Response to comments

Paper #: *GMD-2023-114*
Title: *Modeling biochar effects on soil organic carbon on croplands in a microbial decomposition model (MIMICS-BC_v1.0)*
Journal: *Geoscientific Model Development*

<u>Reviewer #1:</u>

Comment #1

The authors adapted and modified MIMICS model to simulate cropland SOC and the effects of biochar application on cropland SOC. Although some of the processes implemented remain empirical and largely relies on parameter tuning (e.g., the nutrient enriching effect of BC application is simulated through linking BC application rate to the turnover factor rather than changing the C:N ratio of SOC), the development of MIMICS seemed reaching reasonable improvement in simulation results and could fit for the authors' further purpose for model application.

Response #1

We thank the reviewer for the positive comments. Please see the detailed point-by-point response below.

Comment #2

I have just one general comment except for the following minor comments: some of the justifications on why the three aspects (MIC density-dependent process, adsorption and soil moisture) were selected for model improvement in the introduction would be better.

Response #2

We thank the reviewer for the positive comments. Please see the detailed point-by-point response below. The three aspects were selected by reviewing articles related to the MIMICS modeling. We have explained the selection of the MIC density-dependent process on **Line 56-58** in **Introduction**: "The microbial interactions at the community level (e.g., competition) play a crucial role in controlling SOC dynamics, but they are usually omitted in microbial models (Georgiou et al., 2017), resulting in unrestricted growth of microbial community size with more carbon input which is unrealistic (Buchkowski et al., 2017; Wieder et al., 2013).". We added sentences on **Line 63-66** in **Introduction** to justify why the three parts were selected: "The availability SOC is influenced by the adsorption process (Michalzik et al., 2003). Some adsorption kinetic equations, such as the Langmuir isotherm, have commonly been employed to depict the adsorption/desorption process. However, the MIMICS model lacks consideration of the adsorption process, thus not effectively elucidating its role in stabilizing SOC." and **Line 70-80** in **Introduction** as: "In previous MIMICS versions, an implicit or explicit density dependent turnover was introduced (Wieder et al. 2015; Kyker-Snowman et al. 2020; Zhang et al., 2020; Georgiou et al. 2017), which cause an increase in biomass turnover with increasing microbial community size reflecting increasing pressure from competition for other resource other than carbon (e.g. space) and virus infections (Jansson and Wu, 2023), and a water scalar was used to represent the soil moisture effects (Wieder et al. 2019). The inclusion of density-dependent microbial turnover rate improved the accuracy of predicting SOC at the global scale compared to MIMICS without it and eliminated the correlation between simulated biases and input of annual litterfall (Zhang et al., 2020). MIMICS with soil water modifications showed comparable predicted global soil carbon stocks compared to other models, but to what extent soil water influences SOC turnover remains uncertain (Wieder et al., 2019). Therefore, based on these theories and model limitations, it is necessary to integrate the three aspects (density-dependent microbial turnover rate, adsorption/desorption processes, and soil moisture impacts) into one model version to improve the prediction accuracy of SOC dynamics."

Reference:

Michalzik, B., Tipping, E., Mulder, J., Lancho, J. G., Matzner, E., Bryant, C., Clarke, N., Lofts, S., and Esteban, M. V.: Modelling the production and transport of dissolved organic carbon in forest soils, Biogeochemistry, 66, 241-264, 2003.

Wieder, W. R., Sulman, B. N., Hartman, M. D., Koven, C. D., and Bradford, M. A.: Arctic soil governs whether climate change drives global losses or gains in soil carbon, Geophysical Research Letters, 46, 14486-14495, 2019.

Jansson, J. K. and Wu, R.: Soil viral diversity, ecology and climate change, Nature Reviews Microbiology, 21, 296-311, 10.1038/s41579-022-00811-z, 2023.

Comment #3

Line 57: "density-dependent microbial processes": this needs some explanation. I have some basic biogeochemical background but still, I cannot guess its meaning the first time I see it.

Response #3

We added explanations on the density-dependent microbial processes on **Line 70-74** in **Introduction** here: "In previous MIMICS versions, an implicit or explicit density dependent turnover was introduced (Wieder et al. 2015; Kyker-Snowman et al. 2020; Zhang et al., 2020; Georgiou et al. 2017), which cause an increase in biomass turnover with increasing microbial community size reflecting increasing pressure from competition for other resource other than carbon (e.g. space) and virus infections (Jansson and Wu, 2023) , and a water scalar was used to represent the soil moisture effects (Wieder et al. 2019).".

Comment #4

line 165: Equation 4, the sign of square root of LIT_{tot} seems to cover 1.2. Is this intended or an error? Equation (6) might have a similar issue.

Response #4

We thank the reviewer for the careful review. You are right and it was a typo. We revised the equation (4) and (6) accordingly.

Comment #5

Line 175: a few words on the theoretical basis of why turnover rate is density-dependent might be helpful. Readers can then understand why, if this process is critical, it is missing from the original MIMICS version.

Response #5

As suggested, we added sentences on **Line 139-145** in **Section 2.1.2** to explain why turnover is density-dependent here: "Similar to the logistic growth model in population ecology, various regulatory mechanisms (e.g., competition, virus) can limit microbial population size (Buchkowski et al., 2017, Jansson and Wu, 2023). The absence of restrictions on population size other than carbon result in predictions of microbial biomass increasing indefinitely with carbon inputs. Consequently, the response of predicted SOC to changes in carbon inputs is close to zero which contradicts field observations (Georgiou et al., 2017). A density dependent turnover rate with β>1 was adopted to regulate the responses of soil microbial biomass to external environment variations, such as carbon input, thereby SOC dynamics in previous microbial models (Georgiou et al., 2017, Zhang et al., 2017)."

Reference:

Buchkowski, R. W., Bradford, M. A., Grandy, A. S., Schmitz, O. J., and Wieder, W. R.: Applying population and community ecology theory to advance understanding of belowground biogeochemistry, Ecol Lett, 20, 231-245, 10.1111/ele.12712, 2017.

Zhang, H., Goll, D. S., Wang, Y. P., Ciais, P., Wieder, W. R., Abramoff, R., Huang, Y., Guenet, B., Prescher, A. K., Viscarra Rossel, R. A., Barre, P., Chenu, C., Zhou, G., and Tang, X.: Microbial dynamics and soil physicochemical properties explain large-scale variations in soil organic carbon, Glob Chang Biol, 10.1111/gcb.14994, 2020.

Georgiou, K., Abramoff, R. Z., Harte, J., Riley, W. J., and Torn, M. S.: Microbial community-level regulation explains soil carbon responses to long-term litter manipulations, Nat Commun, 8, 1223, 10.1038/s41467-017-01116-z, 2017.

Jansson, J. K. and Wu, R.: Soil viral diversity, ecology and climate change, Nature Reviews Microbiology, 21, 296-311, 10.1038/s41579-022-00811-z, 2023.

Comment #6

Line 180: how the adsorption process in original MIMICS is represented given that it already has the deprotection process being simulated? The SOC might first be adsorbed in the original MIMICS before they can be de-protected?

Response #6

As suggested, we added sentences on **Line 152-157** in **Section 2.1.3** to explain the adsorption/desorption in the MIMICS model: "In the original version of MIMICS, fixed fractions of litter and microbial turnover are transferred to the physically protected SOC pool (SOC_p, Fig. 1), the SOC_p is then deprotected from mineral surfaces or breakdown of aggregates using a desorption rate which is a function of clay fraction. Therefore, we do not think that the original MIMICS actually simulate sorption as a process, as sorption is dependent on substrate concentration, therefore the sorption rate should vary with dissolved organic carbon concentration, rather than being proportional to microbial carbon turnover rate as assumed in the original MIMICS.".

Comment #7

Line 279: why a spatial resolution of 0.5º was selected? The MIMICS model should be resolution-independent and in principle we can run for it for each site?

Response #7

Yes, the MIMICS model can be run for individual sites if input data are available for those sites. In this study, we compiled the studies of SOC decomposition with or without biochar additions from the published literature. For many of those sites, input data required for running MIMICS are not available, and were extracted from the global dataset that are gridded at 0.5º by 0.5º spatial resolution. We added sentences on **Line 320-322** in **Section 2.3.2**: "The MIMICS model can run for each site, but to be consistent with the model input resolution of daily temperature in the transient simulation, the resolution of 0.5º was used for site aggregation. In detail, all sites within a given grid cell of 0.5º × 0.5º were aggregated on average, and the averaged value was used to compare the model result in this grid cell.".

