Global quantification of the eco-hydrological co-benefits of soil carbon sequestration

Biogeosciences

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Abstract

This response letter contains numbered figures and references to these figures. To prevent confusion, the figures embedded within this response letter are called illustrations. Finally, the following convention is applied to denote modification in the original manuscript: new text.

1 Reviewer 1

Reviewer 1 Comment 1

The study uses CTSM v5.2 to simulate soil hydrology under different SOC sequestration scenarios across global cropland and grassland landscapes, focusing on how increased SOC influences plant-available water and water stress.
Simulations were conducted at a 0.5° resolution using prescribed land cover and climate forcing, comparing a control (BAU) with three SOC enhancement scenarios (High, Medium, and 4p1000) applied to the top 30 cm of soil. Soil properties were derived from the WISE30sec dataset, and changes in water holding capacity, saturation, and water stress were analyzed over a 20-year period to assess hydrological impacts.
The modeling results will be primarily dependent on how the CTSM model uses SOC to modify water flow. From the methods, the effect of SOC on water retention was simulated by modifying the SOM fraction, which directly influences saturated water content (theta_s) and subsequently the water retention via the Campbell model: theta/theta_s = (psi/psi_b)̂(-1/b). Note that psi_b and b are only affected by soil texture. The model also affects organic soils.
Thus some issues need to be addressed:

Response

We thank the reviewer for their detailed and constructive assessment of our methods and model setup, and for highlighting important aspects of how SOC influences soil hydraulic properties in CTSM. We have carefully addressed the issues raised and provide detailed responses to each point below.

Reviewer 1 Comment 2

The methods need to clarify how SOC affects water retention and water flow in the soil, as these determine the results. A plot of how the model simulates SOC increase with AWC would be beneficial.

Response

Thank you for this suggestion. We generated the requested plot and now include it in the appendix of the revised manuscript. A more detailed discussion of this relationship and its implications is provided in our response to Reviewer 1, Comment 9 (see below).

Reviewer 1 Comment 3

The modeling of SOC sequestration potential on organic soils which is simply a blanket increase is applied to the top 30 cm of the soil column using scenarios based on mineral soils (e.g., Zomer et al. 2017), assuming a fixed bulk density and SOC conversion factor. The model uses a maximum organic matter density of 130 kg/m^3, corresponding to 100% organic matter. The blanket sequestration rate is mostly unlikely as it depends on climatic conditions and regime, dryer climates could not sequester more carbon as compared to colder and wetter climates.

Response

In the updated manuscript, we mask out grid cells with organic soils (which we define as grid cells with SOC > 120 gC kg^{-1} (WRB, 2022)) in the analysis, as our focus is not to simulate sequestration potential for organic soils (See Reviewer 1 Comment 5 below). This masking has limited effect on the presented results.

In addition, we agree with the reviewer that SOC sequestration rates depend strongly on climate conditions, and that a uniform global increase is a simplification. Several studies indeed show that sequestration potential is highest in humid temperate regions and lowest in arid and semi-arid areas, where limited biomass production and moisture availability constrain SOC accumulation (e.g., Zomer et al., 2017; Minasny et al., 2017). However, to date, no spatially explicit global datasets or scenarios exist that provide consistent estimates of achievable SOC sequestration across all land types and climates. We therefore applied uniform SOC increases to conduct a first-order sensitivity experiment, isolating the model's hydrological response to prescribed SOC changes under idealized conditions. This approach allows assessing the direction and magnitude of hydrological effects independently of region-specific carbon dynamics, which would be better addressed in future studies once such global scenarios become available. Finally, by including the 4p1000 scenario, which represents a relative increase in SOC, we incorporate a more realistic pattern in which carbon-poor soils receive proportionally smaller SOC amounts, reflecting what studies consider a plausible global mitigation target (Rumpel et al., 2018).

> **Reviewer 1 Comment 4**
>
> SOC increase is not linear with time.

Response

In this study, we do not assume a linear SOC increase. Instead, we compare snapshots before and after a 20-year sequestration period. This has been clarified in the scenario description section from L159 onwards:

> The effect of carbon sequestration on soil hydrology is assessed by comparing a control simulation with present-day, fixed SOC content to three distinct scenarios representing the soil carbon content assumed to be reached after 20 years of active sequestration (there is no linear increase over time) (Fig. 1d, Table 1). A 20-year period reflects a commonly cited saturation point after which a new equilibrium in SOC for the upper soil layers is reached (Zomer et al., 2017). Thus, the scenarios represent stable states of SOC after 20 years of management In each scenario, carbon increases are applied to the top 30 cm of the soil column.

> **Reviewer 1 Comment 5**
>
> the Methods section does not specify how SOC sequestration is handled on organic soils. We know that SOM in peatlands are unlikely to sequester more carbon, And thus the model should not simulate sequestration on organic soils. This is especially true for soils high latitudes.

Response

We agree with the reviewer. Therefore, we masked out organic soils in the results and in all figures (see Reviewer 1 Comment 5). As there is no lateral flow between the soil columns in CTSM, this masking out does not influence the results of the remainder of the paper.

We added a sentence in the methods to clarify this (L155):

> Since organic soils are unlikely to sequester additional carbon (Amelung et al., 2020) and are not the focus of this study, grid cells with organic carbon contents above 120 gC kg^{-1} soil are excluded from the analysis.

We also added a small note to the captions of the relevant figures.

> Grid cells with organic soils (organic carbon content > 120 g C kg^{-1} soil) are excluded from the analysis.

Reviewer 1 Comment 6

It is unclear how CTSM simulates water infiltration and how SOC affects water flow.

Response

When precipitation reaches the land surface, CTSM partitions it into canopy interception, surface runoff, or infiltration into the soil column. Infiltration is simulated using the Richards equation, which governs the movement of water in unsaturated soils based on gradients in hydraulic potential. The infiltration rate is limited by the soil's infiltration capacity, which depends on near-surface soil moisture, hydraulic conductivity, and frozen soil conditions. Any water exceeding the infiltration capacity becomes surface runoff. More details and corresponding equations can be found in the CTSM technical documentation (Lawrence et al., 2018).

SOC affects water infiltration and flow indirectly by modifying the soil hydraulic properties that parameterize the Richards equation. Specifically, SOC alters the soil texture-dependent parameters of the Clapp and Hornberger (1978) relationships, which define the soil water retention curve and hydraulic conductivity. Increasing SOC content generally increases porosity and the water retained at a given matric potential, while decreasing bulk density and hydraulic conductivity, especially near saturation. These effects vary with soil texture and are represented through the pedotransfer functions described in Lawrence et al. (2018).

We added this information condensed in the manuscript from L138 onwards:

> Infiltration is simulated using the Richards equation, where water flow depends on soil hydraulic potential gradients and hydraulic conductivity. SOC affects these processes indirectly by altering soil hydraulic parameters such as porosity, bulk density, and the shape of the water retention curve, which together influence infiltration capacity and vertical water redistribution (Lawrence et al., 2018).

Reviewer 1 Comment 7

See more recent studies Bagnall, et al, 2022. Carbon-sensitive pedotransfer functions for plant available water. Soil Science Society of America Journal, 86(3), pp.612-629. Panagea, Ioanna S., et al. "Soil water retention as affected by management induced changes of soil organic carbon: analysis of long-term experiments in Europe." Land 10.12 (2021): 1362.

Response

We thank the reviewer for providing these relevant references. We read the studies in detail, and added them to the introduction of manuscript (see below), as well as to the discussion.

L56-64:

> A meta-analysis of 60 studies by Minasny and McBratney (2018) found that a 1% mass increase in SOC (10 gC kg^{-1} soil) corresponds to a modest gain of 1.16 mm water per 100 mm soil in available water capacity, suggesting that the influence of SOC on plant-available water may be limited. Similar findings were reported by Panagea et al. (2021), who observed no statistically significant changes in soil water retention, and by **?**, who found an average increase of 1.6 mm water per 100 mm soil per 10 gC kg^{-1} SOC increase across 11 sites in Germany. Bagnall et al. (2022) developed new SOC-sensitive pedo-transfer functions based on 124 long-term research sites and reported larger increases of 3.0 mm per 100 mm soil for the same SOC increment in non-calcareous soils indicating that the magnitude of SOC effects likely depends on the empirical relationships used.

L59:

> The effects of SOC changes on soil water content have mostly been investigated using local-scale empirical or modeling studies (e.g. Jordán et al., 2010; Turek et al., 2023; Panagea et al., 2021), meta-analyses (Minasny and McBratney, 2018) and regional or global statistical analyses (e.g. Iizumi and Wagai, 2019; Kane et al., 2021).

L384-389:

> Bagnall et al. (2022) proposed revised carbon-sensitive pedotransfer functions that account for SOC-driven changes in soil structure and aggregation, which result in substantially higher increases in water holding capacity compared to conventional pedotransfer functions. At the field scale, Araya et al. (2022) and **?** showed that SOC sequenstration management techniques increases water holding capacity. Panagea et al. (2021), however shows that the direct impact of SOC on water holding capacity is small, and SOC-induced changes in soil structure and aggregate composition are more important. These findings highlight the need for model developments that incorporate SOC-sensitive hydraulic pedotransfer and soil structural processes to better quantify the effects of carbon sequestration on soil water content.

