Response to Anonymous Referee #1

The study by Pallant et al. aims to investigate the interactions between microbial depolymerization and climate change, specifically the influence of temperature and moisture on SOC decomposition and the differential response of soil layers to warming and drought, using the JSM model. Despite the study's promising title and significant potential contributions to future SOC research, it falls short in several key areas, preventing it from being a comprehensive study. In its present state, it seems incomplete, suitable at best for a sensitivity analysis within a broader, more thorough investigation. I recommend withholding publication until substantial improvements are made.

We thank the reviewer for taking the time to read and comment on our manuscript. Below we provide detailed comments to the reviewer's questions and suggestions, and describe the planned improvements for the updated manuscript. We apologise for the apparent mismatch between the title and the content, and will adjust the title for the updated manuscript. Additionally, the updated manuscript will have clearer descriptions of the study's objectives, novelty and scope, in line with our response to the comments and suggestions of the other anonymous reviewer.

General comments:

The title's implication of a drought-focused study misaligns with the content, which predominantly consists of sensitivity tests devoid of any empirical assessment. The absence of observational data reduces the study to hypothetical model outputs, with an overemphasis on parameter sensitivity to temperature and moisture.

We regret the apparent mismatch between the title and the content, and will adjust the title to "Modelling climate-substrate interactions on soil organic matter decomposition with the Jena Soil Model" so that it better reflects the paper's scope.

This is indeed a modelling study with a strong focus on the sensitivities of depolymerisation rates to changes in temperature and soil moisture changes. These are processes that have partially been overlooked in dynamic modelling studies before, in particular the soil moisture impact. In this work, we aim to study the effect of these temperature and moisture sensitivities parameterized based on data from a lab study by Allison et al. (2018). While JSM is a relatively new model, the processes and parameters for JSM and its predecessor COMISSION have been successfully tested against observations for various applications by Yu et al. (2020, 2023), Ahrens et al. (2015, 2020), and Fleischer et al. (in prep, but see https://meetingorganizer.copernicus.org/EGU22/EGU22-11276.html). Making frequent reference to these existing studies, we are not conducting additional comparisons between model outputs and observational data in this study. It also would be difficult to do here, since e.g. available respiration data would only cover the first few years of the simulations for the experiments, and SOC measurements from warming/drought experiments would be highly impacted by changes in plant productivity (litter inputs). A discussion of this study limitation is already part of the original manuscript.

This study also overlooks other crucial dynamics in SOC, such as diffusion and advection, which could significantly influence SOC distribution within soil columns and thus its response to soil temperature and moisture changes. The omission of factors like soil texture and vegetation dynamics further limits the study's scope.

JSM as it was applied in this study already includes the above-mentioned processes, which are described in Yu et al. (2020) and Ahrens et al. (2015, 2020). Diffusion, advection, and soil texture are all considered by the model. Soil texture influences soil moisture and water fluxes but also the sorption of DOM and microbial residues via the maximum sorption capacity, Qmax. For the sake of brevity, these are not described in detail in this manuscript, but we will mention the inclusion of these processes in the methodology section in the updated version of this manuscript. The aim of our study is to investigate in detail the effects of interacting temperature and moisture sensitivities in a dynamic Michaelis-Menten term. To our knowledge, this has not been done before in a comprehensive manner and this warrants an in-depth modelling study. This novel aspect of our study will be better highlighted in the introduction of the updated manuscript.

To fit the objectives for this study, we made the conscious choice to not have an active response of the vegetation to moisture and temperature changes and use constant litter forcing files over time, to be able to pinpoint the changes in modelled SOC dynamics in response to the climatic drivers in isolation from those driven by changes in litter inputs.

The introduction should be revised to avoid methodological details and instead provide a comprehensive overview of the factors controlling SOC dynamics. Additionally, the methodology does not adequately discuss SOC discretization or the interplay between the topsoil and subsoil layers.

We feel that a comprehensive overview of the factors controlling SOC dynamics falls beyond the scope of the introduction, since we want to focus on the interplay of soil temperature and soil moisture sensitivities in a microbial-mineral model at different soil depths. We will add details on processes that are regulated by temperature and moisture and refer to previously published work with JSM for other controlling factors of SOC decomposition that are beyond the temperature and moisture sensitivity scope of this manuscript. We agree with the reviewer that the methodology section should include a more thorough description of the interplay between top and subsoil layers. This will be changed in the updated version of the manuscript, where also the descriptions of SOC advection and diffusion mentioned in the previous comment can be included.

I have confined my comments to the methodology section because the paper's foundation needs strengthening before the results and discussion can be meaningful.

Specific comments:

L20: Clarify the term "long-term" to provide proper context.