Comment #8

Line 291: Is the climate from CRU-JRA or WorldClim (line 131) being used?

Response #8

The average annual temperature from WorldClim is used to fill the missing values of observative sites, which was used as the input to MIMICS to obtain the steady SOC pool sizes. The 6-hourly temperature from CRU-JRA was used for the transient simulation of SOC at each site using 6-hourly timestep for model integration, started from the initial steady state under average annual temperature conditions. We modified sentences on **Line 332-335** in **Section 2.3.3** as: "In order to meet the daily time step of transient runs required by MIMICS, the two model runs are forced by 6-hour surface temperature at a grid box where the site is located from Climatic Research Unit and Japanese reanalysis data (CRU-JRA, Kobayashi et al., 2015; Harris et al., 2014), which can differ from WordClim (time resolution: year) used in **Section 2.3.1**".

Comment #9

Lines around 290: I understand MIMICS-TSM_b was optimized using SOC observations (considered being at equilibrium) on 58 sites. But then there are 134 paired measurements with BC application. My questions are: (1) Is MIMICS-TSM_b further optimized using the control SOC measurements from these 134 paired observations or you just directly optimize MIMICS-BC targeting only ΔSOC?

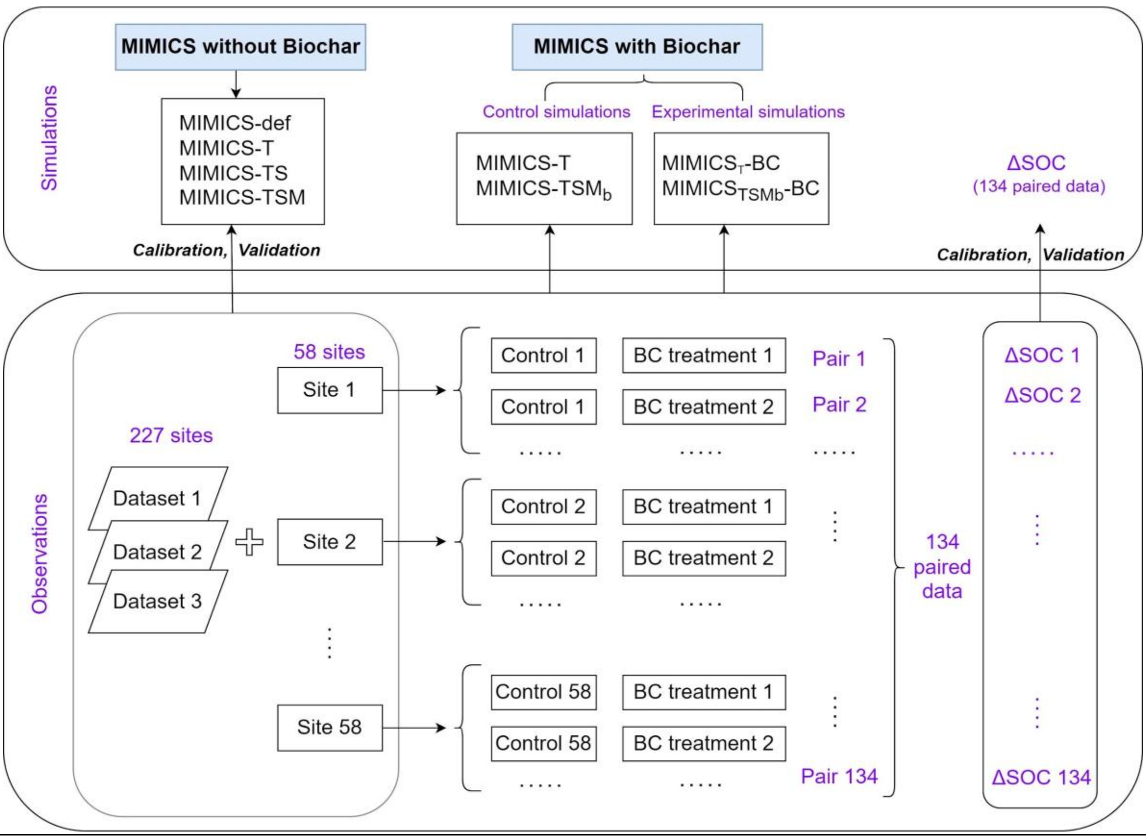
Response #9

We have 134 paired measurements with BC application at 58 sites. Each site has one control but can have multiple BC treatments. In the original manuscript version, we optimized the MIMICS-TSM_b (without biochar addition) using SOC concentrations in the 58 control treatments assuming equilibrium conditions. In the revised version, following suggestions from **Reviewer #2**, we optimized the model versions without biochar addition using the abovementioned 58 data and other published SOC data on croplands (227 in total) from Sun et al. (*2020*), Geisseler et al. (*2017*) and Zhou et al. (*2017b*). Therefore, more data were used for parameter calibration to improve the model robustness (**Fig. R1**, please see **Response #4** to **Reviewer #2**).

For the calibration and validation of the MIMICS-BC versions with biochar addition, the 134 paired field SOC data with BC application treatments were used.

The 58 SOC measurements are exactly the SOC measurements in the control treatments for these 134 paired measurements (**Fig. R1**), because one control treatment may correspond to multiple BC treatments with different applied BC rates. Therefore, we don't need to optimize MIMICS-TSM_b again. ΔSOC between the control treatment and the BC treatment in each of the 134 paired measurements was further used to optimize and validate the MIMICS-BC versions. We added **Fig. 3** (reproduced from **Fig. R1**) and sentences on **Line 271-273** in **Section 2.3.1** to clarify it: "There are SOC measurements on cropland sites from 58 control treatments (no BC application) and 134 measurements from biochar treatments at the 58 sites. One control treatment may correspond to multiple biochar treatments with different applied biochar rates at a single site.".

Fig. R1 Diagram of field measurement SOC data and the model simulation settings. The simulated or observed ΔSOC is equal to SOC with the biochar addition treatment minus that in the control treatment (without biochar addition). Note that one control treatment may correspond to multiple BC treatments with different applied BC rates at one single site.



Comment #10

(2) when optimizing for ΔSOC, how are the training and test samples being handled?

Response #10

In the revised manuscript version, the 134 paired SOC data were randomly spilt into training samples for parameter optimization (80% data) and test samples (the remaining 20% data). We added a sentence on **Line 343-344** in **Section 2.3.3**: "The 134 paired observations were randomly split into training samples for parameter optimization (80% data) and test samples for model validation (20% data).".

Comment #11

(3) in evaluating for ΔSOC, did you pick up the simulated SOC corresponding to the specific years of SOC measurement in field after BC application?

Response #11

Yes, the model was run for specific years of the SOC measurements in field (i.e., Age_BC in **Section 2.3.1**) for each site to get the simulated ΔSOC with biochar treatment, which is used to compare with observed ΔSOC. It has been explained on **Line 330-332** in **Section 2.3.3**: "For the version of MIMICS with biochar addition, we run for each site simulations with control (without biochar addition) and experimental simulation (with biochar addition) for Age_BC year at hourly time steps, restarted from the previous SOC equilibrium.".

Response to comments

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Reviewer #2:

Comment #1

Han and co-authors calibrate the MIMICS soil biogeochemical model to with the addition of density dependent processes, sorption, and soil moisture scalars and validate results with independent observations. They subsequently add a biochar parameterization to the model that is calibrated against field experiments. In the process they conducted additional experiments and sensitivity analysis.

Despite all of this work, I kind of wanted more- more than just results from a calibration and validation exercise. Why does it matter? This is a chance to show off and illustrate why calibrating a model like this matters and how the calibrated parameters alters projections of non-steady state soil C dynamics. For example, does the transient behavior of some version of the calibrated model respond to an idealized warming experiment, compared to the uncalibrated (default) parameterization? How do microbial biomass or soil respiration fluxes change with biochar additions in different versions of the MIMICS-BC calibration? These are just ideas for the authors to consider. I also appreciate you've already done a ton of work, and present additional suggestions to help clarify the study being presented.

Response #1

We thank the reviewer for the thorough and constructive comments and suggestions. Please see the detailed point-by-point responses below.