Reviewer 1 Comment 8

Results
Soil carbon sequestration in the High scenario (+0.55% SOC by mass) leads to a modest but widespread increase in water holding capacity and volumetric water content in the upper 30 cm of soil, especially over croplands. This increased upper-layer moisture increases vegetation transpiration, particularly in clay-rich regions, and leads to small reductions in annual water stress and surface runoff, though with regional variation and minimal impact below 32 cm soil depth. The Medium sequestration scenario (+2.7 gC/kg or 0.27%) causes small, consistent improvements in topsoil water retention and slight reductions in water stress and runoff. While effects are small, the model suggests that even modest carbon gains can improve plant water availability and hydrological resilience in certain environments. The 4 per 1000 scenario causes regionally variable changes in soil moisture, depending on baseline SOC. While it improves water retention in upper layers, the downward redistribution of moisture is reduced, and in some cases, overall soil water content declines. This scenario shows the importance of initial SOC levels and local conditions. The authors should also calculate water storage change (ΔS in water balance) to determine the effect of SOC increase.

Response

We are not entirely certain what the reviewer is requesting. The manuscript already presents the modeled differences in soil water content (i.e., storage) between the control and SOC-increase scenarios. These results are shown in Figure 3 and in the appendix (Figs. A4–A6), and are described in the Results (lines 251–269 for soil water content in meters; lines 270–294 for volumetric soil water content depth profiles in mm^3 mm^{-3} in the three reference regions; Fig. 4).

If the reviewer is referring instead to changes in storage over time (ΔS in the sense of a water-balance diagnostic), we believe this metric is not meaningful in our setup. The simulations are equilibrium “snapshot” experiments following full spin-up, designed to represent steady-state conditions under prescribed SOC levels. By construction, they do not include transient climate forcing or SOC dynamics, and therefore (ΔS over time is expected to be near zero and not informative for interpreting sequestration impacts.

Finally, if the reviewer is referring to potential effects of SOC changes on groundwater storage, we note that groundwater dynamics are not explicitly represented in the model. However, groundwater recharge (represented by subsurface drainage) is simulated. We quantify the effect of SOC sequestration on this flux in Fig. 7b and Section 3.4 of the main text.

Reviewer 1 Comment 9

Discussion
The study adds value by exploring the upper-bound potential of SOC sequestration on soil hydrology, its conclusions are constrained by model limitations, assumptions, and a lack of integration with management, crop response, and local-scale feedbacks. The claim that a 0.55% SOC increase leads to a 2% increase in water holding capacity and volumetric water content depends on how CTSM modelled the effect of SOC. It is not a reality. It also has not been validated (the water retention model). And thus the authors should first clarify how SOC affects AWC though the calculation of the water retention of the Campbell's model. Discuss with regards to recent literature (Bagnall and Pangea). And clarify that the model has not been validated with real data as opposed to meta analysis and other statistical approaches.

Response

We thank the reviewer for this valuable comment and have revised the discussion to better clarify how the relationship between soil organic carbon (SOC) and water holding capacity (WHC = $\theta_{fc} - \theta_{wp}$) arises in CTSM and how it compares to recent empirical studies.

To this end, we added a global sensitivity plot illustrating the modeled relationship between SOC and water holding capacity (WHC) across all grid cells, differentiated by clay fraction (Illustration 1). WHC increases almost linearly with SOC up to about 70 g C kg^{-1} soil, after which the relationship flattens or declines, particularly in coarse-textured soils. This pattern reflects how SOC affects the soil water retention curve through the pedotransfer functions used in CTSM, which are based on the Campbell formulation. These functions were originally developed for static soil properties and are not specifically calibrated to capture dynamic changes in SOC.

Recent studies highlight that conventional pedotransfer functions, which rely primarily on texture, do not fully capture the effects of SOC on soil hydraulic properties. Bagnall et al. (2022) developed carbon-sensitive pedotransfer functions that explicitly account for SOC effects and found that texture-only formulations systematically underestimate SOC-driven increases in plant-available water, especially in coarse-textured soils. Similarly, Panagea et al. (2021) demonstrated, using field and meta-analysis data across European soils, that management-induced SOC increases improve water retention, but with a high degree of nonlinearity and context dependence. These findings suggest that CTSM's texture-based pedotransfer functions likely underestimate the sensitivity of soil water retention to SOC changes, particularly under management conditions that alter soil structure and aggregation.

However, recent empirical studies indicate that traditional pedotransfer functions may underestimate SOC-related changes in water retention. For example, Bagnall et al. (2022) proposed revised carbon-sensitive pedotransfer functions that account for SOC-driven changes in soil structure and aggregation, resulting in stronger increases in WHC than those simulated here. Similarly, Panagea et al. (2021) found that increases in SOC can significantly enhance water retention and plant-available water, though the magnitude varies with texture and management intensity. Field studies such as Araya et al. (2022) further emphasize that management practices promoting SOC accumulation, including cover cropping and reduced tillage, can alter pore size distribution and hydraulic conductivity in ways not captured by standard pedotransfer functions. These findings highlight the need for model developments that incorporate SOC-sensitive hydraulic formulations and structural soil processes, especially under soil management to be able to better quantify the effect of sequestration on soil water content.

We therefore emphasize in the revised manuscript that the relationship between SOC and WHC presented here arises directly from the model parameterization and should be viewed as a first-order response. Future model developments incorporating carbon-sensitive pedotransfer functions, such as those proposed by Bagnall et al. (2022), would enable a more realistic representation of SOC–hydrology interactions.

L379-389:

> The pedotransfer functions in CTSM dictate that water holding capacity increases with SOC up to intermediate levels (Appendix Fig. 1). Yet, this behavior likely underestimates the true effect of SOC sequestration on soil hydraulic properties. Recent studies suggest that SOC influences water retention primarily through changes in soil aggregation, pore size distribution, and connectivity. Bagnall et al. (2022) proposed revised carbon-sensitive pedotransfer functions that account for SOC-driven changes in soil structure and aggregation, which result in substantially higher increases in water holding capacity compared to conventional pedotransfer functions. At the field scale, Araya et al. (2022) and **?** showed that SOC sequenstration management techniques increases water holding capacity. Panagea et al. (2021), however shows that the direct impact of SOC on water holding capacity is small, and SOC-induced changes in soil structure and aggregate composition are more important. These findings highlight the need for model developments that incorporate SOC-sensitive hydraulic pedotransfer and soil structural processes to better quantify the effects of carbon sequestration on soil water content.

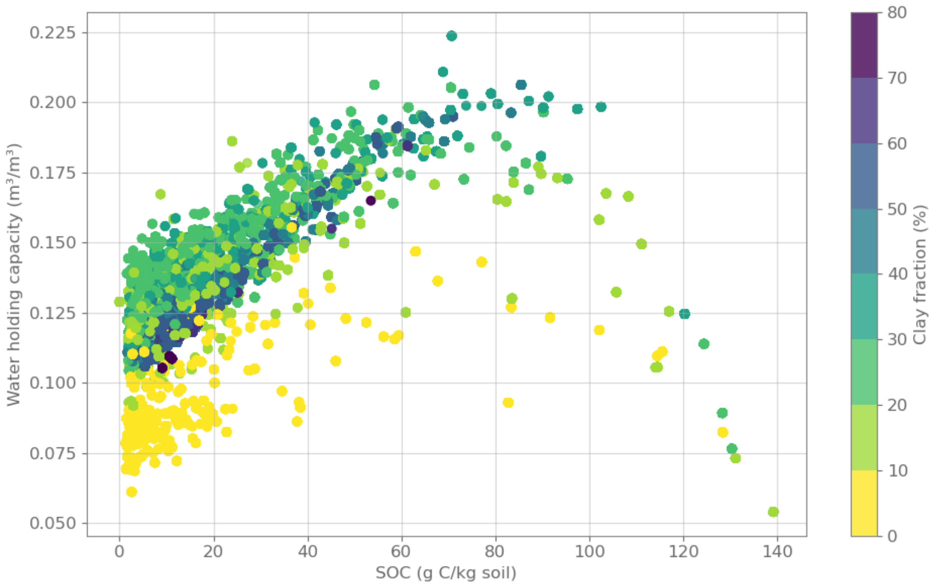

Illustration 1: **Change in water holding capacity with increasing soil organic carbon.** Scatterplot showing the relationship between soil organic carbon (SOC) and water holding capacity (difference between water content at field capacity (θ_{fc} and wilting point θ_{wp}) for 10 soil levels of every grid cell. Points are colored by clay fraction to indicate soil texture. Grid cells with organic soils (organic carbon content > 120 g C kg^{-1} soil) are excluded from the analysis.