We change to "We find that soil warming leads to SOC losses after 100 simulation years"

L20: Define "SOC-specific Q10" to elucidate its relevance to the study.

We clarify this in the abstract by addressing the Q10Km value for plant litter (1.3) and Q10Km for microbial necromass (0.7) in the abstract. These two Q10s have opposing effects *on decomposition and interact with the amount of microbial biomass via the Michaelis-Menten term. This introduces a different sensitivity between topsoil and subsoil as microbial biomass decreases with the amount of root litter inputs and advective and diffusive transport inputs which decrease with depth.*

L21: Distinguish between "reduce" and "accelerated" processes to prevent ambiguity.

We rephrased to: We find that soil warming increases maximum depolymerization rates, but depending on the share of plant litter and microbial biomass, these increased maximum depolymerization rates can be in full effect when microbial biomass is high, as in the topsoil or microbial necromass makes up the majority of SOC (accelerating Q10KM). On the other hand, SOC through increased maximum depolymerization rates are reduced when microbial biomass is low or plant litter makes up the majority of SOC (decelerating Q10).

L23: Replace "SOC gain" with "SOC accumulation" to accurately reflect changes in SOC cycling during different environmental conditions.

We rephrase to SOC accumulation

L24: When using the term "decomposition rate," additional details should be provided for clarity. It might be preferable to use "SOC loss" for simplicity and better understanding.

We rephrase to SOC balance instead of SOC loss, since it can be both a SOC gain or loss.

L25-26: You need to be clearer. Maintain consistency in the comparison of temperature and moisture effects on both topsoil and subsoil.

We rephrase to "In this study, we show that while absolute changes to the SOC balance in response to warming and drought are highest in the topsoil, SOC in the subsoil is more sensitive to these changes due to the intricate interplay between Km, temperature, soil moisture and mineral-associated SOC."

L28-29: These assertions require supporting references for validation

We add the missing references and include Fan et al. (2022), Crowther et al. (2019) in the first part, as well as Davidson (2020) and Kirschbaum (2006) in the second part.

L34-35: The phrase "most important" is subjective and should be reworded to reflect that soil temperature and moisture are significant controlling factors. This section would benefit from an expanded discussion on the key factors that regulate soil dynamics.

We agree the wording can be perceived as subjective and rephrase to "Soil temperature and soil moisture are significant controlling factors of microbial decomposition rates, and thereby the carbon turnover rate of soils (Davidson and Janssens, 2006; Moyano et al., 2013; Yan et al., 2018)*." Additionally, we put higher emphasis on the importance of SOC stabilisation on mineral surfaces as another important factor. In this section (lines 33 - 37), we emphasise the most important factors that fall within the scope of this study.*

L35: Clarify the term "de(stabilisation)" for better understanding.

We include “microbial SOC decomposition, and adsorption and desorption of SOC.”

L37-39: Reformulate these lines for enhanced clarity and readability.

We apologise for unclear wording and rephrase to “Given the importance of SOC stocks and their sensitivities to climate change, a better understanding and representation of these complex interactions in models is extremely important for a better understanding of the carbon-climate feedback”

L41: Specify the models referred to in this line.

We rephrase to “Tang and Riley (2019) showed that the microbial depolymerisation rate can be described using reverse Michaelis-Menten (MM) kinetics.”

L43-80: Shift the detailed methodological exposition to the methods section, using the introduction to provide a broader overview.

This simple description of the reverse Michaelis-Menten kinetics with equations and the conceptual figure is a key component of the introduction. To our knowledge, previous works have primarily focussed on the temperature sensitivities of Vmax (or the apparent sensitivities of (heterotrophic) respiration rates). The novelty of our study is the focus on the temperature and moisture sensitivities on depolymerisation rates through the half-saturation constant (Km), which to our knowledge has not been shown in a modelling study before. As reverse Michaelis-Menten kinetics (compared to forward kinetics) may be less known to the readers of Biogeosciences, we think the equations and conceptual figure help clarify why microbial depolymerisation rates can both increase or decrease in response to soil warming and drought/soil wetting through Km, especially at low microbial biomass concentrations.

L83: A reference is missing and should be included.

Many studies have shown this, but we refer to the recent comprehensive review on deep soil carbon by Hicks Pries (2023).

L88: What about peatlands? Inclusion or exclusion of them would significantly change your findings. It is important to note that the moisture function, decomposition term, and vertical dynamics of SOC distinctly vary in wetland environments.

