

Reviewer #1

(Manuscript number: egusphere-2025-4608)

We sincerely thank reviewer 1 for the thoughtful evaluation and for recognizing the novelty and timeliness of our work on incorporating hydraulic redistribution into a terrestrial ecosystem model. We also thank the reviewer for the constructive suggestions aimed at improving the presentation and emphasizing the broader implications of the work. We have carefully considered each recommendation and have revised the manuscript accordingly to enhance clarity, coherence, and impact. Reviewer comments are shown in blue italic, followed by our detailed responses. We hope these revisions address all concerns satisfactorily.

The manuscript "Hydraulic Redistribution Decreases with Precipitation Magnitude and Frequency in a Dryland Ecosystem: A Data-Model Fusion Approach" tested the incorporation of algorithms that represent hydraulic redistribution in a terrestrial ecosystem model for improved estimates of hydrological processes, which are also used to inform mechanistic understanding of hydraulic redistribution in a dryland ecosystem under different climate conditions. This is a timely and novel contribution because limited mechanistic understanding and limited modeling of hydraulic redistribution can lead to large uncertainty in estimates of hydrological processes. However, the presentation of the work can be improved to better illustrate the importance and implications of the study, and I have the following suggestions for consideration:

Response: We greatly appreciate the reviewer for the constructive assessment of our study.

1. Consider starting the introduction with soil moisture, since most readers are more familiar with that topic. Introduce matric potential and other narrower concepts before discussing hydraulic redistribution and model details. The current introduction does not flow from broad to narrow and it uses terms such as water potential before those terms receive a clear definition later on.

Response: The introduction has been revised to improve the flow from broad concepts (soil moisture) to more specific processes (water potential and hydraulic redistribution), with all technical terms now defined prior to use.

2. Consider providing more justification for model improvements and give a more detailed review of existing models and their gaps to place this study in the current literature. Connect the detailed hypotheses more clearly to the modeling activities.

Response: The justification for model development has been strengthened with a detailed review of existing modeling approaches and their limitations, and the study hypotheses are now more clearly linked to the modeling objectives.

3. State quality control procedures for the soil moisture data, and give the exact depth and time step of the soil moisture records used for parameterization. Those details are currently unclear in the methods and can only be inferred from the results.

Response: The Methods section now includes a detailed description of soil moisture data quality control procedures, as well as explicit information on the depth and temporal resolution of the records used for model parameterization, as follows:

“Soil volumetric water content (VWC) was continuously monitored using multi-sensor frequency domain capacitance probes (Decagon EC-5) installed at four depths (5, 15, 30 and 60 cm), in four soil pits under the tree canopies. All sensors were monitored every minute by a datalogger (model CR6, Campbell Scientific), and 15-minute averages were stored. For model parameterization, we used 15-min VWC records aggregated to daily means. Each sensor was calibrated in the lab before installation for both air and water frequency. Because soil temperature can affect both soil permittivity and the response of capacitance sensors, potentially confounding the small fluctuations in VWC caused by HR, temperature correction factors were applied to the measured VWC at each depth, using the nearest measured temperature, following the method described by Saito et al. (2009). Rather than excluding data below 0 °C, we used this temperature-correction approach to reduce the influence of temperature-driven artifacts on the soil moisture signal. This strategy allows retention of continuous soil moisture records while accounting for the known sensitivity of capacitance sensors to temperature-dependent changes in dielectric permittivity.”

4. Consider using an antecedent precipitation index or a similar metric to represent cumulative precipitation effects, because precipitation often produces lagged responses in hydrological processes.

Response: We thank the reviewer for this insightful suggestion. We agree that cumulative precipitation and lagged hydrological responses are important for understanding soil moisture dynamics and HR. In response, we have incorporated an antecedent precipitation index (API) to represent precipitation memory effects in our analysis.

Specifically, we added the following description to the Methods (section 2.3):

“To evaluate the influence of cumulative precipitation and soil moisture memory on HR, we calculated the Antecedent Precipitation Index (API) for the study period (2018–2021) following Kohler and Linsley (1951). API acts as a proxy for soil moisture status by accounting for the decaying effect of past rainfall events. The daily API (API_t) was calculated using the recursive decay function:

$$API_t = P_t + (k * API_{t-1}) \quad (13)$$

where P_t is the precipitation on day t (mm), API_{t-1} is the index value of the preceding day, and k is a decay constant representing the recession of soil moisture due to evapotranspiration and drainage. We used a decay constant of $k = 0.90$, which falls within the commonly applied range for antecedent precipitation indices and is consistent with optimization analyses indicating

optimal decay constants near 0.90 (Li et al., 2021). This metric enables differentiation between short dry intervals following wet conditions and extended dry spells with limited antecedent moisture."