We acknowledge that this study does not include an explicit model validation against observations, as our focus is on assessing the model sensitivity to soil carbon sequestration. However, the soil hydrology and related processes in Community Terrestrial Systems Model (CTSM) and the Community Land Model (CLM) have been extensively validated in previous studies during model development and benchmarking (e.g., Lawrence et al., 2019; Cheng et al., 2021; Kennedy et al., 2019). We now clarify this in the discussion section of the manuscript and emphasize that the presented results should be interpreted as a model sensitivity experiment rather than an evaluation against observed conditions with changing organic carbon.

L363-366:

> While this study does not include a direct validation against observations of soil carbon sequestration effects, the hydrology and energy balance components of CTSM have been extensively evaluated in previous studies (e.g., Lawrence et al. (2019); Cheng et al. (2021); Kennedy et al. (2019)). The analysis therefore represents a model sensitivity experiment conducted within a well-validated modeling framework.

Reviewer 1 Comment 10

As above, I believe the effect of SOC on soil water could be in terms of water balance or soil moisture storage (delta_s in water balance). The AWC may not be influenced significantly, but delta_s could be significant.

Response

For this comment, we refer to Reviewer 1 Comment 8.

Reviewer 1 Comment 11

The authors could also discuss in terms of other simulation studies
Araya, Samuel N., et al. "Long-term impact of cover crop and reduced disturbance tillage on soil pore size distribution and soil water storage." Soil 8.1 (2022): 177-198.

Response

We thank the reviewer for this suggestion. We have now included a discussion of the study by Araya et al. (2022), which examined the long-term effects of no-till and cover cropping, both management techniques that increase soil carbon on soil structure and water dynamics. Their results showed that improved soil structure enhances infiltration and transient water content in upper soil layers, while reducing deeper percolation—findings that are consistent with our modeled redistribution of soil water under increased soil organic carbon. We mention the study now in the plot-scale references in the introduction (L59):

> The effects of SOC changes on soil water content have mostly been investigated using local-scale empirical or modeling studies (e.g. Jordán et al., 2010; Turek et al., 2023; Panagea et al., 2021; Araya et al., 2022), meta-analyses (Minasny and McBratney, 2018) and regional or global statistical analyses (e.g. Iizumi and Wagai, 2019; Kane et al., 2021).

as well as in the discussion (See Comment 9).

Reviewer 1 Comment 12

Limitations should be discussed. There was no dynamic feedback is modeled between SOC and soil structure, aggregation, macroporosity, or infiltration capacity. This limits the model's ability to capture nonlinear or process-based SOC-water interactions, particularly under management changes or climate stress. As a result, the model may underestimate both the positive potential (e.g. in improving infiltration, reducing runoff) and negative trade-offs (e.g. reduced deep drainage or waterlogging under saturation) of real-world SOC accumulation.

Response

We thank the reviewer for these important additions and limitations to the model and reformulated the limitations paragraph in the discussion section to include the points raised (L340-...):

> In CTSM, as in other global land models, soil hydraulic functions such as water retention and hydraulic conductivity are parameterized through pedotransfer functions that strongly depend on input soil texture maps and organic matter content. These empirical functions are not necessarily designed for sensitivity experiments with changing SOC, as they do not account for dynamic feedbacks between SOC and soil properties. In particular, structural effects such as aggregation, macroporosity, and changes in infiltration capacity are not explicitly represented (Fatichi et al., 2020). As a result, important soil processes associated with SOC accumulation and management practices—such as no-till, cover cropping, compaction, or enhanced biological activity—are only partially captured (Minasny and McBratney, 2018). As a result, the model may not fully represent the complexity of SOC–water interactions, leading to underestimation of both co-benefits (e.g. improved infiltration and reduced runoff) and trade-offs (e.g. reduced deep drainage or oxygen stress due to water logging under saturation).

Reviewer 1 Comment 13

SOC gains in real systems are tightly linked to land management practices, e,g, no-till, cover cropping, etc. which influence soil compaction, infiltration rates, rooting depth, and microbial activity. These management pathways are not modeled in CTSM. As such, the study simulates the effect of added carbon, not the processes or trade-offs involved in achieving that carbon gain. And the model (especially the effect of SOC on hydraulic parameters) has not been validated.

Response

We agree with the reviewer that land management practices are not explicitly modeled, and therefore the associated trade-offs and interactions that determine SOC gains in real systems are not captured in this study. To date, no global land model fully integrates these processes, including the effects of practices such as no-till, cover cropping, or organic amendments on soil compaction, rooting depth, infiltration, and microbial activity. Our approach, which prescribes SOC increases, should therefore be viewed as a first-order sensitivity experiment that isolates the hydrological response to enhanced SOC. Establishing this baseline response is a necessary step before moving toward simulations that account for land management, dynamic vegetation, or coupled land–atmosphere feedbacks. As research in this area advances, future studies should aim to explicitly represent management practices and their interactions with SOC, including structural and biotic processes, to provide a more comprehensive assessment of both the benefits and trade-offs of SOC accumulation on water availability.

We added those elements to the discussion paragraph in the manuscript:

> In particular, structural effects such as aggregation, macroporosity, and changes in infiltration capacity are not explicitly represented (Fatichi et al., 2020). As a result, important soil processes associated with SOC accumulation and management practices—such as no-till, cover cropping, compaction, or enhanced biological activity—are only partially captured (Minasny and McBratney, 2018). As a result, the model may not fully represent the complexity of SOC–water interac-

tions, leading to underestimation of both co-benefits (e.g. improved infiltration and reduced runoff) and trade-offs (e.g. reduced deep drainage or oxygen stress due to water logging under saturation).

While the specific effect of SOC on soil hydrological processes has not been validated, the soil hydrology of CTSM has been extensively evaluated in previous studies. We clarified this point and emphasized in the discussion that our analysis represents a model sensitivity experiment within a validated modeling framework (See Reviewer 2 Comment 4).

2 Reviewer 2

2.1 General Comments

Reviewer 2 Comment 1

This manuscript presents a comprehensive global assessment of the eco-hydrological impacts of soil organic carbon (SOC) sequestration using the Community Terrestrial Systems Model (CTSM). The study is timely and highly relevant given the increasing attention to nature-based climate solutions, particularly soil carbon sequestration, where potentials and limitations should be addressed. The work explores the co-benefits of SOC increase on soil water retention, evapotranspiration, runoff, and water stress.
The paper demonstrates that SOC additions can modestly enhance water retention and plant-available water in many regions, resulting in increased evapotranspiration and reduced water stress. These findings add nuance to discussions on soil-based mitigation by highlighting co-benefits for drought resilience and water use efficiency.

Response

We thank the reviewer for the constructive and thoughtful assessment of our manuscript and for recognizing its relevance to understanding the eco-hydrological co-benefits of soil organic carbon sequestration. Below, we address each of the reviewer's comments in detail and describe the corresponding revisions made to the manuscript.

Reviewer 2 Comment 2

However, some key issues require clarification or expansion. First, the hydrological effects are generally modest and must be contextualized in terms of model sensitivity and uncertainty. In this sense, I agree with Referee 1 that a representation of the effect of increasing SOC to the soil hydraulic properties is recommended. Is the effect linear? Does adding SOC impact differently soils with distinct textures? Is the effect similar in the wet and dry ends of the soil hydraulic properties? Answering these questions can enlighten the model results and give a more comprehensive outlook in the observed effects.

Response

Thank you for bringing up these points. We added an elaborated discussion and additional text to the manuscript that answers these questions in our response to Reviewer 1 Comment

9 (see above).

> Reviewer 2 Comment 3
>
> Second, the discussion would benefit from more critical evaluation of model assumptions and limitations, particularly regarding plant response (phenology), soil physics, and regional heterogeneity.

Response

We have expanded the discussion to provide a more critical assessment of the model's underlying assumptions and limitations. In particular, we now highlight that vegetation phenology is prescribed in our simulations, which constrains dynamic plant responses such as rooting depth adaptation and stomatal regulation under changing soil water conditions. We added a sentence on this in the discussion section (L350-352):

> Furthermore, because vegetation phenology is prescribed, dynamic plant responses such as changes in rooting depth or stomatal regulation cannot adjust to altered soil water conditions, constraining the representation of vegetation–soil feedbacks.

We also elaborate on how soil hydraulic properties in CTSM are derived from pedotransfer functions based on static soil texture and organic matter inputs, limiting the model's ability to represent structural changes in soil physics (e.g., aggregation, macroporosity) associated with SOC accumulation (see Reviewer 1 Comment 12).

Finally, we note that the coarse model resolution (0.5° × 0.5°) and globally uniform parameterizations obscure regional heterogeneity in both soil processes and management practices.

> Finally, the coarse 0.5° × 0.5° spatial resolution and generalized parameterizations smooth regional variability in soil texture, management, and climate, limiting representation of localized processes such as infiltration contrasts or management-induced changes in soil structure. However, the model's tiled approach allows differentiation between land types within a grid cell, for example separating irrigated from rainfed croplands and grasslands, which partially accounts for sub-grid variability.

These additions clarify the scope of our findings and outline important priorities for future model development.

> Reviewer 2 Comment 4
>
> The absence of a model validation has to be acknowledged, pointing this exercise as a model sensitivity evaluation.