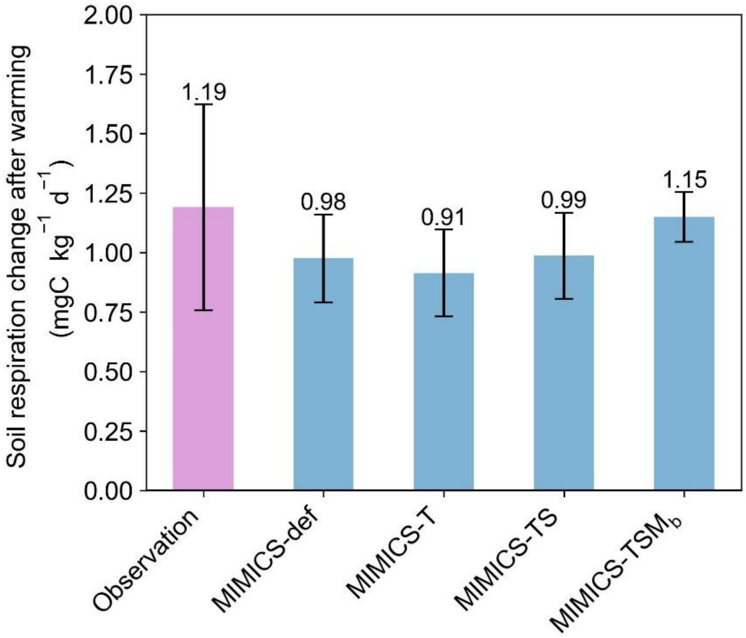
(1) Model response to idealized warming experiments

We used the paired data of soil heterotrophic respiration rates with and without warming treatments on croplands collected by Gao et al. (*2022*) (**Table R1**) to test the model performance on warming responses. We obtained the corresponding warming temperature and duration reported for these sites and extracted crop NPP at the warming sites from the global datasets (**Section 2.3.1**). We simulated the warming experiments using various MIMICS versions, and the simulated mean changes in respiration fluxes with warming are within the range of observations (**Figure R2**). The MIMICS-TSM_b version shows a slightly better magnitude of the response than other versions. We added the contents as a test on **Line 218-227 (Text S1)** in Supplementary Information as: "The paired (with or without warming treatments) soil heterotrophic respiration rates from three soil warming experiments on croplands (Table S4, Gao et al., 2020) were used to evaluate the model performance on warming responses. We obtained the warming temperature and duration reported for these sites in literature and extracted crop NPP from the global datasets (**Section 2.3.1**). We simulated the soil heterotrophic respiration in the control and warming treatments and compared the changes in soil respiration induced by warming with observations. The time span of model simulations is same as the reported warming durations in each site. Changes in the heterotrophic respiration (1.15 ± 0.10 mgC kg^{-1} d^{-1}) simulated by MIMICS-TSM_b can generally overlap the observed range (1.19 ± 0.43 mgC kg^{-1} d^{-1}), while changes from other model versions are within the observed range but lower than the average change from observations (Fig. S20).".

Table R1 Information of experimental warming sites on cropland from Gao et al. (*2022*).

Reference	Longitude	Latitude	MAT (℃)	MAP (mm)	Warming temperature (℃)	Duration	Control (mg kg^{-1} d^{-1})	Warming (mg kg^{-1} d^{-1})	Clay	Bulk density (g cm^{-3})	Soil moisture (cm^3 cm^{-3})	NPP (gC m^{-2} yr^{-1})
Liu et al., 2013	118°51′36″E	32°09′36″N	15.6	1100	2.6	11 months	2.75	3.59	0.26	1.20	0.33	465.6
Liu et al., 2014	120°33′00″E	31°30′00″N	16	1150	2	0.5 year	11.2	11.7	0.24	1.20	0.40	586.0
Qiu et al., 2018	78°40′00″W	35°43′00″N	16	1183	3.6	2 weeks	5.42	7.66	0.20	1.48	0.30	626.5

Fig. R2 Comparison of soil respiration changes with warming from observations and simulations by various MIMICS versions. The mean soil respiration changes between the control and warming experiments across calibrated sites are shown. Error bars indicate the standard error.

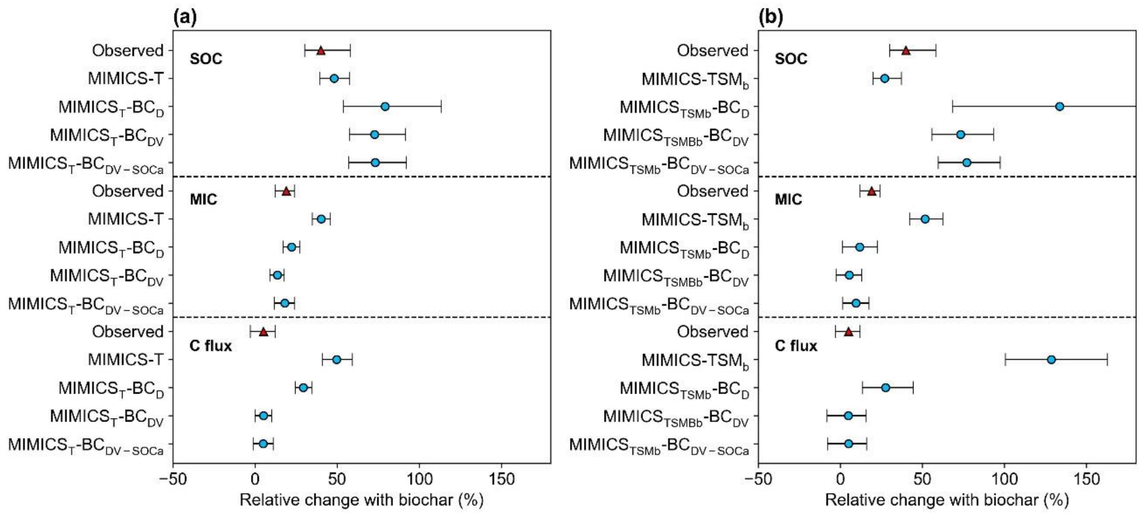


(2) Microbial biomass and soil respiration fluxes change with biochar additions

As suggested, we added analyses on the microbial biomass and soil respiration fluxes, and further compared the model results with the observation ranges from Liu et al. (*2016*) (the coordinates of sites are not available in these two papers and were thus not used in the first submission). Accordingly, we ran various MIMICS-BC versions to obtain the relative changes in SOC, microbial biomass carbon (MIC) and the total carbon fluxes from soil to atmosphere after biochar addition.

We added sentences on **Line 229-250** (**Text S2**) in **Supplementary Information**: "We also added a test by calibrating the model using changes in SOC, microbial biomass carbon (MIC) and the total carbon flux from Liu et al. (2016). In addition to matching the observed SOC changes, we also add the mismatch in MIC and respiration fluxes between the modelled and the observed into the cost function for optimization. Because the specific locations of MIC and carbon flux observations are not available (Liu et al., 2016), the mean simulated changes across all sites were used to match the observed changes in MIC and carbon fluxes from Liu et al. (*2016*). The 95% confidential interval (CI) was obtained using the bootstrapping method. Changes in SOC after biochar addition simulated by the four MIMICS$_T$-BC versions range from 48.1% (95% CI = 39.5%~57.5%) to 79.2% (53.7~113.2%), which are higher than the observed change of 40% (30% ~ 58%) (Fig. S21). Changes in MIC by the MIMICS$_T$-BC versions range from 13.5% (8.9% ~ 17.7%) to 40.3% (95% CI: 34.8% ~ 45.8%), and they are all mostly within the observed 95% CI range of 12% ~24%. However, the simulated responses of respiration flux to biochar addition by the MIMICS$_T$-BC versions are greater than the observed, and the simulated responses by MIMICS$_T$-BC$_{DV}$ and MIMICS$_T$-BC$_{DV\text{-}SOCa}$ fall within the observed range. The simulated decrease in MIC led to an increase of SOC and a decrease of respiration fluxes in the model. In general, the MIMICS$_T$-BC$_{DV}$ and MIMICS$_T$-BC$_{DV\text{-}SOCa}$ versions can simulate changes of the three aspects after biochar addition (Fig. S21a). The range of simulated relative changes across the $MIMICS_{TSMb}$-BC versions (Fig. S21b) is greater than the range across the $MIMICS_{T}$-BC versions (Fig. S21a). Consistent with the better performance on simulating the short-term SOC changes after biochar addition (Fig. 6), $MIMICS_{TSMb}$-BC_{DV} and $MIMICS_{TSMb}$-$BC_{DV\text{-}SOCa}$ are the better versions for reproducing the observed changes in the SOC, MIC and respiration among the four $MIMICS_{TSMb}$-BC versions (Fig. S21b). It should be noted that some factors such as synthetic nitrogen fertilizer application or biochar pyrolysis temperature can also impact the changes in SOC, MIC and respiration after biochar addition (Liu et al., 2016), but these factors were not considered in the model simulations in this study.".