We have updated Results (section 3.5) as follows:

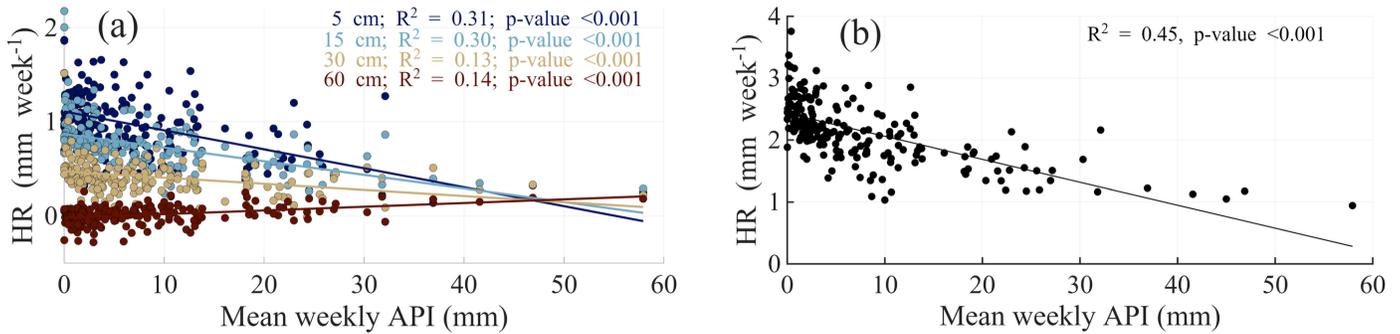


Figure 5: Relationships between hydraulic redistribution (HR) and Antecedent Precipitation Index (API). (a) Weekly HR rates versus mean weekly API at different soil depths (5, 15, 30, and 60 cm). For each depth, the trend lines, R^2 , and corresponding p-value are shown. (b) Depth-integrated weekly HR across 0–60 cm soil profile versus mean weekly API, with trend line, R^2 , and p-value.

5. Consider reducing repetition between the discussion and the results. Also consider comparing this study with similar work, expanding mechanistic explanations where needed, and discussing future implications more thoroughly to strengthen the discussion section.

Response: We have revised the Discussion to reduce overlap with the Results, added comparisons with related studies, expanded the mechanistic interpretation of our findings, and strengthened the discussion of broader implications and future directions to improve the overall depth and clarity of the section.

Specific comments:

L21: "Dryland" should be emphasized in the abstract.

Response: We have revised the opening sentence of the abstract to explicitly emphasize dryland ecosystem as follows:

“Hydraulic redistribution (HR), the movement of water via plant root systems that connect soil compartments with different water potential, should influence soil moisture dynamics particularly in dryland ecosystems, where water availability strongly constrains ecosystem function.”

L52-54: Is it necessary to have the lumped citations for this concept?

Response: Thank you for the comment. The grouped citations were included to reflect the broad body of literature demonstrating hydraulic redistribution across ecosystems and species. However, we agree that excessive clustering may reduce readability. To improve clarity, we have streamlined the citations while still acknowledging the key foundational studies. The revised sentence now includes a more focused set of representative references rather than an extended list.

L59: Try to be more specific about how often HR is ignored in models. Also consider discussing this later in the introduction to make the logic flow better.

Response: Revised as follows:

“Despite its potential role in regulating plant and ecosystem productivity, nutrient cycling and soil microbial activity (Grünzweig et al., 2022; Sardans and Peñuelas, 2014), most current dynamic global vegetation models and Earth system model still lack an explicit representation of HR (Fu et al., 2016).”

L83. Water potential was used previously before being introduced and defined here. See my suggestions about rearrangement.

Response: Following the suggested reorganization, we have revised the introduction to ensure that soil moisture is introduced first, followed by water potential.

L141. Is there quality control to remove data from the freezing point?

Response: Yes, quality control procedures were applied to address potential temperature effects on soil moisture measurements, including conditions near the freezing point. To improve clarity on soil moisture data quality control, the following text has been added to the Methods section:

“Soil volumetric water content (VWC) was continuously monitored using multi-sensor frequency domain capacitance probes (Decagon EC-5) installed at four depths (5, 15, 30 and 60 cm), in four soil pits under the tree canopies. All sensors were monitored every minute by a datalogger (model CR6, Campbell Scientific), and 15-minute averages were stored. For model parameterization, we used 15-min VWC records aggregated to daily means. Each sensor was calibrated in the lab before installation for both air and water frequency. Because soil temperature can affect both soil permittivity and the response of capacitance sensors, potentially confounding the small fluctuations in VWC caused by HR, temperature correction factors were applied to the measured VWC at each depth, using the nearest measured temperature, following the method described by Saito et al. (2009). Rather than excluding data below 0 °C, we used this temperature-correction approach to reduce the influence of temperature-driven artifacts on the soil moisture signal. This strategy allows retention of continuous soil moisture records while accounting for the known sensitivity of capacitance sensors to temperature-dependent changes in dielectric permittivity.”

Table 1: What sources are used to inform the priors for the first six parameters?

Response: The prior ranges for the soil hydraulic parameters were informed by Rawls et al. (1982) and Clapp and Hornberger (1978) and the HR related parameter (C_{RT}) by Fu et al. (2016). We have revised the text as follows:

“The prior range of soil hydraulic parameters were informed by established relationships between soil texture and hydraulic properties (Rawls et al., 1982; Clapp and Hornberger, 1978). The prior range for C_{RT} was based on values reported in Fu et al. (2016).”