Response

We acknowledge that this study does not include an explicit model validation against observations, as our focus is on assessing the model sensitivity to soil carbon sequestration. However, the soil hydrology and related processes in Community Terrestrial Systems Model

(CTSM) and the Community Land Model (CLM) have been extensively validated in previous studies during model development and benchmarking (e.g., Lawrence et al., 2019; Cheng et al., 2021; Kennedy et al., 2019). We now clarify this in the discussion section of the manuscript and emphasize that the presented results should be interpreted as a model sensitivity experiment rather than an evaluation against observed conditions with changing organic carbon.

> While this study does not include a direct validation against observations of soil carbon sequestration effects, the hydrology and energy balance components of CTSM have been extensively evaluated in previous studies (e.g., Lawrence et al. (2019); Cheng et al. (2021); Kennedy et al. (2019)). The analysis therefore represents a model sensitivity experiment conducted within a well-validated modeling framework.

Reviewer 2 Comment 5

Finally, the authors should provide more consistent terminology (e.g., soil water content vs. soil moisture vs. liquid water content; soil carbon sequestration vs. sequestration, etc.) and improve clarity around the time averaging of results, especially in the figure captions.

Response

We carefully reviewed the manuscript to ensure consistent terminology, and its intentional use. In the results, we now added a sentence that when "soil water content", expressed as depth per unit area (m) is used, this is pointed towards liquid soil water content. In the remainder of the text, the term "liquid" has been omitted, and solely "soil water content" is used. This has been clarified in the first sentence that soil water content is used in the results:

> The effect on mean total water availability and total soil water content shows an increase of 2 mm averaged globally, and varies by region (Fig. 3a); hereafter, soil water content refers to the liquid fraction.

Further, in the results and discussion thereof, we now ensure consistent terminology and replaced "soil moisture" by volumetric water content to denote (θ)

In the introduction and abstract, we decided to keep the term "soil moisture" as this denotes the general, overall water of the soil. The term “sequestration” is now generally used as “soil carbon sequestration.” In a few instances, “soil” was omitted where it was already clear from the context, to improve readability and avoid redundancy.

To clarify the time averaging of the results, we added the following explanatory sentence in Section 2.4 Analysis (L199):

> To this end, we compare mean values from the 20-year simulation period across experiments (Section 2.2).

We also updated the figure captions of figures 2-8 to include the averaging periods as follows:

> Difference in the High and CTL scenarios averaged over 20 simulation years for [...]

2.2 Specific Comments

Reviewer 2 Comment 6

SOC "increases the size of the bucket," but...
Increasing water holding capacity only improves resilience when water is present. In drought scenarios, especially in very dry regions, no extra water may be available to be held. This should be emphasized in the discussion to temper expectations about SOC's effectiveness as a drought mitigation tool unless paired with other strategies like irrigation. The authors also present conflicting information on the effect of SOC increase in sandy/arid regions (see detailed comment below).

Response

On the second point, we refer to our response to Reviewer 2 Comment 25 below.

Reviewer 2 Comment 7

Waterlogging/oxygen stress: In wet regions, increasing water retention can increase the risk of oxygen stress. This potential trade-off is worth mentioning, even if not captured by the current model setup.

Response

We agree with the reviewer, and added a sentence on this potential trade-off to the paragraph on limitations in the discussion section (L349-350):

> As a result, the model may not fully represent the complexity of SOC–water interactions, leading to underestimation of both co-benefits (e.g. improved infiltration and reduced runoff) and trade-offs (e.g. reduced deep drainage or oxygen stress due to water logging under saturation).

Reviewer 2 Comment 8

Vegetation dynamics: The model uses prescribed vegetation phenology and does not allow dynamic feedback from changes in water availability. This limitation should be clearly stated in the methods. It likely leads to over/underestimation of the full eco-hydrological co-benefits. The separation of the results between croplands and grasslands are also not clear. Is it an average over everything? It could be beneficial to see if effects are different for each of those.

Response

We added a sentence to the methods to clearly state this limitation (L143-144).

> The biogeochemistry module is not activated, so soil organic matter remains

> constant throughout the simulations, and vegetation responses to changes in water availability are not represented.

We also elaborate on this in the discussion section (See Reviewer 2 Comment 3).

In this study, we focus specifically on the effects of adding SOC in cropland soils. To avoid confusion, we removed earlier references to grasslands from the main text, while retaining the dedicated discussion paragraph on grasslands (lines 397–404). We also refined the manuscript to more explicitly state this focus, as follows:

In the methods: L 171

> The main land cover types targeted for soil carbon sequestration are cropland. Here, we focus on soil column variables specific to the crop fraction of each grid cell (Fig. A2).

In the discussion paragraph L397:

> Here, we focused on croplands to apply soil carbon sequestration. However, next to croplands, other agricultural land such as meadows and pastures where herbaceous forage crops are grown, provide potential to store carbon (Sommer and Bossio, 2014; Tessema et al., 2020).

Reviewer 2 Comment 9

> Water stress: The simulations showed that transpiration of the plants is increased with enhanced SOC, but water stress is only slightly affected. As mentioned in the manuscript, this is related to the very conservative definition of water stress and cannot be put in the context of irrigation. No one would wait until the soil reaches PWP to start irrigation. Since the manuscript is written in terms of cropland use, it would be beneficial to see if other drought criteria are more realistic with its needs, such as 50% of FC, or a some critical soil matric potential that is not as low as PWP. It is also not clear in which conditions irrigation is applied. Is it in all regions?

Response

We thank the reviewer for this valid point, and we revised he water stress analysis by adopting a less extreme definition of water stress, namely when volumetric soil moisture drops below 50% of the field capacity, as suggested by the reviewer. In addition, we only retain the cumulative water stress figure in the updated manuscript.

We updated the methods section to account for this change (L 224-228):

$$\text{Water stress} = \sum_{i=1}^{7} \sum_{month=1}^{12} (0.5 \cdot \theta_{fc,i} - \theta_{month,i}) \cdot d \qquad \text{for} \qquad \theta_{month,i} < 0.5 \cdot \theta_{fc,i} \tag{1}$$

And included the updated paragraph and figure in the results section:

> Annual water stress decreases across most regions, particularly in Western North America, parts of South America, the Sahel, Western Southern Africa,

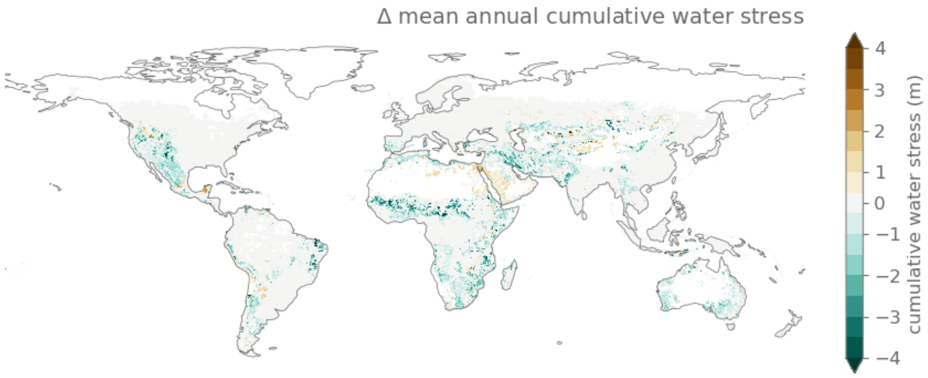

Illustration 2: **Effect of soil carbon sequestration scenario on water stress.** Difference of annual cumulative water stress in the soil layers above 60 cm and in the High and Control scenarios for the column hosting crop fraction, annually averaged over a 20 simulation years. Grid cells with organic soils (organic carbon content > 120 g C kg^{-1} soil) are excluded from the analysis.

> South Asia and the Middle East, which correspond to areas with high sand contents. The decrease in water stress reaches several meters per year in some areas (Fig. 6a), indicating that carbon sequestration reduces the accumulated soil moisture deficit below the stress threshold over the annual cycle, particularly in coarse-textured regions. These results shows the potential for reducing irrigation demands. It is however not possible to quantify the direct reduction in irrigation needs due to the way irrigation is parametrized in the CTSM, using a threshold soil moisture value that also changes with increased soil carbon.

We thank the reviewer for pointing out the confusion regarding irrigation in our simulations. In the conducted simulations, irrigation was not applied. This decision was made because it is not possible to directly quantify reductions in irrigation demand in CTSM, given the way irrigation is parameterized, as the model uses a threshold soil moisture value that would itself change with increased SOC. Running the simulations without irrigation allows us to isolate the effects of SOC on soil moisture dynamics and to fully quantify potential irrigation needs.

We clarified this in the methods section (L161–...):

> The soil column is not shared by other PFTs. The simulations assume a generic C3 crop and are conducted without irrigation to isolate the effects of SOC changes on soil moisture and water availability.

Additionally, in the water stress section (L311–...), we explicitly state the limitation regarding the quantification of irrigation reductions:

> It is not possible to directly quantify reductions in irrigation demand, as irrigation in CTSM is parameterized using a soil moisture threshold that is itself influenced by changes in soil carbon content.