Fig. R3 Relative changes in SOC, microbial biomass carbon (MIC) and the total carbon flux from soil to atmosphere with biochar addition simulated by $MIMICS_{T}$-BC (a) and $MIMICS_{TSMb}$-BC (b). Blue dots are the simulated mean values from the paired simulations in calibrated sites, and error bars indicate the 95% confidence interval (CI). See model versions in Table 1.



Reference:

Gao, H., Tian, H., Zhang, Z., and Xia, X.: Warming-induced greenhouse gas fluxes from global croplands modified by agricultural practices: A meta-analysis, Science of The Total Environment, 820, 153288, 2022.

Liu S, Zhang Y, Zong Y, et al.: Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. GCB Bioenergy, 8(2): 392-406, 2016.

Comment #2

I found the inconsistent organization of the paper made the work difficult to follow. Greater attention to the organization of the text will help readers follow all that's going on with this work. For example:

- The introduction claims to calibrate density dependent processes, sorption, and soil moisture scalars with data of SOC densities from 58 sites. Subsequently, it seems like different data were used to calibrate the new biochar submodule (line 98-104). This is fine, and it lays out a clear expectation for readers. What immediately follows in section 2.1, however, is a bunch of details on the biochar measurement that were collected for what I assumed was the second half of this calibration activity.
- Similarly, the caption describing new features of the model in Fig 1 is reverse of how the introduction is set up.
- Finally, the conclusion seemingly conflates: new processes added to the model (e.g., adsorption and soil moisture), agricultural management practices (not addressed in this paper), and long-term field experiments for biochar addition (although I'm still not really clear why this is needed based on the results presented?).

Response #2

(1) As suggested, we reorganized the text to make it more consistent and easier to follow. We moved the description about validation without or with biochar addition from the original **Section 2.1** to **Section 2.3.1** in the revised version. **Section 2.3** was divided into three parts to make it more organized: **Section 2.3.1** "2.3.1 Observational data collection". **Section 2.3.2** "2.3.2 Calibration and validation for MIMICS versions without biochar" and **Section 2.3.3** "2.3.3 Calibration and validation for MIMICS versions with biochar (MIMICS-BC)".

In fact, the SOC measurements from 58 control sites as used in optimizing the MIMICS versions without biochar are exactly the SOC measurements from the control treatments of 134 paired measurements (used to optimize the MIMICS versions with biochar). The reason why biochar treated sites were more than the control sites is because one control treatment may correspond to multiple BC treatments with different applied BC rates at a given site. We clarified this point in the revised version. Please see **Response #9** to **Reviewer #1** for details.

(2) We re-ordered the description in **Fig. 1** to be consistent with the introduction. The new caption of **Fig. 1** is: "**Fig. 1** Framework of the MIMICS model with biochar addition (MIMICS-BC; adapted from Wieder et al. (2015)). The turnover of microbial biomass (τ, blue arrows) is modified with density-dependent microbial turnover rate (Eq. 6, MIMICS-T). The adsorption process of SOC_p to SOC_a (purple arrow) is newly added and is associated with the adsorption rate (K_{ads}) and the maximum sorption capacity (Q_{max}) (Eq. 7-9, MIMICS-TS). The carbon decomposition processes (red arrows) are modified further with three soil moisture scalers that are applied to microbial maximum reaction velocity (V_{max}) and the half-saturation constant (K_m) (Eq. 10-12, MIMICS-TSM_a, MIMICS-TSM_b, MIMICS-TSM_c). When biochar is added to soil, the biochar (BC) carbon with an assumed fraction loss (f_{loss}) is partitioned into SOC_p, SOC_a and SOC_c based on f_{bp}, f_{ba} and f_{bc}, respectively (purple arrows from BC to SOC pools). The desorption process (orange arrow from SOC_p to SOC_a) is modified through changes in the desorption rate of SOC_p (D') with biochar addition. The carbon decomposition processes (red arrows) are modified by adjusting the microbial maximum reaction velocity (V'_{max}) with biochar addition."

(3) We revised the conclusions on **Line 573-577** based on the main results of our study：
"Our study shows that the updated MIMICS versions with new processes (e.g., adsorption and soil moisture) improves the model performance on simulating SOC dynamics on croplands. The model versions implemented with biochar processes can generally capture the SOC changes after biochar application from observations. Biochar is believed to have a large CDR potential, and its application on soils would affect the soil carbon and nutrient cycles. These impacts need to be incorporated ESMs to accurately simulate the mitigation potential of biochar under future climate change."

Comment #3

Line 261 Wow, the matrix works for non-linear models like MIMICS? This seems like it needs to be described, as it would be an important contribution, the details of which seem appropriate for a journal like GMD.

Response #3

At steady state (e.g., change of pool size with respect to time is equal to zero), the set of differential equations governing the dynamics of different soil carbon pools became a set of algebraic equations, in case of nonlinear dynamics, such as MIMICS, that set of algebraic equations are also nonlinear, and can be solved numerically using Newton-Ralphson method. We added description of the approach on **Line 299-302** in **Section 2.3.2**: "This approach is constructed based on the fundamental principles governing biogeochemical cycle processes in terrestrial ecosystems (e.g., respiration, carbon distribution). A set of first-order ordinary differential equations were built to express the dynamics of carbon flows in soil over time and it can be solved numerically to obtain steady carbon pool sizes. See codes for further details in Code availability)."

Comment #4

Section 3.1. I wonder if the data are sufficient for calibrating all the features for part one of the calibration (density dependent processes, sorption, and soil moisture scalars)? Declines in model performance with the validation data for the 'optimized model' (MIMICS-TSM_b) shown in Table S5 suggests that the model isn't that well calibrated? I also wonder why the model with (nearly) the highest AIC values was chosen as the best?

Response #4

About the data sufficiency, we used 58 observation sites for model calibration because these sites have paired SOC measurements from the control treatment (without biochar addition) and BC treatment (with biochar addition). Note that one control treatment may correspond to multiple BC treatments at a given site, so there are 134 paired observations for biochar addition in total. As we mentioned in the manuscript, we did a systematical search of published studies, and this is the best we can get.

For calibrating density dependent processes, sorption, and soil moisture scalars in the MIMICS versions without biochar, we also used cropland SOC observations from other individual sites in Sun et al., (*2020*), Geisseler et al., (*2017*) and Zhou et al., (*2017*). We added sentences on **Line 273-276** in **Section 2.3.1** as: "Considering the 58 site observations may be inadequate to constrain all the new features in the revised model, we also collected SOC data on croplands (no biochar addition) from other three published global datasets (227 sites in total, Sun et al., 2020; Geisseler et al., 2017; Zhou et al., 2017b). Therefore, 285 sites in total were used to calibrate and evaluate the model performance for simulating cropland SOC without biochar addition (Fig. 2).".

Therefore, we changed the settings of model calibration and validation and added sentences on **Line 326-328** in **Section 2.3.2**: "We randomly separated 80% of all the 285 sites for MIMICS versions (MIMICS-def, MIMICS-T, MIMICS-TS and MIMICS-TSM_b) calibration, and 20% for model validation. The R^2, RMSE and AIC were calculated by comparing simulated SOC with the observed SOC in training and test datasets.".

For the declines in model performance in **Table S5** in the original manuscript, although MIMICS-TSM_b is not the best model with a highest R^2 and lowest RMSE and AIC, the differences of R^2, RMSE and AIC among various versions are relatively small (**Fig. S5**). The new processes (density dependent processes, sorption, and soil moisture scalars) have been proven important to model SOC dynamics in previous studies. A previous study found that the SOC oscillations in response to changes in carbon inputs can be reduced or completely removed when the density dependent turnover rate with $\beta > 1$ was adopted in model (Georgiou et al., 2017). The inclusion of density-dependent microbial turnover rate also improved the accuracy of predicting SOC at the global scale compared to MIMICS without it and eliminated the correlation between simulated biases and input of annual litterfall (Zhang et al., 2020). In addition, parameterizations of soil moisture effects are important for simulating soil carbon turnover and respiration (Yan et al., 2018), and MIMICS with soil water modifications showed comparable predicted global soil carbon stocks compared to other models (Wieder et al., 2019). We clarified these points on **Line 74-80**. So we would like to use this version for further development of biochar processes despite of a slightly higher AIC. We acknowledge that we cannot rule out the possibility that the model is unconstrained, but we believe it is the best we can do.