L271: Is the "balanced results" expected because of the method used? If so is this more for methods than results?

Response: Yes, conservation of soil water mass balance is an expected property of the model formulation, as the TECO model explicitly enforces water conservation through its mass-balance equations. This framework is described in the Methods section, where we detail how the soil profile is divided into 10 layers (to 180 cm depth) and how volumetric water content in each layer is updated based on the balance between incoming and outgoing fluxes, including vertical unsaturated flow, evapotranspiration, precipitation, runoff, and drainage. Evaporation is restricted to the upper two layers, while transpiration is distributed across rooting layers according to the prescribed root fraction. Under the predominantly arid conditions of the study site, runoff and drainage are negligible, and water movement among layers is governed primarily by internal redistribution processes.

Although mass balance conservation is therefore a methodological expectation, we reported it in the Results section to demonstrate that incorporating hydraulic redistribution (HR) did not introduce numerical artifacts or spurious gains or losses of water. Verifying that soil water mass balance remains conserved after adding HR serves as an important diagnostic outcome of the simulations, confirming that the HR implementation is physically consistent with the original TECO model structure.

Figure 2: State how many days or percentage of days are in the "dry" and "wet" periods, respectively. If the data size is very different they may influence the interpretation of error metrics.

Response: We agree that clarifying the relative sample sizes improves the interpretation of error metrics. We found that wet days account for 22% of the total simulation periods, while the remaining 78% correspond to dry days. We have added this information to the text associated with Figure 2 as follows:

“Model performance was assessed by comparing simulated outputs with observed data during full simulation periods (2018- 2021), dry, and wet periods, defined as days without and with rainfall events, respectively. During the study period, wet days accounted for 22% of all days, whereas dry days comprised the remaining 78%.”

L426. This paragraph seems more like results than discussion.

Response: The suggested paragraph has been moved to the results under a new section 3.3 Effects of HR on soil moisture.

Technical comments:

L44: Remove the comma after "drylands".

Response: Fixed.

L70. Fix the broken citation.

Response: The broken citation has been fixed.

L132. Spell out abbreviations at their first appearances.

Response: We have revised the manuscript to spell out all abbreviations at their first occurrence.

L135. "Storing" and "store" seem repetitive.

Response: The sentence has been updated as “All sensors were monitored every minute by a datalogger (model CR6, Campbell Scientific), and 15-minute averages were stored.”

L417 and L446. The citation does not seem correct since it has the full name of an author.

Response: Thanks for pointing it out. The citation format has been corrected.

Reference

- Clapp, R. B. and Hornberger, G. M.: Empirical equations for some soil hydraulic properties, *Water resources research*, 14, 601-604, 1978.
- Fu, C. S., Wang, G. L., Goulden, M. L., Scott, R. L., Bible, K., and Cardon, Z. G.: Combined measurement and modeling of the hydrological impact of hydraulic redistribution using CLM4.5 at eight AmeriFlux sites, *Hydrology and Earth System Sciences*, 20, 2001-2018, 10.5194/hess-20-2001-2016, 2016.
- Grünzweig, J. M., De Boeck, H. J., Rey, A., Santos, M. J., Adam, O., Bahn, M., Belnap, J., Deckmyn, G., Dekker, S. C., and Flores, O.: Dryland mechanisms could widely control ecosystem functioning in a drier and warmer world, *Nature ecology & evolution*, 6, 1064-1076, 2022.
- Kohler, M. A. and Linsley, R. K.: Predicting the runoff from storm rainfall, US Department of Commerce, Weather Bureau 1951.
- Li, X., Wei, Y., and Li, F.: Optimality of antecedent precipitation index and its application, *Journal of Hydrology*, 595, 126027, 2021.
- Rawls, W. J., Brakensiek, D. L., and Saxton, K.: Estimation of soil water properties, *Transactions of the ASAE*, 25, 1316-1320, 1982.
- Saito, T., Fujimaki, H., Yasuda, H., and Inoue, M.: Empirical temperature calibration of capacitance probes to measure soil water, *Soil Science Society of America Journal*, 73, 1931-1937, 2009.
- Sardans, J. and Peñuelas, J.: Hydraulic redistribution by plants and nutrient stoichiometry: Shifts under global change, *Ecohydrology*, 7, 1-20, 2014.

Reviewer #2

(Manuscript number: egusphere-2025-4608)

We sincerely thank reviewer 2 for the thoughtful and encouraging comments. We appreciate the recognition of the significance of integrating hydraulic redistribution into the TECO model and the relevance of our findings for improving predictions of soil moisture and ecosystem processes. We are grateful for the reviewer's constructive suggestions, and we have carefully addressed all comments to improve the clarity and presentation of the manuscript. Reviewer comments are shown in blue italic, followed by our detailed responses. We hope these revisions address all concerns satisfactorily.