Reviewer 2 Comment 10

Recent literature in effects of SOC to be considered in the discussion
Skadell, L.E., Dettmann, U., Guggenberger, G. and Don, A. (2025), Effects of Agricultural Management on Water Retention via Changes in Organic Carbon in Topsoil and Subsoil. J. Plant Nutr. Soil Sci.. https://doi.org/10.1002/jpln.70004

Response

We thank the reviewer for providing this relevant reference. We added it to the introduction of manuscript (see below), as well as to the discussion (See Reviewer 2 Comment 2). L56-64:

> A meta-analysis of 60 studies by Minasny and McBratney (2018) found that a 1% mass increase in SOC (10 gC kg^{-1} soil) corresponds to a modest gain of 1.16 mm water per 100 mm soil in available water capacity, suggesting that the influence of SOC on plant-available water may be limited. Similar findings were reported by Panagea et al. (2021), who observed no statistically significant changes in soil water retention, and by Skadell et al. (2025), who found an average increase of 1.6 mm water per 100 mm soil per 10 gC kg^{-1} SOC increase across 11 sites in Germany. In contrast, Bagnall et al. (2022) developed new SOC-sensitive pedotransfer functions based on 124 long-term research sites and reported larger increases of 3.0 mm per 100 mm soil for the same SOC increment in non-calcareous soils indicating that the magnitude of SOC effects likely depends on the empirical relationships used.

2.3 Technical corrections

Reviewer 2 Comment 11

L. 9 – how much SOC?

Response

> Global average soil liquid water content increases by 4 mm in the first 30 cm under a scenario with a uniform SOC increase of 5.5 gC kg^{-1} soil.

Reviewer 2 Comment 12

L. 82, 95, 143 and elsewhere – references missing

Response

The missing references are added throughout manuscript.

Reviewer 2 Comment 13

L. 85 – what is meant by soil energy? Matric potential?

Response

In this context, “soil energy” refers to soil temperature, representing the thermal energy contained in the soil. To avoid confusion, the text has been updated accordingly:

L85:

> Each land unit includes one or more columns that define the state variables for soil temperature and water content.

Reviewer 2 Comment 14

L. 116 – porosity is not always the same as soil water content at saturation.

Response

Porosity represents the total fraction of soil volume occupied by pores, while the water content at saturation (θ_{sat}) corresponds to the fraction of pores actually filled with water under saturated conditions, which is typically slightly lower than the total porosity due to entrapped air. We have revised the manuscript to clarify this distinction and removed references to porosity where it was used interchangeably with θ_{sat}.

Reviewer 2 Comment 15

L. 124 – equation 4 must be reviewed. The matric potential at saturation is zero.

Response

In CTSM, the saturated soil matric potential (ψ_{sat}) is not zero. Instead, it is computed as a weighted combination of the mineral and organic fractions within each soil layer, reflecting the matric potential at saturation for the mixed soil. This empirical parameter, derived from pedotransfer functions, is typically negative and represents the tension at which the soil just reaches θ_{sat}, allowing internally consistent soil water retention curves across soil types. Therefore, ψ_{sat} in the model differs from the theoretical definition of zero matric potential at saturation.

To clarify this in the methods, we added the following sentence:

> The saturated matric potential ψ_{sat} is similarly calculated as a weighted average, with the organic component fixed at -10.3 mm and the mineral component defined as $\psi_{sat,min,i} = -10.0 \cdot 10^{(1.88-0.0131 \cdot f_{sand,i})}$. Note that in CTSM, ψ_{sat} is therefore not zero but reflects the combined properties of the mineral and organic fractions in each soil layer.

$$\theta_{\text{wp}} = \theta_{\text{sat}} \cdot \left(\frac{\psi_{\text{wp}}}{\psi_{\text{sat}}}\right)^{-1/B} \tag{2}$$

Reviewer 2 Comment 16

L. 151 – constant only in year 2000?

Response

We adapted the sentence to increase clarity on this point:

> Throughout the simulations, land use is fixed to the state of the year 2000.

Reviewer 2 Comment 17

L. 172 – per cent or per mile?

Response

4 per mille equals 0.4 per cent.

> The third scenario, 4p1000, is based on the 4 per 1000 initiative and assumes an annual increase of 0.4%.

Reviewer 2 Comment 18

Table 1 – I find it confusing the mixture of % and gC/kg soil in the same table. I would also remove the + sign from the medium and high scenarios, it gives the impression that this values was added to something, when in fact it is just constant everywhere. I would also recommend more clarity to the scenario description, I read it many times and could not be sure of what they mean: constant value over the whole globe or constant addition to current values over the whole globe? If the first, then how are the model representing organic soils, that have more SOC than that?

Response

We thank the reviewer for the helpful suggestions to improve clarity in Table 1. We have removed the "(%)" from the table header, but retained it for the 4p1000 scenario. The values in Table 1 represent additions to present-day SOC and therefore are not uniform across all locations. We also revised the table caption to clarify this, and kept the "+" sign to emphasize that the values are added to current SOC.

We also added some clarity in the scenario description:

L161:

> In each scenario, carbon increases are applied to the top 30 cm of the soil column, relative to present-day SOC values.

L166:

> The first two scenarios assume uniform carbon sequestration applied globally to all cropland grid cells on top of present-day SOC.

Table 1: Soil carbon sequestration scenarios. All values are added to current SOC and correspond to SOC after 20 years.

Scenario	Δ SOC after 20 years	Reference
High	+ 5.5 gC kg soil^{-1}	Zomer et al. (2017); Sommer and Bossio (2014)
Medium	+ 2.7 gC kg soil^{-1}	Zomer et al. (2017); Sommer and Bossio (2014)
4p1000	+ 8 % of present-day SOC (gC kg soil^{-1})	Minasny et al. (2017); Rumpel et al. (2020)

Reviewer 2 Comment 19

L. 194 – how do you define FC? Do you really need to evaluate this water holding capacity since your results derive from a Richards-based model?

Response

In CTSM, field capacity is defined as the soil water content retained in each soil layer at a matric potential of -33 kPa, representing the water remaining after gravitational drainage. It is derived from soil texture, bulk density, and organic carbon content using pedotransfer functions.

We specified this in the methods on L140:

> Field capacity is defined as the soil water content in each soil layer at a matric potential of -33 kPa.

While we agree that changes in water holding capacity follow directly from the Richards equation, which governs the temporal dynamics of soil moisture, we consider it valuable to evaluate this static property. Field capacity provides a direct measure of the initial effects of SOC changes on soil porosity and retention curves and allows quantification of changes in plant-available water. Furthermore, reporting water holding capacity facilitates comparison with other studies that focus on SOC effects on this metric, such as Minasny and McBratney (2018).

Reviewer 2 Comment 20

Figure 1 – differing scales

Response

We appreciate the reviewer's observation. Figure 1 has been revised to include, alongside the spatial distribution of absolute SOC content, the corresponding sand and clay fractions (Figure 3). The increase in soil organic carbon under the 4p1000 scenario has been moved to Appendix Figure A3 (Figure 4).

All figure references and captions have been updated accordingly throughout the manuscript.