We also added the sentences on **Line 495-498** in **Section 4.1** for discussion: "By considering more plausible mechanisms, the performance of MIMICS model changes little with a slightly higher AIC. It is possible that the model is still not fully constrained. With more emerging technologies and observation data available, the parameters related to these processes can be further calibrated.".

As an alternative model version, we also tested implementation of biochar processes in MIMICS-T in the revised manuscript, in addition to implementing biochar processes in MIMICS-TSM_b in the original manuscript.

We added the sentences on **Line 349-355** in **Section 2.3.3** to clarify these points: "Although MIMICS-TSM_b is not the model with the highest R^2 and lowest RMSE and AIC, the differences of R^2, RMSE and AIC among various versions are relatively small (Fig. S5). The new processes (density dependent processes, sorption, and soil moisture scalars) are based on theoretical understanding and have shown to improve predictions of soil carbon in previous studies (Zhang et al., 2020, Liang et al., 2019, Abramoff et al. 2022). Thus, this version was used for further development of biochar processes in MIMICS. As an alternative model version, we also tested implementation of biochar processes in MIMICS-T that have a highest R^2 and lowest RMSE and AIC in model validation (Fig. S5b).".

Comment #5

Finally, the authors have 5 figures in the main text and 20 in the SI. This isn't a nature paper. Would including more of the results in the main part of the manuscript clarify the experimental design (e.g. Fig S1) and results (e.g, Fig S8)?

Response #5

As suggested, we moved these figures to the main text. In addition, we also added **Fig. 3** to the main text of the revised manuscript to present the newly added content in the revision.

Comment #6

Clarifications + Minor and technical concerns:

Line 43: This clause is incomplete, "therefore add further constraint to stabilize future warming under 2 ℃.: I'd remove it or clarify and reference what's being stated said.

Response #6

As suggested, this sentence was removed.

Comment #7

Lines 41-45. A two-sentence paragraph is pretty short. Maybe combine with other text?

Response #7

As suggested, we combined this part with the following paragraph.

Comment #8

Line 57. These statements seem inaccurate or misleading. Since 2015 MIMCIS included an implicit density dependent turnover term (see Wieder et al. 2015; Georgou et al. 2017, also Eq. 4) and one CN version of MIMICS does too (Kyker-Snowman et al. 2020) as well as Zhang et al., 2020. Moreover, different versions of MIMICS also include a 'water scalar' that reduces microbial kinetics (Wieder et al. 2019)

References:

Georgiou, K., Abramoff, R. Z., Harte, J., Riley, W. J., & Torn, M. S.: Microbial community-level regulation explains soil carbon responses to long-term litter manipulations, Nature Communications, 8(1), 1223, 2017.

Kyker-Snowman, E., Wieder, W. R., Frey, S. D., & Grandy, A. S.: Stoichiometrically coupled carbon and nitrogen cycling in the MIcrobial-MIneral Carbon Stabilization model version 1.0 (MIMICS-CN v1.0), Geoscientific Model Development, 13(9), 4413-4434, 2020.

Wieder, W. R., Grandy, A. S., Kallenbach, C. M., Taylor, P. G., & Bonan, G. B.: Representing life in the Earth system with soil microbial functional traits in the MIMICS model. Geoscientific Model Development, 8(6), 1789-1808, 2015.

Wieder, W. R., Sulman, B. N., Hartman, M. D., Koven, C. D., & Bradford, M. A.: Arctic Soil Governs Whether Climate Change Drives Global Losses or Gains in Soil Carbon, Geophysical Research Letters, 46(24), 14486-14495, 2019.

Response #8

As suggested, we removed the misleading part in this sentence. The suggested references were added correspondingly in the next paragraph where these processes were described.

Line 70-74: "In previous MIMICS versions, an implicit or explicit density dependent turnover was introduced (Wieder et al. 2015; Kyker-Snowman et al. 2020; Zhang et al., 2020; Georgiou et al. 2017), which cause an increase in biomass turnover with increasing microbial community size reflecting increasing pressure from competition for other resource other than carbon (e.g. space) and virus infections (Jansson and Wu, 2023), and a water scalar was used to represent the soil moisture effects (Wieder et al. 2019).".

Comment #9

Section 2.1. How was depth handled for all of these different measurements? How do you handle this depth to which you're calibrating the model?

Response #9

We added a sentence on **Line 315-316** in **Section 2.3.2**: "Soil depth was not explicitly considered in this study, and we assumed that the soil carbon concentrations (g kg^{-1}) are similar within the top 30 cm."

Comment #10

Line 122, I might make this independent validation activity more obvious. It seems like there's a really nice model calibration (58 sites; Fig 2) and validation (224 sites; Fig S8) for the non-biochar part of the study, but this is kind of obscure in all sections of the paper.

Response #10

Following suggestions here and in **Comment #4 and #25**, we used 80% of the 285 sites for model calibration, and the remaining 20% for model validation (see details in **Response #4** to **Reviewer #2**).

Comment #11

Line 137-141. This text seems redundant with text in the following paragraph. Can it be removed?

Response #11

Removed as suggested.

Comment #12

Line 144. Why is Fig S3 included, it seems identical to Fig 1 but with a different caption (that seems redundant with text already in the manuscript. Consider removing?

Response #12

Removed as suggested.

Comment #13

Line 169, 240, and elsewhere. Is deprotection a word? I think the MIMICS papers call in desorption.

Response #13

We changed the word of "deprotection" to "desorption" in the full text.

Comment #14

What is the ecological or theoretical implications of modifying K_m by the soil moisture term (eq 14)? I'm trying to figure out if (or why) the half saturation constant of substrates would be moisture limited or if concentrations of microbes or substrates themselves would be modified by soil water content? Some discussion of the assumptions here would be helpful.

Response #14

As suggested, we added sentences to explain our assumption on modifying K_m by soil moisture on **Line 185-189** in **Section 2.1.4** as: "We assumed that the kinetic parameters V_{max} and K_m respond to soil moisture, similarly to temperature in Michaelis-Menten equation by affecting enzyme activity and enzyme-substrate affinity, respectively. The soil enzyme-substrate affinity was found to increase with soil moisture due to the increased diffusion and movement of substrate, but the affinity may also decrease due to decreased substrate concentrations (Zhang et al., 2009). Thus, we translated the impacts of soil moisture on the enzyme-substrate affinity to changes in K_m.".

In addition, we conducted a test by modifying V_{max} and microbial turnover (τ) multiped by soil moisture scalar following Wieder et al., (*2019*), but the model performance didn't improve. **Line 465-469** in **Section 4.1**: "We also tried a test by assuming that soil moisture affects the microbial growth rate through mediating microbial growth (V_{max}) and turnover (τ) of MIC_r and MIC_k (Wieder et al., 2019) and thus added the soil moisture factor (i.e., $f(\theta)$ in Eq. 11) on V_{max} and τ. But the model does not predict SOC concentrations more accurately (R^2=0.46, RMSE=5.06 g kg^{-1}, AIC=198.9, Fig. S13b) than the MIMICS-TSM_b version where V_{max} and K_m are affected (R^2=0.52, RMSE=5.05 g kg^{-1}, AIC=198.6, Fig. 4d, Fig. S5b)".

Reference:

Wieder, W. R., Sulman, B. N., Hartman, M. D., Koven, C. D., & Bradford, M. A.: Arctic Soil Governs Whether Climate Change Drives Global Losses or Gains in Soil Carbon, Geophysical Research Letters, 46(24), 14486-14495, 2019.

Zhang Y L, Sun C X, Chen L J, et al: Catalytic potential of soil hydrolases in northeast China under different soil moisture conditions, Revista de la ciencia del suelo y nutrición vegetal, 9(2): 116-124, 2009.

Comment #15

Line 223, Table S3. This seems like a low %N for wood, but what crop inputs are included in the site-level calibration that are even providing wood litter inputs?