This study integrated the hydraulic redistribution into a process-based ecosystem model (TECO) and found that the TECO with HR greatly improved model prediction of soil moisture during dry periods in a pinon-juniper woodland. The authors also found that the HR decreased with increasing precipitation magnitude and frequency and that upward HR in the top 60 cm was more pronounced as dry conditions progressed. This is a very interesting and meaningful study. As soil moisture is a key factor regulating ecosystem processes, this work provided an important foundation for further improving the capacity of ecosystem models to predict carbon and water cycles. I only had a few minor comments, which could help further enhance the clarity of the manuscript. Please see the comments below.

Response: We appreciate the reviewer's accurate summary of our study, positive evaluation, and helpful comments that have improved the manuscript's clarity.

L47: Altered precipitation

Response: Corrected.

L152–154 Please specify the total depth of the soil profile, which would save readers the effort of summing the individual soil layers.

Response: We have revised the text to explicitly state the total depth of the modeled soil profile, as follows:

“The soil profile is divided into 10 layers with a total depth of 180 cm, with varying thickness: 5 cm for the first layer; 10, 15, and 30 cm for the second, third, fourth layers, respectively; and 20 cm for each of the fifth through tenth layers.”

In addition, it appeared that the data assimilation was applied only to the upper four soil layers, whereas the remaining deeper layers were not considered, despite the soil profile being divided into ten layers. Please clarify this point.

Data assimilation was applied only to the upper four soil layers (5, 15, 30, and 60 cm), because soil moisture observations were available only at these depths. The remaining deeper layers were included in the model to represent the full soil profile and to allow simulation of vertical water

movement. However, they were not directly constrained by observations and therefore were not included in the parameter optimization.

This approach reflects common practice in hydrological and land surface data assimilation studies, where models resolve multiple soil layers to capture vertical hydrological processes, but observational data are typically available only for certain soil depths. For example, Fu et al. (2016) represented a multi-layer soil profile in CLM4.5+HR to simulate hydraulic redistribution effects throughout the soil column, despite limited observational constraints at depth. Similarly, Zhang et al. (2016) assimilated soil moisture at available depths while relying on model physics to represent deeper subsurface dynamics.

Parameters for the deeper layers in our study were prescribed based on soil texture information and values reported in the literature and were held fixed during data assimilation. This strategy allowed the model to simulate each soil layer moisture. We have clarified this point in the revised manuscript to avoid confusion, as follows:

“To evaluate the impact of HR on soil moisture dynamics in a PJ woodland, we conducted two multi-year simulations using two configurations of the TECO model: TECO+HR (with HR) and default TECO (HR turned off). To distinguish the influence of HR from soil hydraulic properties, we adopted a data assimilation approach focused on calibrating only the TECO+HR model. Soil moisture observations were available at 5, 15, 30 and 60 cm depths, and data assimilation was therefore applied only to these four soil layers over a four-year period and data-model comparisons are presented exclusively for these depths. The parameters values deeper than 60 cm were not calibrated and were empirically defined from literature values. This modeling strategy is consistent with other data assimilation studies, in which model calibration is restricted to soil layers with available observations (Fu et al., 2016; Zhang et al., 2016)”

L188 Please explain what the subscript j represents, as this would help clarify the meaning of R_j and soil matric potential associated with index j .

Response: Thank you for helpful suggestion. In Eq. (6), the subscript j denotes the other soil layers interacting with layer i through hydraulic redistribution. Thus, Ψ_j represents the soil matric potential of layer j , and R_j represents the root fraction in layer j . We have clarified this in the text to ensure the meaning of the indices is explicit.

“Using these assumptions, the net water movement into soil layer i from other soil layers j can be expressed as:”

L204–205 Please specify then number of parameters that were optimized in the model.

Response: We have now explicitly specified the total number of parameters optimized through data assimilation. The TECO+HR model optimized 21 parameters in total, including 20 soil hydraulic parameters (θ_s , θ_r , K_s , m , and Ψ_b for each of the four soil depths) and one HR-related parameter (C_{RT}). This information has been added to the revised text as follows:

“In total, 21 parameters were optimized including 20 soil hydraulic parameters (θ_s , θ_r , K_s , m , and Ψ_b for each of the four soil depths) across four soil layers and one HR-related parameter (C_{RT}).”

L233–235 During the spin-up period, did you use the default TECO model?

Response: Thank you for this comment. Because the two model configurations (TECO+HR and default TECO) were simulated separately with the same optimized parameters values, each model required its own spin up to establish consistent initial conditions. Accordingly, we performed a 200-year spin-up for both configurations, with each model using its respective process (HR active in TECO+HR and HR inactive in default TECO).

To clarify this in the manuscript, we have revised the text as follows:

“Before each model simulation, we performed a 200-year spin-up separately for both model configuration (TECO+HR with HR active and default TECO with HR disabled) to ensure that each model reached stable carbon stocks as initial conditions.”

L255–256 Please explain the rationale for using these two different metrics to evaluate model performance.

