the laboratory study by Allison et al. (2018). We dedicated a complete section of the manuscript (Section 2.3) explaining the choice and rationale for these chosen parameter values. The laboratory data from these enzyme assays are published by Allison et al. (2018). Since these results are not generated by us, we feel it is inappropriate to report them in our manuscript beyond what is already written in Section 2.3.

If the reviewer uses the term "model experiments" to refer to the temperature and moisture experiments, we clarify that we did not state anywhere that these are based on laboratory studies, but on findings reported by Soong et al. (2020) and Berg et al. (2017). The different model experiments for our study are summarised in Table 2, and in the manuscript we clearly motivate the choices for the temperature and moisture changes:

- For temperature (L. 255 – 257): "*We chose a 4.5 K step increase for soil warming, because soils, including the deep soil up to 1m, are expected to warm by 4.5 K by the end of the century under representative concentration pathway (RCP) 8.5 (Soong et al., 2020).*"
- For soil moisture (L. 268 – 277): "*Soil drying is expected for most of the globe (Wang et al., 2022b and references therein), but drought intensity is uncertain and may vary locally (Cook et al., 2020; Hsu and Dirmeyer, 2023). Soil moisture change projections are very uncertain: 60 projected global lateral and vertical distributions of future soil moisture were highly diverse in their predicted lateral and vertical distributions (Berg et al., 2017). The multi-model mean of this study showed reductions in subsurface and deep surface soil moisture up to 30% by the year 2100. Given the large divergence between these model projections, we chose to simulate drought by reducing the depth-specific soil moisture values from the forcing dataset in steps of 10%, to be able to compare the effects of a relatively mild versus increasingly stronger droughts on SOC stocks. Specifically, we compared three drought scenarios, where the model's ambient SM inputs are reduced by 10%: Each ambient SM value is multiplied by 0.9, 0.8 or 0.7, respectively (Table 2). As with the warming experiment, the original seasonality in the ambient SM input values is kept intact.*"

Furthermore, independent of prior model evaluations, incorporating such comparisons in the current study would elucidate any improvements or drawbacks of the model relative to earlier versions and observational data. I recommend that the authors revise this aspect to include appropriate comparisons of SOC and/or respiration rates, wherever available. A further analysis detailing the benefits of this study over previous ones, particularly regarding how depolymerisation rates are influenced by temperature and soil moisture, is advised.

We respond to this feedback in several smaller sections, where we break down and quote the reviewer's points in italics:

1) Improvements or drawbacks of the model relative to earlier versions and observations:

We clarify that the JSM model has been previously published and calibrated (Yu et al. 2020; Ahrens et al. 2015, 2020) and refer to these studies often throughout the manuscript. This published model version represents the 'ambient model run' in our manuscript and is used to evaluate the impacts of the different moisture and temperature sensitivities of microbial depolymerisation rates on the SOC pools. We have made this aspect more clear in the manuscript by changing the title of Section 2.4 to "*ambient model run and model experiments*" and including additional information in L. 248 – 250:
"*This ambient model run represents the published C-cycle version of JSM with its default settings (Yu et al. 2020), so that the results of the model experiments with varying temperature and moisture interactions can be evaluated against this default.*"

JSM belongs to the new generation of models that explore SOM decomposition with explicit representations of microbial controls on decomposition and stabilisation of SOM through interactions with mineral surfaces, rather than using empirical representations of SOM turnover. The equations and parameter values in JSM are based on our current scientific understanding and insights from data-driven studies as much as possible and we cite these studies in the Methods section and Table 1. To our knowledge, no other model incorporates distinct temperature and moisture sensitivities for the different SOC decomposition processes. This in itself makes our study with JSM extremely novel and beneficial over previous ones. With JSM, we individually assign and study these intrinsic temperature and moisture sensitivities and their effects on SOC decomposition under different climate change scenarios.