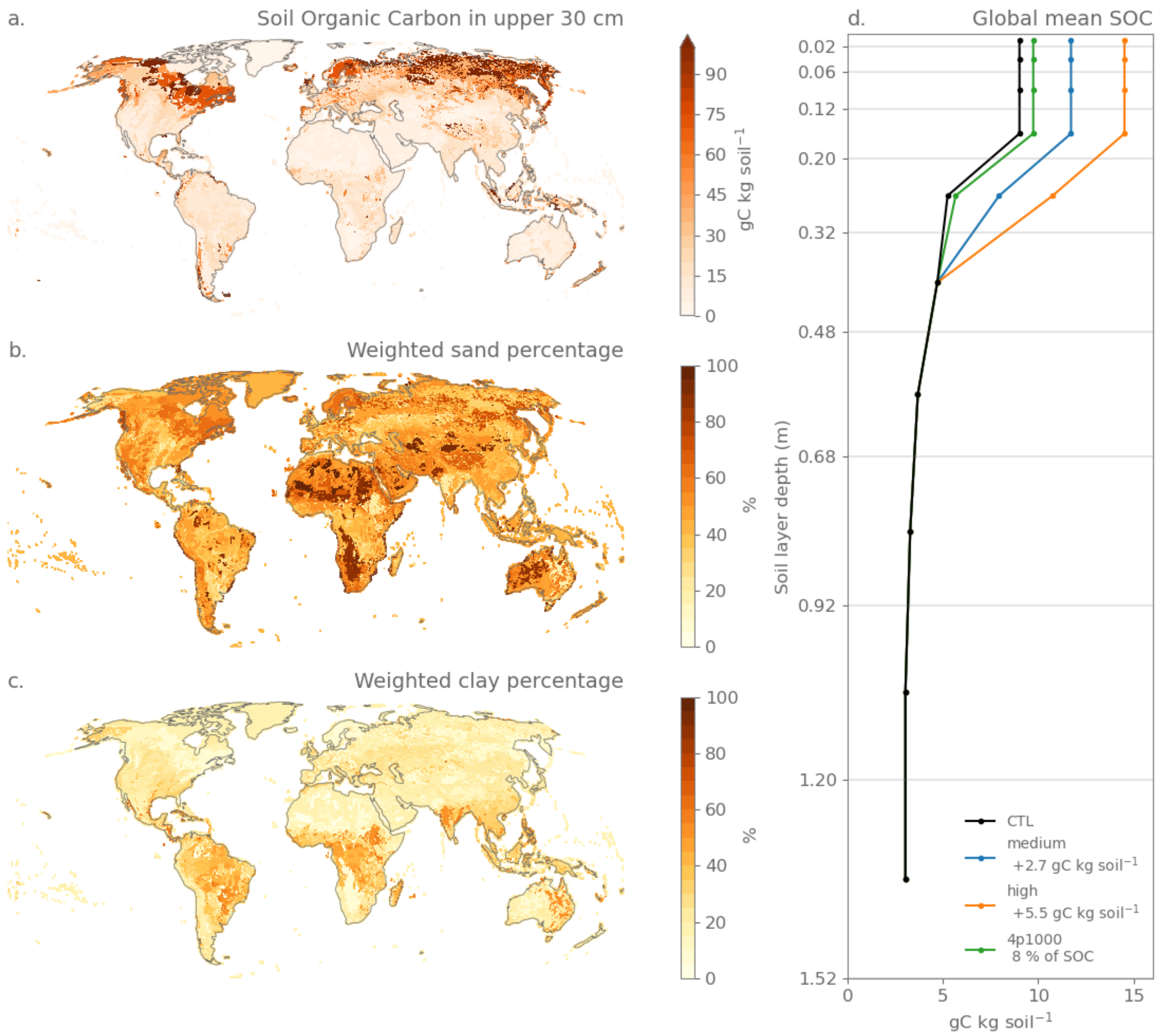

Illustration 3: **Soil Organic Carbon (SOC), soil textures and different soil carbon sequestration scenarios used as model input** Spatial distribution of SOC in the top 30 cm of soil based on the WISE30sec dataset (a), percentage sand (b) and clay (c), both weighted over the different soil layers following the WISE30sec dataset. Vertical profiles of global mean SOC in the control simulation (CTL) and the three soil carbon sequestration scenarios: medium, high, and 4p1000 (d).

Reviewer 2 Comment 21

L. 214 – wilting point soil moisture = soil water content at wilting point. Also, use either soil moisture or soil water content for consistent terminology. Is soil liquid water the same thing as soil moisture?

Response

We followed the reviewer's suggestion and replaced *soil moisture* with *soil water content* for

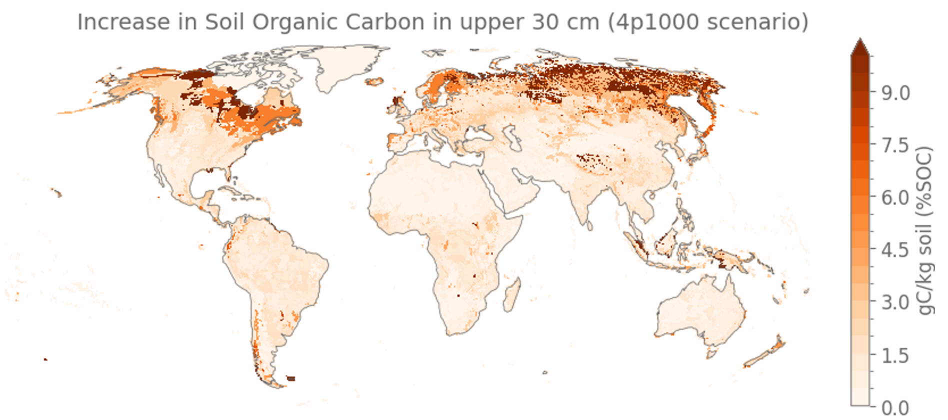

Illustration 4: Increase in SOC in the top 30 cm following the 4p1000 scenario, assuming a 0.4% annual increase of the current carbon stocks over a period of 20 years, corresponding to an 8% increase of present-day SOC

consistency. The sentence now reads:

> While soil water content at wilting point also increases, this effect is less widespread and less pronounced.

These terminology changes were applied consistently throughout the results and discussion sections (see also Reviewer 2, Comment 5) to ensure clarity and avoid confusion.

Reviewer 2 Comment 22

L. 214 – I would connect differences in soil porosity to the saturated fraction, but not necessarily to the FC. Maybe change it to "improved soil pore distribution" from the addition of SOC.

Response

We thank the reviewer for raising this, and applied the suggestion in the manuscript:

L214:

> This pattern is driven by a consistent increase in soil water content at field capacity, strongly influenced by the soil organic carbon (SOC) fraction (Appendix Fig. A4b) and reflects the model's representation of the improved soil pore distribution from added organic carbon.

Reviewer 2 Comment 23

L. 217-218 – very confusing. What is the actual water content? An average over all evaluated years?

Response

The term actual water content refers to the simulated mean volumetric soil water content (θ), averaged over the 20-year simulation period and across the soil column. To clarify, we revised the sentence as follows:

> These decreases occur when the soil water content at saturation (θ_{sat}) increases more than the mean simulated volumetric soil water content (θ), averaged over all years. This mean volumetric water content generally increases when weighted over the soil layers, with a global mean increase of 0.002 m3 m-3 (Fig. 2c).

Reviewer 2 Comment 24

L. 235 – isn't it a result of water being hold in the topsoil, therefore less input is going to deeper soils?

Response

We agree with the reviewer's interpretation and have clarified this in the text. The increase in topsoil water content indeed reflects a redistribution of water within the soil profile, with more water being retained in the upper layers and consequently less percolating downward. The revised sentence now reads:

> In the upper 32 cm of the soil, where carbon sequestration is applied, mean liquid water content consistently increases across all crop regions, with a global average increase of +4 mm (Fig. 3b) , likely reflecting a redistribution of water that is retained in the topsoil and therefore less available for percolation to deeper layers.

Reviewer 2 Comment 25

L. 242-243 – this go against your abstract: "Our results show that soil organic carbon redistributes water within the soil profile, retaining moisture in the rooting zone and limiting percolation into deeper layers, which is particularly pronounced in arid regions with sandy soils."

Response

We respectfully disagree with the reviewer's interpretation. The sentence on L242–243 ("Areas with strong declines in water content tend to correspond with more arid or sandy regions (Fig. 1b).") refers specifically to the deeper soil layers (below 32 cm; Fig. 3c). These declines indicate that in arid and sandy regions, less water percolates downward, consistent with increased water retention in the upper layers. Thus, this finding supports—rather than contradicts—the statement in the abstract.

To clarify this and avoid potential confusion, we revised the sentence as follows:

> Areas with strong declines in water content tend to correspond with more arid or sandy regions (Fig. 1b) , indicating that water is retained in the upper soil layers rather than percolating into deeper depths.

Reviewer 2 Comment 26

L. 259 – Which soil texture effects?

Response

We added the effects to the sentence:

> This pattern suggests that increased SOC in the upper layers enhances water retention in the upper layers, thereby reducing percolation and limiting the downward movement of moisture through soil texture effects increasing water retention and reducing hydraulic conductivity.

Reviewer 2 Comment 27

L. 265 – soil water storage capacity is not the same as saturation.

Response

The reviewer is right and the sentence has been updated to:

> Especially in the surface layers, the increase in saturated fraction is not fully matched by the actual increase in water content from percolation, resulting in less saturated surface soil layers.

Saturation denotes the state in which all soil pores are filled with water, whereas soil water storage capacity refers to the effective amount of water the soil can retain and make available for use, typically defined between field capacity and wilting point.

Reviewer 2 Comment 28

L. 274 – SOC sequestration

Response

We added "SOC" to the start of the sentence.

Reviewer 2 Comment 29

L. 275 – could it be that increase in SOC makes the water to be "trapped" in the topsoil and susceptible to evaporation, and therefore not available to the plant roots?

Response

<Additional feedback welcomed!>

This is possible, however carbon sequestration notably traps the water most in the lowest sequestered layer, here until 30 cm (see first row Figure 4). However, in this figure, soil evaporation might have happened already.

Reviewer 2 Comment 30

L. 283-285 – the two sentences say the same thing?

Response

We have removed the first sentence accordingly.

Reviewer 2 Comment 31

L. 375-381 – is that in the correct place?

Response

We thank the reviewer for this comment regarding the placement of the final paragraph. After the paragraph summarizing the study, this paragraph serves as a concluding statement providing a concise summary of the study's implications, highlighting potential directions for future work and connect our findings to broader climate mitigation considerations and implications, which we believe is important to retain at the end of the manuscript

Reviewer 2 Comment 32

L. 387 – ? ¨

Response

This is fixed.