Response: Thank you for pointing this out. We have clarified the rationale for using both RMSE and MAE in evaluating model performance as follows:

“Model performance was evaluated using two statistical metrics: root mean square error (RMSE) and absolute mean error (MAE). RMSE is widely used to quantify model accuracy, but its squared-error formulation overemphasizes the effects of large deviations (Willmott and Matsuura, 2005). Therefore, MAE was also calculated as a measure of the average magnitude of deviation from observed values (Alfieri et al., 2017). Both metrics were calculated as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (m_i - o_i)^2} \quad (13)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |m_i - o_i| \quad (14)$$

Where: o_i represents observed values, m_i represents modeled values, and n represents the number of data points.”

L285 “Vertical bars indicate”: Missing information here. It is hard to see any vertical bars in the figure. Also, please indicate what the different colors represent in the figure legend.

Response: We have updated Figure 1 by changing the precipitation curve from an area plot to bar graph to improve clarity and we have corrected the caption accordingly.

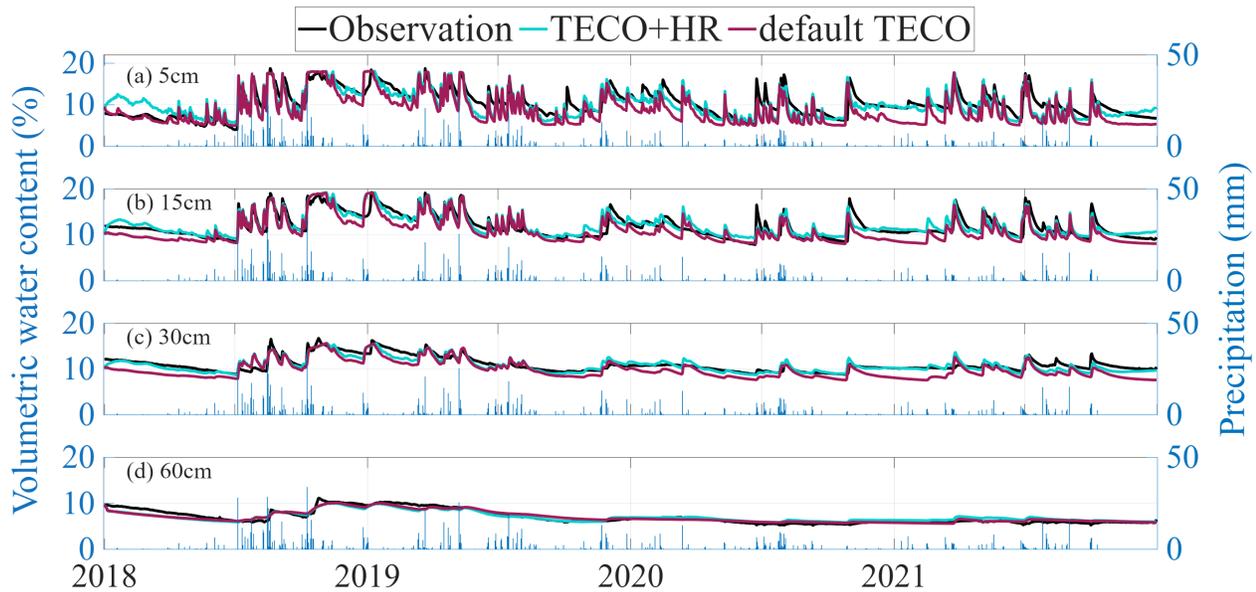


Figure 1a-d: Observed and simulated soil volumetric water content for the year 2019 (January 1, 2018 to December 31, 2021) at soil depths of 5 cm (a), 15 cm (b), 30 cm (c), and 60 cm (d). Black lines indicate observations, cyan lines indicate TECO+HR, and magenta lines indicate default TECO. Vertical blue bars indicate daily precipitation (right axis).

Figure 2 Please include a sentence in the figure legend to indicate that smaller values of the metrics correspond to better model performance. Please include the unit for the x-axis label.

Response: We have updated Figure 2 to include x-axis unit and caption as follows:

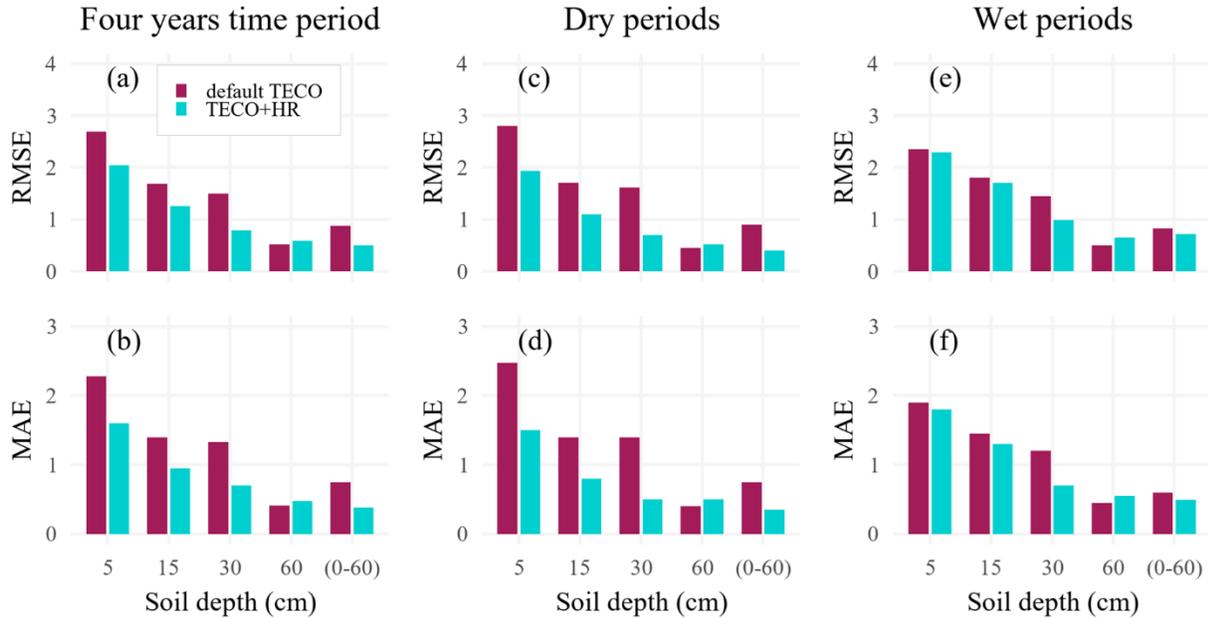


Figure 2: Model performance for soil moisture across different depths (5, 15, 30, and 60 cm, and 0-60 cm integrated soil profile), considering temporal variations in soil moisture conditions. Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) are presented for the complete time series (a, b), dry periods (c, d), and wet periods (e, f). Lower values of RMSE and MAE indicate better model performance.

L358–360 Only after reading this section did I realize why the bottom five layers were shown in Fig. 3. Including this information in the Methods section would help prevent reader confusion.

Response: We clarified it in the methods as follows:

“Soil moisture observations were available at 5, 15, 30 and 60 cm depths, and data assimilation was therefore applied only to these four soil layers over a four-year period and data-model comparisons are presented exclusively for these depths.”

Fig. 5 While I understood that $\log_{10}(\text{days}+1)$ was used on the x-axis to deal with zero values, it would be helpful to indicate this clearly in the figure legend.

Response: Thank you for the suggestion. We have now updated the Figure 5 caption to explicitly state the uses of $\log_{10}(\text{days}+1)$ as follow:

“The x-axis shows dry spell length transformed as $\log_{10}(\text{days} + 1)$ to allow inclusion of zero-length dry spells.”

L417 Correct “Xing Ming Hao et al.” to “Hao et al.”.

Response: Corrected

L426–433 It seemed that Figs. 1 and 6 were based on the same dataset, but presented differently. Is my understanding correct? If so, I would suggest considering combining Fig. 6 with Fig. 1 to avoid redundancy. Additionally, the content in this paragraph seems more appropriate for the Results rather the Discussion section.

Response: Thank you for your thoughtful comment. Figure 1 and figure 6 (Figure 3 in revised version) are indeed derived from the same underlying soil moisture dataset. However, they serve distinct analytical purposes. Figure 1 presents the absolute observed and simulated soil moisture time series across depths, allowing readers to evaluate how well the two model configurations reproduce seasonal and event-scale dynamics. In contrast, Figure 6 (fig. 3 in revised version) presents the relative change in simulated soil moisture attributable to HR, expressed as percent difference between TECO+HR and default TECO. This figure illustrates the magnitude and depth-dependent effect of HR, which cannot be inferred from Figure 1 alone.

Because these figures highlight different aspects of model behavior, model-data agreement (Fig. 1) versus HR-induced changes in soil water content, we believe combining them would reduce clarity and hinder interpretation. We therefore prefer to keep them as separate figures.

Regarding placement, we appreciate the reviewer’s observation. The paragraph in question has now been moved from the Discussion to the Results section in section 3.3 Effect of HR on soil moisture.

L450 Please correct to “Ryel et al. (2002)”.

Response: Corrected.

L458 “(typically from November to May)”

Response: Corrected.

L459 “(usually from June to October)”

Response: Corrected.

L471–472 “reported by Howard et al. (2009) and Neumann et al. (2014), which could...”?

Response: Corrected.

L481–484 Please rewrite this sentence so that the two subsequent clauses convey consistent meanings.

Response: We have revised the suggested sentence as follows:

“Our model results indicate that HR rates vary in response to the duration of dry spells between rainfall events. Generally, HR rates tend to increase as soil becomes drier and decreases with increasing precipitation magnitude and frequency. Across the wet to dry transition, HR rates exhibit a range of 0.10 to 0.50 mm d⁻¹.”

Reference

- Alfieri, J. G., Anderson, M. C., Kustas, W. P., and Cammalleri, C.: Effect of the revisit interval and temporal upscaling methods on the accuracy of remotely sensed evapotranspiration estimates, *Hydrology and Earth System Sciences*, 21, 83-98, 10.5194/hess-21-83-2017, 2017.
- Fu, C. S., Wang, G. L., Goulden, M. L., Scott, R. L., Bible, K., and Cardon, Z. G.: Combined measurement and modeling of the hydrological impact of hydraulic redistribution using CLM4.5 at eight AmeriFlux sites, *Hydrology and Earth System Sciences*, 20, 2001-2018, 10.5194/hess-20-2001-2016, 2016.
- Willmott, C. J. and Matsuura, K.: Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance, *Climate research*, 30, 79-82, 2005.
- Zhang, D., Madsen, H., Ridler, M. E., Kidmose, J., Jensen, K. H., and Refsgaard, J. C.: Multivariate hydrological data assimilation of soil moisture and groundwater head, *Hydrology and Earth System Sciences*, 20, 4341-4357, 2016.