2a) *Further analysis detailing the benefits of this study over previous ones, particularly regarding how depolymerisation rates are influenced by <u>temperature</u> and soil moisture:*

The temperature sensitivity of Vmax has been successfully implemented in JSM before by Ahrens et al. (2020), but a completely novel aspect of our study is the exploration of the individual temperature and soil moisture sensitivities of the depolymerisation rates through the half-saturation constant for depolymerisation (Km_X in Eq. 1). In the manuscript we thoroughly evaluate the temperature sensitivity of Km against the already published model implementation (Yu et al., 2020, ambient model run) which is equal to $Q_{10,Km}$ = 1.0. For these model experiments, the only newly added parameters in our manuscript are $Q_{10,Km,P}$ and $Q_{10,Km,R}$, (Table 1, Table 2), which represent the temperature sensitivities of the half-saturation constants for the depolymerisation of the polymeric litter pool and microbial residues pools, respectively. Our choice for these two parameter values is, like all other parameters in JSM, process-based as much as possible and therefore taken from literature.

In this case, the values are based on a recent laboratory study using enzyme assays by Steven Allison et al. (2018).

2b) *Further analysis detailing the benefits of this study over previous ones, particularly regarding how depolymerisation rates are influenced by temperature and soil moisture:*

The moisture dependency of Km was implemented into JSM by Yu et al (2020), but has not been evaluated extensively (Ahrens et al., 2015, 2020; Yu et al. 2020, 2023). We evaluate the effects of this moisture sensitivity against this previously developed version (ambient model run) in the drought experiments, where the Q10 value of Km is kept at 1 (no sensitivity). We show that these moisture effects through Km are particularly important in the subsoil, when microbial biomass is low and effects of mineral sorption are strong, which is important for future model developments that consider microbial dynamics, microbial interactions, and vertically explicit SOC pools.

3) Include appropriate comparisons of SOC and/or respiration rates, wherever available:
We would like to reiterate from the previous response, that comparing the model results to measured C content or respiration rates can only be done for past simulations (i.e. the ambient model run), and that such a comparison would not help interpret the results from the perturbation experiments. We clarify that our study serves as a testbed for the various model experiments regarding the intrinsic and apparent temperature and moisture sensitivities of microbial depolymerisation rates. A model like JSM, however, needs climate and litter inputs for its simulation, and instead of generating a synthetic input dataset, we chose Hainich forest because it is a representative example for a forested site on mineral soil in temperate climate. We revised the manuscript to better clarify this (L. 194 – 196): "*JSM requires depth-specific soil temperature, soil moisture and litterfall forcing data at a half hourly time step as input. Following Thum et al. (2019), these soil forcing data were generated for a temperate forest site in Germany as a realistic testbed for in-silico model experiments (Hainich, DE-Hai)*".

Additionally, we discuss and compare the outcomes of our model results against other relevant studies throughout Section 4. Specifically, we discuss the 1) Warming experiments, by comparing our results to other modelling studies (L. 400 – 401) and field studies (L. 401 – 403); and 2) Drought experiments, by comparing our results to other modelling studies (L. 471 – 473) and the very few existing field studies (L.489-501); and 3) Warming & drought experiments, by comparing our results to other modeling studies (L. 510 – 514).

Lastly, we present an explorative modeling study, which showcases the potential impacts of soil warming and drought on SOC stocks along a vertical soil profile. Along this vertical gradient, the interplay between C substrate supply, microbial biomass and mineral sorption changes, which results in different responses to soil warming and drought between the top- and deeper surface layers. As such, we do not report bulk soil fluxes and SOC stock changes in the manuscript, but the relative changes of the different SOC pools at different depths (as % change per year since the start of the experiment) in response to the experimental soil moisture and temperature perturbations. This normalisation was done deliberately, as it allows us to independently compare the effects of the temperature and soil moisture interactions between the model runs.