Response #15

The word "wood" here refers to "stem" for crops. So, the adjusted value in **Table S3** in the original manuscript version was based on the measurements for crop stem. We clarified this point in the revised version.

Comment #16

How are you handling wood litter inputs into MIMICS (Fig 1)?

Response #16

The word "wood" here refers to "stem" for crops. We added explanations on **Line 197-200** in **Section 2.1.5**: "Crop NPP at each site was used as the litter input to soil, but different crop types (e.g., maize, rice and wheat) were not specified in the model. The leaf, root and stem litter were assumed as a fixed fraction of crop NPP. The ratio of carbon to nitrogen (C: N) and the ratio of lignin to carbon (lignin: C) of leaf, root, and stem (Table S2) were used to calculate the metabolic fraction in the total crop litter (f_{met}).".

Comment #17

Section 2.2.5. Does this mean that you're making steady state assumptions about agricultural soils that they reflect present day crop productivity (less harvest removal) and litter quality estimates? This should maybe be stated clearly in the methods (e.g. line 260)?

Response #17

As suggested, we added a statement on **Line 294-296** in **Section 2.3.2**: "All field SOC observations in the control treatments (without biochar) from the paired measurements and SOC from the other three global datasets (Fig. 2) were assumed at a steady state, which is under present climate and continuous input of crop NPP after 45% removal of grain with a specific crop litter quality (**Section 2.1.5**, Table S2)".

Comment #18

Line 231 At first pass, this assumption of adding char directly to physically protected, available and chemical protected pools seem surprising. This is mainly because in my mind biochar has a turnover time that's longer (~600 years, but I don't know where this number came from) than the residence time of the default MIMICS pools, and a distinct chemical signature. Maybe provide a brief justification for the simplifying assumptions being made here? I see this is discussed at the end of section 4.2, but maybe a brief explanation is still warranted in the methods.

Response #18

As suggested, we added a brief explanation on **Line 207-209** in **Section 2.2**: "Although biochar is recalcitrant to decompose with a long turnover time (556 ± 484 yr) in general, it contains some labile fraction (108 ± 196 day), and its stability varies with different biochar feedstocks, pyrolysis temperatures and soil properties (Wang et al., 2016a).

Comment #19

Ex 15 & 16 + Table S1. are the units for Fv and Fd correct here?

Response #19

After careful checking, the units are correct, but to be more clear, we modified the Eq. (15) & (16) as: " $D' = D \times (1 + f_d \times Rate\_BC \times BC\_C)$ " and " $V'_{max} = V_{max} \times (1 + f_v \times Rate\_BC \times BC\_C)$ ", respectively. The Rate_BC is the application rate with the unit of "t BC ha^{-1}", and BC_C is the proportion carbon in biochar, thus yielding the unit of f_d or f_v of "$(t\ C\ ha^{-1})^{-1}$", i.e., ha t^{-1} C. We added a sentence below Eq. (15) & (16): "The Rate_BC is the application rate of biochar (t BC ha^{-1}) and BC_C is the carbon content in biochar (tC t^{-1}BC).".

Comment #20

Section 2.3 I also am struggling to understand the assumptions of 'negative priming' vs. 'positive priming' that are going into the biochar calibrated parameterizations here.

First, I think of priming as a microbial explicit process and you're working with a microbial explicit model- but the mechanisms for negative priming seem more to do with substrate affinity of biochar for available SOM, which is an abiotic process. Is this assumption consistent with discussion of negative priming elsewhere in the literature (e.g. Zimmerman et al 2011 paper cited earlier?). Sorry, this is literature I'm not very familiar with.

Second, if biochar is supposed to have a "strong adsorption affinity for organic matter" shouldn't you modify some part of eq 7-9, not eq 5 as is presently done? I understand why you did it this way, eq 5 is simple to modify, whereas I'm not sure what the adsorption functions seem more challenging. Can you clarify your rationale here?

Third, "positive priming" involves increasing Vmax for all fluxes (modifying Vmax), but would MIMICS give you a positive priming effect via increases in microbial biomass just by increasing SOM_a concentrations as a function of biochar additions? That is, do you need to hard wire the positive priming effects, or may they be an emergent property of the model of the existing model structure?

Response #20

(1) "Priming effects" refer to the changes in the mineralization of native SOC due to the addition of new substrates. The observed direction and magnitude of the priming effect varied with biochar type, soil type, and incubation stage (*Zimmerman et al., 2011*). As an exogenous organic matter, biochar may increase (positive priming), decrease (negative priming) or have no effect on SOC mineralization rates, but there is no consensus. We added sentences on **Line 230-235** in **Section 2.2** to clarify: "The negative priming effects of biochar addition on SOC may be caused by the inhibition of microbial activity due to changes in the soil environments by biochar, or by the SOC protection against microbial utilization through mineral adsorption or aggregates (Zimmerman et al., 2011). We assumed that biochar addition decreases the mineralization of native SOC (negative PE) because of its porous structure and strong adsorption affinity to organic matter (Kasozi et al., 2010), which was reported to be an important negative PE mechanism for biochar (Zheng et al., 2018, Zimmerman et al., 2011).".

(2) Yes, the Eq. (5) is simple to modify to represent the effects of biochar's sorption on SOC. As suggested, we added a sentence to clarify the rationale on **Line 240-242** in **Section 2.2**: "Because the adsorption and desorption of SOC are interrelated dynamic processes, modification of the desorption process with biochar addition also impacts the adsorption process. Therefore, we only modified f_d in Eq. (15) to represent the negative PE of biochar".

(3) We agree that biochar may have a positive priming effect on SOC by mainly increasing the degradation rate of available SOC by microbes (i.e., SOC_a in MIMICS). Following your suggestion, we added a test by modifying V_{max} as a function of biochar addition rate only in the fluxes from SOC_a to MIC (MIC_r and MIC_k).

The results are shown in **Fig. R4** (copied from **Fig. 5** in the revised manuscript) and **Fig. R5** (copied from **Fig. 6** in the revised manuscript). The corresponding revisions include:

Line 250-252 in **Section 2.2**: "Biochar may also have a positive priming effect on SOC by increasing the degradation rate of available SOC by microbes (i.e., SOC_a in MIMICS). Therefore, we added a test through modifying the V_{max} as a function of biochar addition rate only in the fluxes from SOC_a to MIC_r and MIC_k, instead of in all fluxes of decomposition (Eq. 16, red arrows in Fig. 1)."

Line 344-349 in **Section 2.3.3**: "Four tests were conducted to evaluate the performance of $MIMICS_{TSMb}$-BC on simulating SOC changes after biochar addition using the optimized parameters values in MIMICS-TSM_b (i.e., a_v, a_k, k_d, β, k_{ba}, c_1, c_2; Table S3): 1) without biochar-related parameters; 2) with only one new biochar-related parameter (i.e., the desorption coefficient, f_d, Eq. 15) optimized ($MIMICS_{TSMb}$-BC_D); 3) with two new biochar-related parameters (i.e., f_d and the decomposition rate coefficient, f_v, Eq. 16) optimized in all decomposition processes ($MIMICS_{TSMb}$-BC_{DV}); 4) with two new biochar-related parameter (i.e., f_d and f_v) optimized only in the fluxes from SOC_a to MIC pools ($MIMICS_{TSMb}$-$BC_{DV\text{-}SOCa}$)"

Line 409-415 in **Section 3.2.1**: "For the calibration of short-term SOC changes after biochar addition, $MIMICS_T$-BC and $MIMICS_{TSMb}$-BC versions with new biochar processes show a better performance with higher R^2, lower RMSE and AIC than MIMICS-T and MIMICS-TSM_b, respectively (Fig. S9-10). For the model validation using observation data that are not used for calibration, the performance of $MIMICS_T$-$BC_{DV\text{-}SOCa}$ (R^2=0.80, RMSE=3.38 g kg^{-1}, AIC=69.8, Fig. 5e-g) is slightly better than $MIMICS_T$-BC_D (R^2=0.79, RMSE=3.43 g kg^{-1}, AIC=68.5) and $MIMICS_T$-BC_{DV} (R^2=0.76, RMSE=3.66 g kg^{-1}, AIC=74.1), except for the AIC (69.8) is higher than that of $MIMICS_T$-BC_D (68.5) (Fig. 5). By comparison, the performance of MIMICS-T is poorer than these three versions."