Reviewer #3

(Manuscript number: egusphere-2025-4608)

We sincerely thank the reviewer 3 for the thoughtful and positive evaluation of our manuscript. We greatly appreciate the reviewer's assessment of the study design, modeling framework, and clarity of presentation.

All specific comments and suggestions have been carefully considered and addressed in the revised manuscript to further improve clarity. Reviewer comments are shown in blue italic, followed by our detailed responses. We hope that the revisions satisfactorily address all concerns and strengthen the manuscript for publication.

This study uses a modeling approach to investigate the impacts of hydrologic redistribution (HR) on soil moisture dynamics in semi-arid woodland ecosystems. The authors incorporated HR into the TECO model and optimized model parameters using Bayesian MCMC techniques constrained by field soil moisture observations. The enhanced model substantially improved soil moisture simulations, particularly for surface soils during dry periods. The results indicate that HR increases surface soil moisture, with both its rate and magnitude closely linked to dry conditions.

Response: We appreciate the reviewer's accurate summary of our study.

Overall, this is a well-designed and interesting study with important implications, as soil moisture plays a dominant role in regulating the structure and functioning of dryland ecosystems. Incorporating HR into ecosystem models has strong potential to improve predictions of plant growth as well as ecosystem water and carbon cycling. The TECO model has been widely and successfully applied to dryland systems, and the Bayesian optimization framework used here has been shown to be effective. The impacts of HR are clearly presented, particularly with respect to depth-dependent responses, diurnal and seasonal dynamics, and relationships with precipitation events. Potential limitations of the study are appropriately discussed. The manuscript is generally well written and easy to follow. I have no major concerns and recommend minor revision.

Response: We greatly appreciate the reviewer for the positive assessment of our study.

Specific comments:

L31: Consider deleting "mostly during dry periods," as this is already stated in L29.

Response: Deleted

L35: "Likely role" seems tentative. Since this study explicitly demonstrates the role of HR, consider using more definitive wording.

Response: Revised the sentence as follows:

“These findings highlight that HR plays a critical role in sustaining soil moisture during extended dry periods and has a limited effect during precipitation events.”

L69, L417: For “Xing-Ming Hao,” consider deleting “Xing-Ming” and using “Hao et al.” for consistency.

Response: Corrected

L70: Citation appears as “{Hultine, 2003 #211}”; please correct formatting.

Response: Corrected

L74: Replace “understood” with “limited.”

Response: Corrected

L86: Clarify “plant availability” (e.g., “availability for plant uptake”).

Response: Replaced plant availability with availability for plant uptake.

L134–135: Please revise this sentence for clarity.

Response: Revised the sentence as follows:

“All sensors were monitored every minute by a datalogger (model CR6, Campbell Scientific), and 15-minute averages were stored.”

L174: Please clarify how parameter m was determined.

Response: We have clarified how m and other parameters were determined as follows”

“To evaluate the impact of HR on soil moisture dynamics in a PJ woodland, we conducted two multi-year simulations using two configurations of the TECO model: TECO+HR (with HR) and default TECO (HR turned off). To distinguish the influence of HR from soil hydraulic properties, we adopted a data assimilation approach focused on calibrating only the TECO+HR model. Soil moisture observations were available at 5, 15, 30 and 60 cm depths, and data assimilation was therefore applied only to these four soil layers over a four-year period and data-model comparisons are presented exclusively for these depths. The parameters values deeper than 60 cm were not calibrated and were empirically defined from literature values. This modeling strategy is consistent with other data assimilation studies, in which model calibration is restricted to soil layers with available observations (Fu et al., 2016; Zhang et al., 2016). In total, 21 parameters were optimized including 20 soil hydraulic parameters (θ_s , θ_r , K_s , m , and Ψ_b for each of the four soil depths) across four soil layers and one HR-related parameter (C_{RT}). The prior range of soil hydraulic parameters were informed by established relationships between soil texture and hydraulic properties (Rawls et al., 1982; Clapp and Hornberger, 1978). The prior range for C_{RT} was based on values reported in (Fu et al., 2016)”

Fig. 1: While TECO+HR generally simulates SWC well, some model–observation mismatches may reflect measurement issues. For example, at 5 cm depth, a soil moisture peak occurs prior to 2020 without a corresponding precipitation event, and in 2021 soil moisture shows a smooth decline that may indicate limited sensor sensitivity to precipitation.

Response: Thank you for this comment. We agree that some of the mismatches between modeled and observed soil water content (SWC), particularly at 5 cm depth, likely reflect measurement limitations. Shallow soil moisture sensors are sensitive to sensor–soil contact, microscale heterogeneity, and rapid evaporative dynamics, which can lead to apparent fluctuations not always associated with precipitation (Miele et al., 2023; Cattray et al., 2025).