- The decision to disable the vegetation response to moisture and temperature is questionable. The response of vegetation influences the type, decomposability, and quantity of plant material contributed to the soil, which in turn affects SOC input.

JSM is a stand-alone model, where the litter inputs are generated beforehand by the land surface model QUINCY (described in Section 2.2). We want to reiterate from the previous response that keeping the litter inputs the same for each model experiment is a deliberate choice for this study, and actually a feature rather than a "bug". We mention this in the manuscript's discussion (L. 501 – 503): "*An advantage of our stand-alone soil model environment with prescribed litter inputs is that it allows us to individually test soil warming and drying effects on long-term SOC stocks, while eliminating the potentially confounding effects from changes in plant productivity.*"

Within the current study, the interactions between temperature, soil moisture, mineral stabilisation mechanisms and microbial biomass are already highly non-linear. Adding another major feedback by also changing plant litter inputs over the 100-year simulation period would hide the isolated effects that soil warming and drought can have on SOC stocks. Furthermore, while it is true that the multitude of feedbacks between plant productivity and thus litter production and soil conditions are important, the processes regulating these feedbacks are not so well known that everybody would agree on their model description. In other words, we would need to make many additional assumptions. Overall, we acknowledge that this would be an interesting and important study, but indeed a large and separate study in itself, and therefore falls outside of the scope of this paper. We do discuss the option for a combined vegetation-soil simulation, i.e., where plant productivity simultaneously changes in response to soil warming and drought, in L. 566 – 572 of the manuscript. The option to repeat this study within a coupled plant-soil model framework will be available in the near future, once JSM is fully coupled with the land surface model QUINCY.

Furthermore, the manuscript still lacks an adequate description of the diffusion and advection processes shown in Figure 2. It is essential to explain how they work concerning soil carbon fluxes following the line 215 in the revised version and further elaboration in the discussion. Moreover, the vertical processes described are inadequate to understand how model includes the interaction between the top and bottom layer of the soil.

Following the suggestion of the reviewer we added the following vertically explicit process descriptions to the methodology in section 2.2 (Vertical process presentations in JSM):

- The buildup of the organic layer and the additional downward advective C flux this creates;
- Bioturbation fluxes;
- Vertical DOC transport from percolation.

Specifically, we add (L. 188 – 192):
"*In JSM, all pools are transported via bioturbation according to the formulation by Jarvis et al. (2010) as a diffusive process whose diffusion coefficient decreases as a function of bulk density. The DOC pool is additionally transported via an advection velocity which represents the water mass flow between soil layers. A special feature of JSM is the vertically continuous modelling of potential organic layers and mineral soil layers via an additional advective transport term that accounts for the accumulation and decomposition of organic matter on*

top and within the soil profile. This ensures that the buildup of organic matter, for example in the form of an organic layer, leads to a concurrent decrease in the mineral soil volumetric fraction and thereby the sorption capacity qmax. For a full description of JSM, a reference is made to Yu et al. (2020)."

We also carefully revised section 4.1 of the discussion to better highlight the role of transport (L. 410 – 415):
"*The increase in the proportion of MAOC is partly driven by the advective transport term that represents the downward displacement of mineral matrix and SOC when organic matter builds up in organic layers but also within the soil profile. The lower SOC concentrations with increasing soil depth lead to a higher proportion of soil volume occupied by minerals compared to organic matter. The higher mineral soil volume thereby provides higher sorption capacities qmax. Adsorption rates in the subsoil are consequently higher than in the topsoil since qmax is farther from saturation.*"

- The authors' focus solely on the first 50 cm of soil, while noting that the lower layers have not reached equilibrium, is concerning. Stating similar pattern observed at depths of 50-100 cm requires further clarification to ensure credibility.

We believe that there is confusion on the importance of steady state for the study. Steady state in the ambient run and as a starting point for our experiments simply facilitates interpretation: we start from steady state for the experiments and stay at steady state for the ambient run (dark blue line in Figure 3, for details on steady state confirmation see our reply below). If we did not start from steady state conditions, there would be an additional confounding factor to disentangle in each model experiment.