Yes, this is definitely true for peatlands, and the traditional empirical model approaches we refer to here also don’t describe SOC-moisture-temperature dynamics in these ecosystems very well (or even do consider them at all, see e.g. Chadburn et al. (2022)). Our results are for a mineral soil profile, so we feel explicitly discussing peatlands in the introduction falls outside of the scope. We will mention that our modelling approach covers upland mineral soils in the introduction. Peatlands and their different moisture dynamics, however, are briefly discussed at the end of Section 4.4.

L95-99: Avoid repeating information from the methods section to streamline the text.

We will remove and/or move redundant information on JSM.

L113: Incorporate the previously mentioned introductory information here for coherence.

As mentioned in the earlier comments above, we will include additional information for JSM on the processes of diffusion, advection, and soil texture, with textual edits and an update of Fig. 2 and its caption (see comment below on L116).

L115: Briefly explain each parameter, including those in Table 1, and cite the source of the formulations. Additionally, explain the rational for such formulation for DOC?

This formulation describes the depolymerisation of litter and microbes to DOC. Hence, it is not a formulation for DOC. The formulation is based on the derivations by Tang and Riley that we mentioned in the previous sentence. We apologise for the unclear language and rephrase.

Eq1: For this and all subsequent equations, it is necessary to specify the units of the calculated flux. Additionally, clarify if any conversions were performed to derive these units from the parameters listed in Table 1.

We will add the units of all fluxes defined for Eqs. 1 – 7 and apologise for some small typesetting mistakes we found in the superscript of the units in Table 1.

L116: Although the layered structure of the soil has been mentioned and is depicted in Figure 2, there is a noticeable absence of any depth indicators in the equations or in the estimations provided.

We will add a clarification in the methods section to explain that all C pools and forcings are functions of time and depth, e.g. Tsoil (t,z), $C_B(t,z)$*. In addition, this will be made clear in the updated Fig. 2.*

Figure 2: The figure needs to be revised for clarity, including an explanation of the brown arrows and a clear differentiation between soil pools and depth indicators.

We will revise Fig. 2: The brown arrows represent the above and belowground inputs. We separate these labels into 'aboveground litter' and 'root litter', and move the label for the belowground arrows (root litter inputs) to the left. Every model pool is present in each depth. We clarify in the caption that this is a vertical model structure and the pools are just zoomed in for one layer as an example.

Table 1: Complete the table by labelling parameters that lack units as "unitless." Additionally, is there a reference for the parameter R that can be provided?

R, the universal gas constant, is not a parameter but a well-known constant, as mentioned under Eq. 5, L.139. We report the universal gas constant in J K^{-1} mol^{-1}*, adhering to the journal's use of standard SI units. We add 'unitless' to Table 1 where applicable, and also update the heading from "Parameter"to "Parameter/constant" for clarity.*

L145: The nutrient dynamics have a significant influence on uptake and other soil processes. While you state that the model accounts for nutrients, there's a missed opportunity to thoroughly explore and discuss this aspect within the current study.

We focus on one novel aspect in this study: the interaction of soil moisture and soil temperature sensitivity of a dynamic Michaelis-Menten term. We add a discussion on how *microbial carbon use efficiency (CUE) may be temperature sensitive. Carbon use efficiency is one major process that can be influenced by nutrients and temperature. The temperature sensitivity of CUE is, however, not well described empirically and even less so the moisture sensitivity of CUE. Extending this work by including nutrient dynamics and its temperature and moisture sensitivity leads to a path far outside the domain covered by our study's model approach.*

L147: Consideration of root distribution across various soil depths is missing. An analysis of how roots are spread throughout the soil profile could offer valuable insights into soil dynamics.

We apologise for not clearly communicating that we consider root distribution across various root depths (see revised Fig. 2). The root distribution is the main factor for different microbial biomass levels in different depths (Ahrens et al., 2020).

L153: Include the sorption/desorption equation to complete the methodological description.

Sorption and desorption are clearly described in Ahrens et al. (2015, 2020), which we refer to here. While checking this sentence we found a small mistake in the description of the activation energies, which we intend to correct: All Q10 values used in this study are based on literature, and not calibrated.

L184: What do you mean by first model run? Explain the rationale behind the first model run and the selection of a 100-year period.

We rephrase this section and start by describing the spin-up and then the 'first' model run, which is now labelled as the ambient model run to be consistent with the rest of the manuscript.

L185: The decision to focus solely on the 0-50 cm soil layer raises questions. Should processes like advection or diffusion be considered, the entire soil column to its maximum depth would likely experience changes during the spin-up period. Why then, is the analysis limited to this specific depth range?