3 Reviewer 3

Reviewer 3 Comment 1

The research presented in the manuscript is extremely relevant to evaluate and support ongoing policy discussion and NBS implementations of soil carbon sequestration as climate change mitigation. Specifically, to verify and validate eco-hydrological co-benefits of soil carbon sequestration at global scale as climate change mitigation following some policy-relevant scenarios. The assessment follows an implementation through earth system models, which provides a global evaluation but implies some simplification and generalization both in terms of vegetation systems under scrutiny (unmanaged C3 crop), spatial resolution (0.5 degrees) and through empirical pedotransfer functions. However, this generalization also grants an harmonized assessment to compare results across different regions worldwide.

Response

We thank the reviewer for the constructive and insightful comments. We appreciate the recognition of the study's relevance and address the specific points raised in detail below.

Reviewer 3 Comment 2

- The understanding of results would definitively benefit by a more specific and detailed description of some modelling characteristics and especially in relation to vegetation. I would emphasize for instance a more detailed linkage to the original model and technical description of the current version used in this paper. I could not find manual for CSTM v5.2 and is not clear if the CSTM is embedding the CLM v5 (line 82).

Response

We added a clarification with correct references to both the CLM v5 scientific paper and technical documentation of this starting from L81:

> The Community Terrestrial Systems Model (CTSM version 5.2) is an advanced land model that simulates physical, chemical, and biological processes in terrestrial ecosystems and climate across varying spatial and temporal scales (Lawrence et al., 2019), in which the Community Land Model (CLM 5) serves as the core land surface component (Lawrence et al., 2018).

Reviewer 3 Comment 3

Would be useful to know certain characteristics of the crop PFT like rooting depth, or crop development characteristics, in order to evaluate results. The extent of rooting depth would be relevant to evaluate eco-hydrological effects at depths below and above 32 cm.

Response

We thank the reviewer for this suggestion. Rooting depth is modeled through the vertical root distribution, which depends on the plant functional type:

$$r_i = \left(\beta^{z_{h,i-1}\cdot 100} - \beta^{z_{h,i}\cdot 100}\right) \quad \text{for } 1 \leq i \leq N_{\text{levsoi}} \tag{3}$$

with β the plant-dependent root distribution parameter, which for crops equals 0.943 (Lawrence et al., 2018).

To clarify this in the manuscript, we added the following sentence at L138:

> The vertical root distribution used in CTSM follows an exponential decay with depth, resulting in the majority of roots concentrated in the upper soil layers, which are not varying in time (Fig. 5).

We also added the following figure to the appendix for illustration:

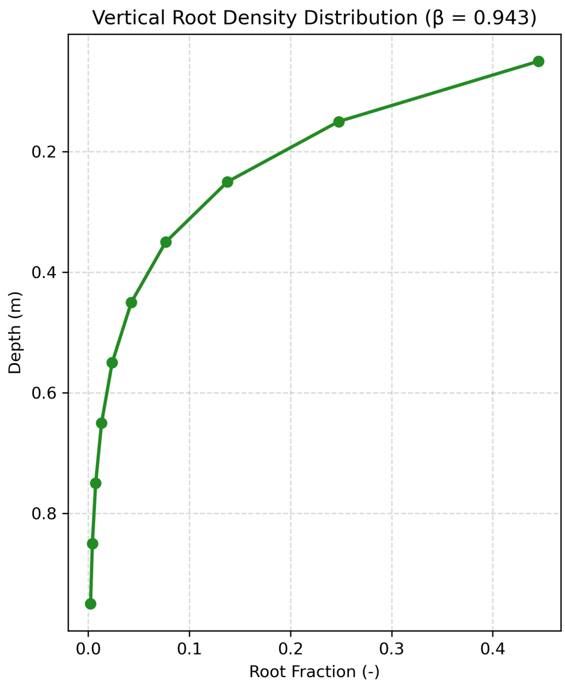

Illustration 5: Vertical root density distribution for crops, calculated using the root distribution parameter $\beta = 0.943$ following Lawrence et al. (2018). The figure shows the normalized fraction of roots per soil layer (r_i), derived from the vertical root distribution equation $r_i = (\beta^{z_{h,i-1} \cdot 100} - \beta^{z_{h,i} \cdot 100})$, where z_h denotes soil layer boundaries in meters. Depth increases downward.

Reviewer 3 Comment 4

- Moreover, authors should clarify what constitutes vegetation evaporation … I can only think of evaporation from vegetation rainfall interception, which is not linked to soil water content. This could explain why there is such a limited effect of SOC increase on vegetation evaporation. Figure 9 also may be moved to methodology, and there to better explain these concepts.

Response

We thank the reviewer for this comment. Vegetation evaporation in CTSM refers to the evaporation of rainfall intercepted by the vegetation canopy, which is modeled as a separate flux. As this process does not depend on soil water content, its response to SOC increase is indeed minimal. We have clarified this point in the manuscript as follows:

> In contrast, the impact on vegetation evaporation, i.e., evaporation from precipitation intercepted by the canopy, is minimal (Fig. 5c). This can be explained by the fact that this flux is independent of soil water content. However, because 2-meter temperature is a diagnostic variable in CTSM, a small temperature-related feedback is observed in vegetation evaporation rates.

We chose to keep Figure 9 in the discussion section, as it synthesizes the main effects of soil organic carbon on the water balance components and directly follows from the presented results.

Reviewer 3 Comment 5

- The concept behind and comparison and result across cumulative water stress and days with water stress (Page 15) require some reconciliation in the methods and explanations in the results. While n of days with water stressed refers to days with extreme water stress (theta below wilting point), cumulative water stress refers to the cumulated value when theta is lower than theta at wilting point (as specified in the methods). The latter seem quite counterintuitive and lead to difficult understanding in results (Figure 6a) where cumulative water stress can go up to 2-3 meters. Please clarify.

Response

We revised the water stress analysis by adopting a less extreme definition of water stress, namely conditions where volumetric soil water content drops below 50% of field capacity, as suggested by the reviewer. This threshold represents the onset of plant water limitation more realistically than the wilting point. In addition, we retain only the cumulative water stress metric in the updated manuscript, as we identified inconsistencies in the original calculation of "days with water stress" and found this metric less robust for interpretation.

The cumulative annual water stress represents the time-integrated deficit of root-zone soil moisture below the defined stress threshold, thereby capturing both the severity and duration of soil water limitation experienced by vegetation over a year. The resulting values (expressed in units of water depth) reflect an accumulated moisture deficit rather than instantaneous soil water storage, which explains the magnitude of the values shown in Fig. 6a. Assessing the effect of soil carbon sequestration on this integrated metric allows us to quantify its influence on the intensity and persistence of soil water stress in a consistent and physically meaningful way.

We updated the methods section to account for this change (L 224-228):

> Soil water stress conditions are defined based on a threshold relative to field capacity. Water stress occurs when the volumetric soil water content (θ) falls below 50% of the water content at field capacity (θ_{fc}). The annual water stress is then quantified as the cumulative deficit between $0.5 \cdot \theta_{fc}$ and the actual soil water content (θ), accumulated over the year and summed across the first seven soil layers ($d = 0.68$ m), representing the upper 60 cm of the soil profile corresponding to the depth affected by irrigation (Eq. 4).
>
> $$\text{Water stress} = \sum_{i=1}^{7} \sum_{month=1}^{12} (0.5 \cdot \theta_{fc,i} - \theta_{month,i}) \cdot d \qquad \text{for} \qquad \theta_{month,i} < 0.5 \cdot \theta_{fc,i} \tag{4}$$

And included the updated paragraph and figure in the results section:

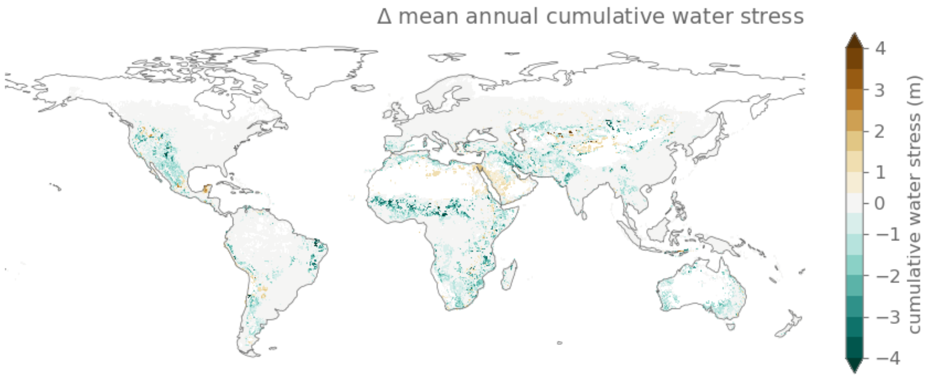

Illustration 6: **Effect of soil carbon sequestration scenario on water stress.** Difference of annual cumulative water stress in the soil layers above 60 cm and in the High and Control scenarios for the column hosting crop fraction, annually averaged over a 20 simulation years. Grid cells with organic soils (organic carbon content > 120 g C kg^{-1} soil) are excluded from the analysis.