In the lower soil layers, it simply takes more time (and hence significantly more computational resources) than 500 spinup years to reach equilibrium.

- Regarding the assessment of steady-state conditions, the authors should provide supporting documents, such as results from the spin-up phase. The claim that steady-state conditions were achieved for each run is not evident in Figure 3, nor convincing overall. Authors are urged to include supporting documentation, such as report from log files, to substantiate this claim.

We think confusion may have arisen from poor phrasing in lines 240 - 242 of the previous manuscript and we corrected this (L. 251 – 253 and L. 297 – 299, see below). We do not claim that steady state was reached after 100 simulation years *at the end of our model experiments*.

Our steady state claim only applies to the beginning of the experiment so that we start each model experiment at steady state condition, i.e. immediately after the 500-year spinup phase.

The manuscript already contains 'supporting documents, such as results from the spinup phase' as requested by the reviewer: The results from the spinup phase are fully presented in the paper as the ambient model run (dark blue line in Fig. 3), where spinup conditions simply continue for another 100 simulation years. Steady state for the ambient run is clearly evident from visual inspection by the absence of a slope in the dark blue line, but also by the statistical evidence we provide: we tested with a simple linear regression on the slope of the change in the SOC pools for the ambient run between simulation year 0 and simulation year 100, which showed no significant deviation from 0.

This was tested in R, using the linear model “lm” (y = *ax* + *b*). For completeness we include here the result of the regression test for % SOC stock changes (y) in the ambient run over 100 years (x) between 0 - 50 cm depth, corresponding to the blue line in Fig. 3a:

```
lm(formula = y ~ x)

Residuals:
     Min       1Q   Median       3Q      Max
-0.11457 -0.05263  0.02249  0.05477  0.09216

Coefficients:
               Estimate Std. Error t value Pr(>|t|)
(Intercept)   0.0566782  0.0115585   4.904 3.69e-06 ***
y$x 0.0002990  0.0001997   1.497    0.138
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Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.05851 on 99 degrees of freedom
Multiple R-squared:  0.02214,   Adjusted R-squared:  0.01226
F-statistic: 2.241 on 1 and 99 DF,  p-value: 0.1376
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which shows an extremely low estimate for the slope (*a,* 0.0003 % change in SOC stock per simulation year), which is not significant and thus confirms the slope of the relationship approximates 0. There is a very small but significant bias in the estimated intercept (*b)* of 0.0567%. As such, we tested the linear model again but forcing the intercept *b* through 0 (y = *ax* + 0): the estimated slope (*a*) would be then 0.00114% SOC per simulation year (significant, P < 2e-16), which effectively means that under ambient conditions, SOC stocks between 0-50 cm would increase by ~1% after 1000 simulation years.

To avoid further confusion we changed:
1) L. 251 – 253 in the methods section of the manuscript to “*To ensure that all model experiments started from steady state conditions, we verify that the SOC pools between 0 - 50 cm depth reached steady state after the 500-year spinup period by applying a simple linear regression on the slope of the change in SOC pools for the ambient model run.*”
2) L. 297 – 299 in the results section of the manuscript to “*The ambient model run was conducted as a reference to compare our model experiments to. To check whether JSM reached steady state after spinup, a linear regression test confirmed that the first 6 soil layers of the ambient model run (0 - 50 cm) are in steady state, as there is no SOC loss or accumulation over the complete simulation period (Fig. 3, dark blue).*”

Other modifications to the manuscript
During the revisions we found and corrected a few minor spelling and grammar mistakes, and a small mistake in Eq. 3, which are visible in the tracked changes pdf file. In-text positions of the tables and figures were slightly shifted so they would not span across

multiple pages while making efficient use of page space, but their contents are identical to the previously submitted manuscript.

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