The processes of advection of DOC and diffusion to represent bioturbation are considered in JSM. In JSM, there are 15 soil layers, of which 6 layers between 0 and 50 cm depth, and we will make this more clear in the methodology section. These 6 layers experience the strongest influence of transport. Soil layer thickness increases with increasing soil depth, at the following depth intervals: 0 – 6, 6 – 13, 13 – 20, 20 – 26, 26 – 36, and 30 – 50 cm. So we did not focus on only one layer between 0 – 50 cm, but compared the processes in the vertical profile setting with multiple soil layers. By comparing a shallow and a deeper layer, we were able to look at the differences along a gradient of microbial activity – the majority of microbial activity and the resulting heterotrophic respiration flux takes place in the upper soil layers. Additionally, the difference between the shallow and deeper layer illustrate the effect of decreasing root litter inputs with depth.

JSM also provides model outputs below 50 cm, which were checked but not shown in the manuscript. These deeper soil layers indeed take many years to reach equilibrium, as the reviewer points out. So another, more practical reason for choosing to focus on the layers *until 50 cm depth is that this significantly reduces the necessary model spin-up time and thereby the use of computational resources. Despite these layers not being in steady state after spinup period, we did check the patterns in the layers between 50 and 100 cm depth and found they are similar to what we show in the manuscript. We also found that for the drought and warming experiments, these deeper layers needed more than 100 simulation years to reach a new steady state after disturbance, but they did eventually reach it.*

L186: Detail the approach used to assess steady-state conditions.

We used a linear regression model to check the steady state assumptions and will mention this in the methods. It is also visually very clear from the model results, e.g. in Figure 3.

L189: Clarification is needed on the term "all ambient soil temperature." Does this refer to temperatures at every soil depth? Moreover, to isolate the impact of temperature alone, it would be necessary to perform simulations with varying temperature and moisture, and then compare these to simulations with only temperature variation to accurately determine temperature sensitivity.

We apologise for unclear wording. Temperatures are depth-specific, which will be better clarified in the methods section. These depth-specific temperatures were increased by 4.5 K for each depth. Similarly, the depth-specific moisture values were decreased by 10, 20 or 30% in the different drought experiments. We did consider the isolated effects of soil warming or drought by including model experiments where either temperature or soil moisture was kept at its original, depth-specific input values.

L194-196: Justify the chosen experimental values.

The full justification for these values was provided in the original manuscript in lines 166-183, under a separate section of the manuscript titled “2.3 Choice of Q10,Km values for polymeric litter and microbial residues‘’. In short, the values are based on a lab study on the temperature sensitivities for different enzymes involved in the breakdown of soil carbon substrates (Allison et al., 2018). The Q10,Km value for the depolymerisation of litter was based on measurements for the enzymes β-xylosidase and total oxidase, and the Q10,Km value for the depolymerisation of microbial residues was based on measurements for the enzyme leucine aminopeptidase.

L201: What was the rational for 10% changes and why only between 0.9-0.7 values?

We apologise for not clarifying this in the methodology section. Part of the rationale was somewhat hidden in the introduction, and we will restructure the document and state the rationale in L201. We used the following rationale:

For projected soil moisture changes there is much uncertainty in model projections: 60 projected global lateral and vertical distributions of future soil moisture are highly diverse both in the predicted spatial and vertical distributions of future soil moisture (Berg et al., 2017). We chose the strengths of the drought intensity (up to 30% reduction in SM) based on the ranges of Berg et al. (2017) Figures 3 and 4, showing the multi-model mean and medians for subsurface and deep surface soil moisture changes by 2100. Given the divergence between models, we chose to simulate drought by simply reducing the depth-

specific soil moisture values from the forcing dataset. We chose 10% changes for clarity, to be able to compare the effects of a relatively mild versus increasingly stronger droughts.

L210: Confirm whether equilibrium was reached after 100 spins and discuss mass balance and steady-state conditions for each run.

We used a linear regression model to check the steady state assumptions and expand the text describing the steady-state check in the methodology (section 2.4). Mass balance checks are performed in the QUINCY-JSM model code, and for every run we have log files showing that the mass balance is closed. Furthermore, the QUINCY-JSM model is part of the EucFACE-MIP data-model comparison project, and a reference (in revision with Science Advances) to the detailed descriptions of the mass balance checks for C, N and P is:
Title: Carbon-phosphorus cycle models over-estimate CO_2 enrichment response in a mature Eucalyptus forest

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L216: The mention of R packages is less critical than a thorough analysis of the outputs. Consider focusing on the methods to output evaluation here.

We expand this section with a short description of the smoothed curve shown in Figures 3-5 which visually support the data points plotted for the 100 simulation years. We strongly feel that the mentioning of R packages with citations are important and should remain part of the manuscript, as we are grateful to the many (scientific) open source software developers for their important contributions, and acknowledge this by crediting their work with citations.

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