> Annual water stress decreases across most regions, particularly in Western North America, parts of South America, the Sahel, Western Southern Africa, South Asia and the Middle East, which correspond to areas with high sand contents. The decrease in water stress reaches several meters per year in some areas (Fig. 6a), indicating that carbon sequestration reduces the accumulated soil moisture deficit below the stress threshold over the annual cycle, particularly in coarse-textured regions. These results shows the potential for reducing irrigation demands. It is however not possible to quantify the direct reduction in irrigation needs due to the way irrigation is parametrized in the CTSM, using a threshold soil moisture value that also changes with increased soil carbon.

Reviewer 3 Comment 6

- The results and in general research question are quite relevant and could bring forwards a richer elaboration in the discussion

Response

We added a discussion paragraph on the relation between SOC and water holding capacity, including the role of pedotransfer functions therein. For this, we refer to the answer to Reviewer 1 Comment 9 above.

Reviewer 3 Comment 7

- There are several typos, double punctuations, and often use of long sentences which could be shortened or made more direct for more clear understanding. Please consider a revision.

Response

We thank the reviewer for noticing this, and gave the manuscript a throughout review, correcting typos and shortening long sentences.

3.1 More specific recommendations:

Reviewer 3 Comment 8

Line 10 – Under a scenario with a uniform SOC increase of gC kg-1 soil, globally averaged total global soil liquid water content increases by 4 mm in the first 30 cm. -> How much gC? Line 10 consider rephrasing as following .... Global average soil liquid water content increases ...

Response

Thank you for noticing this typo. We corrected this in the abstract and reformulated the sentence:

> Global average soil liquid water content increases by 4 mm in the first 30 cm under a scenario with a uniform SOC increase of 5.5 gC kg^{-1} soil.

Reviewer 3 Comment 9

Line 60-65 : better to provide also some quantitative results in terms of the effect of SOC, from literature

Response

We thank the reviewer for this helpful suggestion and have added new text to the introduction that includes more quantitative context, L56-64:

> A meta-analysis of 60 studies by Minasny and McBratney (2018) found that a 1% mass increase in SOC (10 gC kg^{-1} soil) corresponds to a modest gain of 1.16 mm water per 100 mm soil in available water capacity, suggesting that the influence of SOC on plant-available water may be limited. Similar findings were reported by Panagea et al. (2021), who observed no statistically significant changes in soil water retention, and by **?**, who found an average increase of 1.6 mm water per 100 mm soil per 10 gC kg^{-1} SOC increase across 11 sites in Germany. In contrast, Bagnall et al. (2022) developed new SOC-sensitive pedotransfer functions based on 124 long-term research sites and reported larger increases of 3.0 mm per 100 mm soil for the same SOC increment in non-calcareous soils indicating that the magnitude of SOC effects likely depends on the empirical relationships used.

Reviewer 3 Comment 10

Line 140: Theta at Wp is calculated from Theta at sat through empirical functions. Such empirical functions may explain how sometimes increase of SOC may induced an estimated decrease of water holding capacity (higher theta wp??), downplaying the role of enhanced SOC especially in some more prone areas to drought (fig 2a and 2c). Wonder how water content at field capacity may decrease with increasing SOC ... fig A4 (page 25)

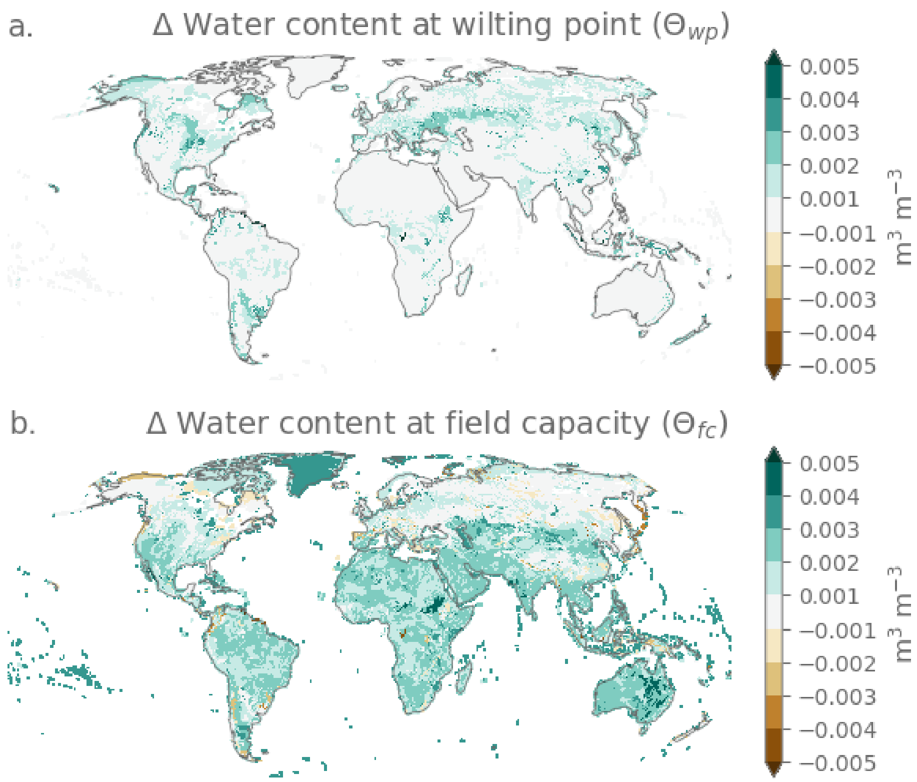

Illustration 7: **Effect of soil carbon sequestration on the water content at wilting point and field capacity.** (a.) Difference in the High and CTL scenarios for all land grid cells in the soil columns volumetric water content at permanent wilting point and (b.) field capacity, all weighted averages over the first 10 soil layers of CTSM. Grid cells with organic soils (organic carbon content > 120 g C kg^{-1} soil) are excluded from the analysis.

Response

We thank the reviewer for this comment, which prompted us to re-examine Fig. A4. The figure has been updated with the correct field capacity values (Illustration 7). As the reviewer correctly points out, field capacity can decrease with increasing SOC in some regions. This counterintuitive behavior results from the empirical pedotransfer functions used in CTSM and happens for grid cells with high SOM values. We have added a paragraph in the discussion elaborating on the limitations of these pedotransfer functions and how such relationships compare with findings from the literature (See Reviewer 3 Comment 6).

Reviewer 3 Comment 11

Line 180. Would be relevant to know how it was aggregated: WISE30sec and aggregated to the horizontal resolution of 0.5° by 0.5°

Response

The WISE30sec data were aggregated to the CTSM 0.5°by 0.5 °grid using area-weighted averaging over all underlying 30″ pixels within each grid cell, after applying the land mask.

Reviewer 3 Comment 12

Line 190-195 Some of these variables (like water holding capacity) varies through the scenarios and control, but still climate invariant

Response

The reviewer is correct. We therefore omitted the word "climatological" in the following sentence: "comparing *climatological* differences between the scenarios and CTL simulations"

Reviewer 3 Comment 13

Line 263-264 ... I thought that carbon sequestration in upper layer limits percolation to deeper layers, also from previous sentence, while here it states that it promotes water percolation into deeper layers. Please clarify any misunderstanding

Response

We thank the reviewer for pointing this out. We have clarified the wording in the text to avoid confusion between percolation within the sequestration layer and percolation below it:

> Relative increases in volumetric water content reach up to 10% at the deepest sequestration layer, with minimal seasonal variation compared to absolute values (Appendix Fig. A7). This indicates that carbon sequestration enhances water retention within the sequestration layers, thereby amplifying soil water seasonality. At the same time, it reduces the downward percolation of water into layers below the sequestration depth.

Reviewer 3 Comment 14

Figure 1. a and b seem to report SOC and increase in SOC, while in the caption indicate weighted sand percentage and clay percentage. Please verify.

Response

Thanks for pointing this out. We updated the figure caption:

> **Soil Organic Carbon (SOC) and different soil carbon sequestration scenarios used as model input** Spatial distribution of SOC in the top 30 cm of soil based on the WISE30sec dataset (a), increase in soil organic carbon in the top 30 cm following the 4p1000 scenario, corresponding to an 8% increase of present-day SOC (b). Vertical profiles of global mean SOC in the control simulation (CTL) and the three sequestration scenarios: medium, high, and 4p1000 (c).

Reviewer 3 Comment 15

279: It is odd to think that carbon sequestration boost vegetation transpiration in tropical areas, because of enhanced water availability . . . where water should not be a limiting factor. Would be possible that enhanced OM can favour the biogeochemical cycle rather than hydrological cycle.

Response

We thank the reviewer for this insightful comment. Indeed, while carbon sequestration can influence both hydrological and biogeochemical cycles, the latter is not represented in the current model configuration and therefore not captured in our analysis.

> Carbon sequestration generally boosts vegetation transpiration, suggesting that plants have more access to water (Fig. 5b). This effect is particularly notable in clay-rich regions, such as in India, Southeast Asia and the tropical rain forests. In these areas water is typically not limiting, and the effect likely reflects local increases in soil water retention and root-zone moisture storage rather than a true alleviation of water stress.

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