Line 421-432 in **Section 3.2.1**: "For the long-term (extended to 8 yr based on biochar decomposition curve, Wang et al., 2016a) SOC changes after biochar addition, $MIMICS_T$-BC_{DV} and $MIMICS_{TSMb}$-BC_{DV} show the best performance among all versions in the model calibration (Fig. S9-10). In the model validation, MIMICS-T and MIMICS-TSM_b underestimates the extrapolated observations of SOC change (Fig. 5a, Fig. 6a). $MIMICS_T$-BC_D shows the best performance with the lowest RMSE (3.84 g kg^{-1}) and AIC (74.7) among all the $MIMICS_T$-BC versions (Fig. 5). Compared to MIMICS-TSM_b (R^2 =0.88, RMSE=9.35 g kg^{-1}, slope=0.08, AIC=120.7, Fig. 6a, e, f, g), predictions of $MIMICS_{TSMb}$-BC_D, $MIMICS_{TSMb}$-BC_{DV} and $MIMICS_{TSMb}$-$BC_{DV\text{-}SOCa}$ are more accurate with a smaller RMSE (8.12 g kg^{-1}, 6.08 g kg^{-1} and 6.78 g kg^{-1}, Fig. 6f), a smaller AIC (115.1, 101.5 and 107.4, Fig. 6g), a linear slope closer to 1 (0.29, 1.68 and 1.74, Fig. 6a-d), and a reasonable accuracy of R^2 (0.45, 0.97 and 0.94, Fig. 6e). Among the $MIMICS_{TSMb}$-BC versions, $MIMICS_{TSMb}$-BC_{DV} shows the best performance (Fig. 6). When assuming that biochar produces a priming effect only through affecting the utilization rate of SOC_a by microbes ($MIMICS_{TSMb}$-$BC_{DV\text{-}SOCa}$), the model accuracy is slightly decreased with lower R^2 (=0.94), higher RMSE (=6.78 g kg^{-1}) and higher AIC (=107.4) than $MIMICS_{TSMb}$-BC_{DV} that assumes all decomposition processes were affected (Fig. 6)."

Fig. R4 Relationships of short-term (≤ 6 yr; black) and long-term (i.e., extended to 8yr; red) SOC changes with biochar addition (ΔSOC) between observations and models in validation dataset. The MIMICS versions are used, including MIMICS-T (a), MIMICST-BC_D (b), $MIMICS_T$-BC_{DV} (c) and $MIMICS_T$-$BC_{DV\text{-}SOCa}$ (d). Comparisons of R^2 (e), the root mean square error (RMSE, f) and the Akaike information criterion (AIC, g) among the four $MIMICS_T$-BC versions are shown separately. See model versions in Table 1.

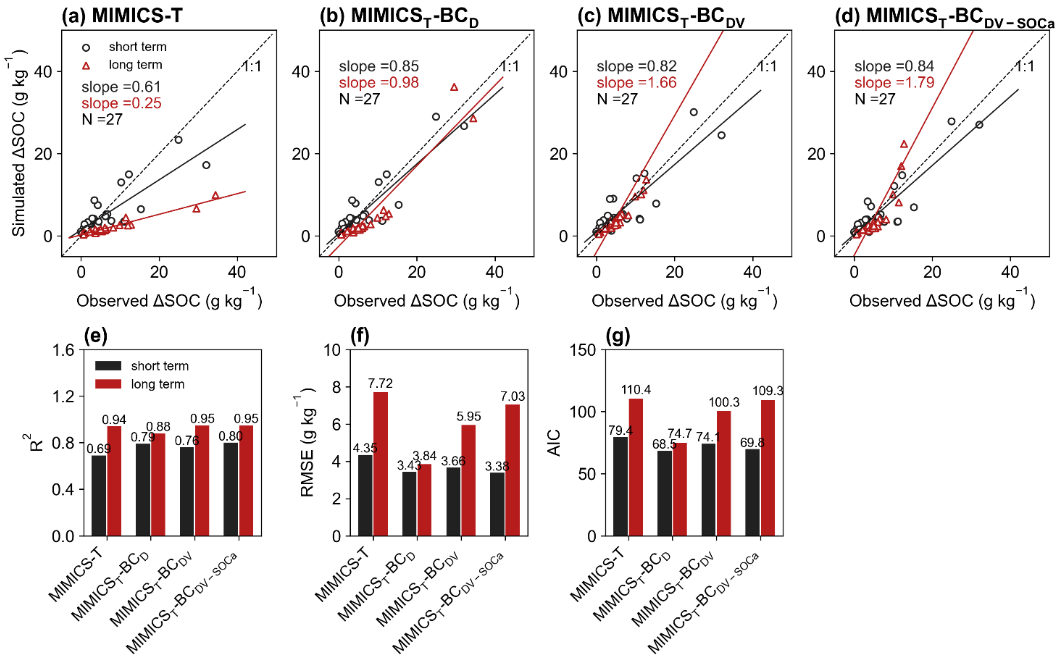
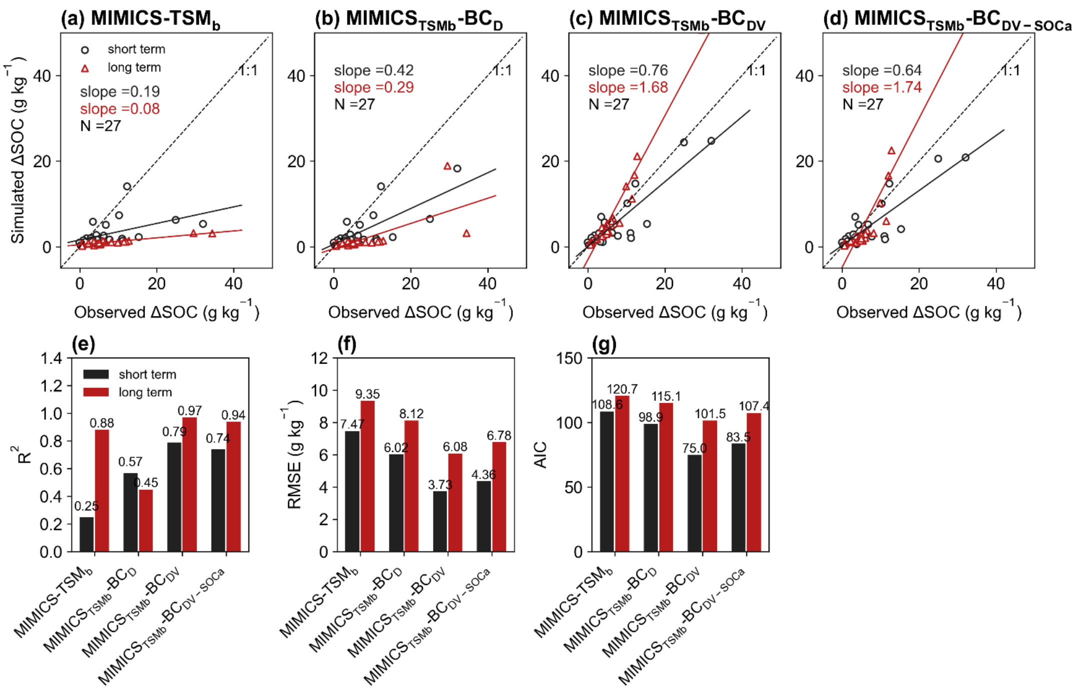


Fig. R5 Relationships of short-term (≤ 6 yr; black) and long-term (i.e., extended to 8yr; red) SOC changes with biochar addition (ΔSOC) between observations and models in validation dataset. The MIMICS versions are used, including MIMICS-TSM$_b$ (a), MIMICS$_{TSMb}$-BC$_D$ (b), and MIMICS$_{TSMb}$-BC$_{DV}$ (c) and MIMICS$_{TSMb}$-BC$_{DV\text{-}SOCa}$ (d). Comparisons of R^2 (e), the root mean square error (RMSE, f) and the Akaike information criterion (AIC, g) among the four MIMICS$_{TSMb}$-BC versions are shown separately. See model versions in Table 1.



Reference:

Zimmerman, A. R., Gao, B., & Ahn, M.-Y.: Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils, Soil Biology and Biochemistry, 43, 1169-1179, 2011.

Kasozi G N, Zimmerman A R, Nkedi-Kizza P, et al.: Catechol and humic acid sorption onto a range of laboratory-produced black carbons (biochars), Environmental science & technology, 44(16): 6189-6195,2010.

Zheng, H., Wang, X., Luo, X., Wang, Z., & Xing, B.: Biochar-induced negative carbon mineralization priming effects in a coastal wetland soil: Roles of soil aggregation and microbial modulation, Sci Total Environ, 610-611, 951-960, 2018.

Han L, Sun K, Yang Y, et al.: Biochar's stability and effect on the content, composition and turnover of soil organic carbon, Geoderma, 364: 114184, 2020.

Comment #21

Line 283-305. I'm struck that the control plots (without biochar) are a really good opportunity to validate the non-char calibration that was done in step 1 of the calibration (MIMICS-TSM_b). How well are the calibrated parameters from 58 locations doing at what seems like an independent set of observations? Or, I may not be understanding the experimental design accurately? Are the 387 paired measurements included in the 58 locations (e.g. 58 control / calibration plots + a bunch more BC treatment plots (section 2.1)? The introduction and table 1 make it seem like there are an additional 134 paired measurements being used for the MIMICS-BC evaluation. This seems implied in the conclusion "We further validated MIMICS against field measurements on global croplands without… biochar addition", but I can't find these results presented.

Response #21

Yes, the 387 paired measurements included in the 58 locations are 58 control plots plus more BC treatments plots because one control treatment may correspond to multiple BC treatments with different applied BC rates at a given site. We added a figure to show the organization of the observation data and model settings (**Fig. R1**, copied from **Fig. 3** in the revised manuscript, see **Response #9** to **Reviewer #1**).

Comment #22

Line 311, Fig S6. I'm not really clear how this double exponential model was applied in MIMICS? Or was this just used to extend the "observational record" for sites with < 8 years of data?

Response #22

The double exponential model was just used to extend the short-term SOC observations to a specific 8 year, NOT used in MIMICS. We clarified it on **Line 364-365** in **Section 2.3.3**: "Note that the double exponential decay function is only applied to the observational records of measurement data, and this function is not used in the MIMICS model".

Comment #23

Why not add AIC information to Fig 2e (Similar to Fig S7)?

Response #23

Added as suggested.

Comment #24

Why are AIC values for calibration data in Table S5 different than those reported in Fig S7?

Response #24

In the revised version, we changed the settings of model calibration and validation (see **Response #4** to **Reviewer #2**), so this problem no longer exists.

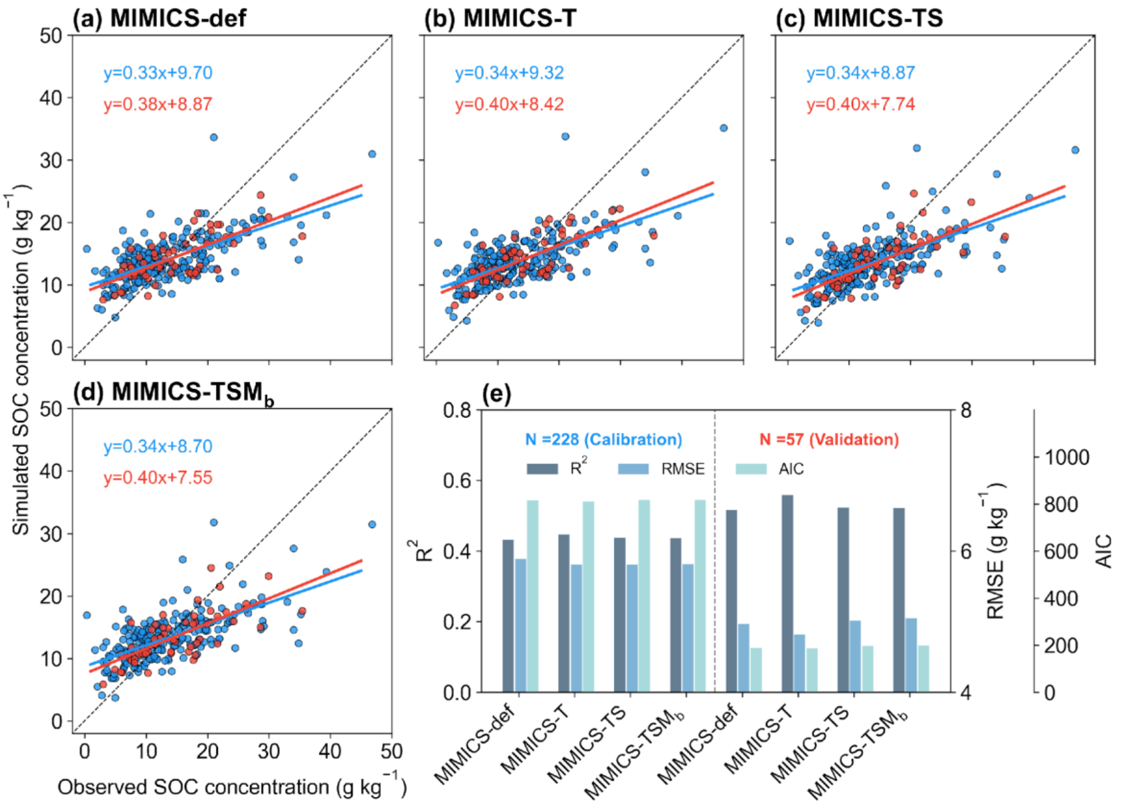
Comment #25

I might suggest bringing in a clearer model validation figure into the main part of the text (e.g. Fig S8)? Or even combining these 3 datasets (rows in Fig S8) into a single set of plots for each model configuration with statistics reported as in Fig 2.

Response #25

As suggested, we added a figure with a set of plots for model calibration and validation in the main text (**Fig. R6**, copied from **Fig. 4** in the revised manuscript).

Fig. R6 Comparison between the observed and simulated SOC concentrations by (a) MIMICS-def, (b) MIMICS-T, (c) MIMICS-TS and (d) MIMICS-TSM$_b$. Blue and red dots in (a-d) represents observation sites for model calibration (80% sites) and validation (20% sites). (e) R^2, root mean square error (RMSE) and Akaike information criterion (AIC) from the model calibration (left panel) and validation (right panel) for the four MIMICS versions. Relationships for the other MIMICS versions can be found in Fig. S8.



Comment #26

Line 342, I don't or maize rice and wheat as cover crops. Maybe replace 'cover crops' with crop type?

Response #26

Revised accordingly.

Comment #27

Section 3.2 and 3.2.1 aren't really about model evaluation, as this is where you're calibrating the biochar module?

Response #27

As suggested, we modified them as **"**3.2 Calibration and evaluation of MIMICS-BC**"** and "3.2.1 Model calibration and validation".

Comment #28

Section 4.1 & 4.2 Parts of this discussion are a little odd, as results from a bunch of other things the authors tried are all introduced and displayed in the SI. I appreciate including this information and analyses, I think they belong in the paper, and are appropriate for the journal. I also wonder if it's better presented in the results, with a clearer interpretation of your findings discussed in section 4 of the paper.

Response #28

In order to keep the main model calibration part concise, we would like to keep it separate from sensitivity tests. We changed the title of **Section 3** to "3. Results of model calibration and validation" and **Section 4** to "4. Sensitivity tests and discussion". We also moved some figures from SI in the original manuscript to the main text in the revised manuscript (please also see **Response #5** to **Reviewer #2**).

Comment #29

Fig 5. I don't love reporting new results in the discussion. Since this is already described in the methods (line 305-315), consider moving this text to results (e.g., 3.2.3 Sensitivity analysis).

Response #29

We changed the title of this section, and please see **Response #28** to **Reviewer #2.**

Comment #30

447-449 This sentence is phrased in a confusing way "reduced the correlations between model-observation biases and input variables". Clay also doesn't need to be capitalized.

Response #30

As suggested, we modified the sentence on **Line 519-521** in **Section 4.2** to make it clearer: "The correlations between model-observation biases and input variables become weaker for MIMICS-BC_{DV}, but the correlation with biochar application (Rate_BC) and soil moisture (SM) is still significant ($p < 0.05$, Fig. 7), implying that some processes related to these variables are not well represented in the model.".

Comment #31

Line 460, again I don't really think the end of the discussion is the place to add a bunch of new results from new model calibrations.

Response #31

We modified the title of **Section 4**, and please see details in **Response #28** to **Reviewer #2.**