The soil moisture peak observed prior to 2020 without a corresponding rainfall event may therefore reflect localized redistribution or sensor response effects, as similar patterns are not evident at deeper depths. Likewise, the smooth decline in surface SWC during 2021 is consistent with periods when initial rainfall is largely offset by evaporation following prolonged dry conditions, resulting in muted soil moisture responses (Asadollahi et al., 2022). We have clarified this interpretation in the revised manuscript.

“Minor mismatches at the topsoil (5 cm) likely reflect the complexity of near-surface processes that are not fully represented in simplified models and potential sensor lag due to imperfect soil contact, as similar discrepancies are not observed at deeper layers. In addition, following prolonged dry periods, initial rainfall can be largely offset by evaporation, resulting in muted surface soil moisture responses (Miele et al., 2023; Cattray et al., 2025; Asadollahi et al., 2022).”

Fig. 6: The figure requires clearer explanation. The impacts of HR are not easy to discern from the current presentation. In addition, the color gradient is confusing, as similar colors appear to represent both low and high values, making it difficult to interpret the magnitude and direction of HR effects.

Response: We have revised Figure 6 to use a continuous color gradient from minimum to maximum values. We hope the changes make both the magnitude and direction of the HR effects easier to interpret. In addition, following other reviewers' suggestions, we have moved this figure to Section 3.3 of the Results, and it is now presented as figure 3.

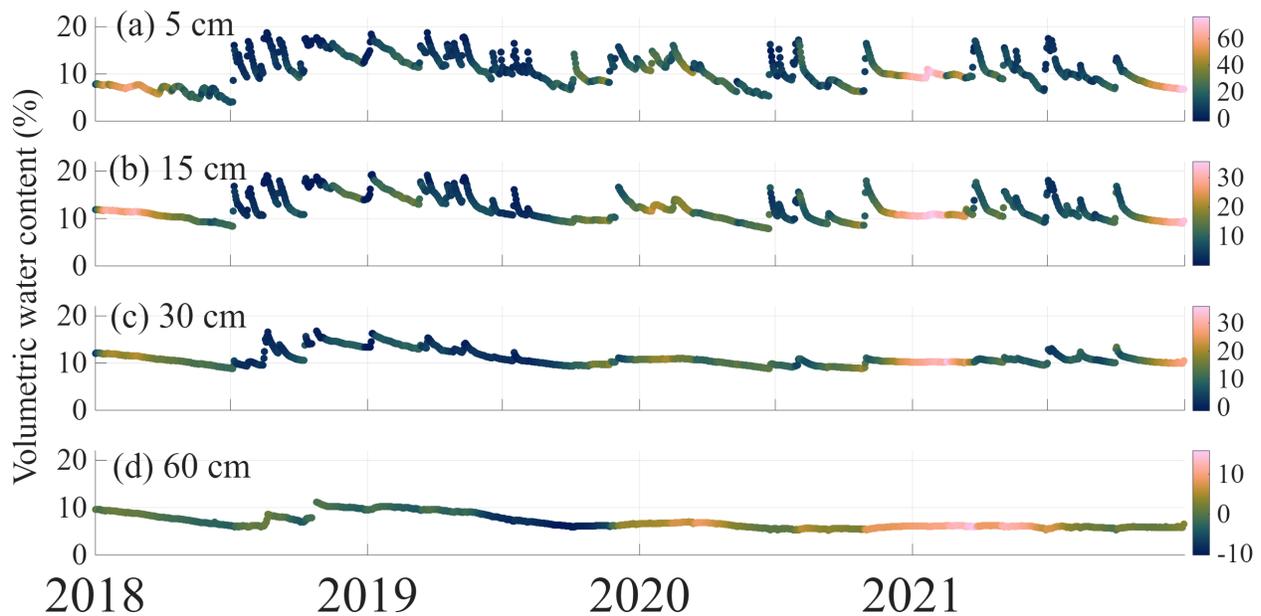


Figure 3: Observed volumetric water content (solid curves) at (a) 5 cm, (b) 15 cm, (c) 30 cm, and (d) 60 cm soil depths from 2018-2021. The overlaid color gradient denotes the relative change in soil water content (%) between simulations with and without HR, calculated as $(HR - \text{No HR}) / \text{No HR} \times 100$, where HR and No HR represent simulations with and without hydraulic redistribution, respectively."

L446: Please check citation formatting (e.g., "Hao et al., 2013") and ensure consistency elsewhere (e.g., L450).

Response: Corrected

L471: Please change to "Howard et al. (2009) and Neumann et al. (2014)"

Response: Corrected

Reference

- Asadollahi, M., Nehemy, M. F., McDonnell, J. J., Rinaldo, A., and Benettin, P.: Toward a closure of catchment mass balance: Insight on the missing link from a vegetated lysimeter, *Water Resources Research*, 58, e2021WR030698, 2022.
- Cattry, M., Miele, F., Wang, S., Frutschi, M., and Rinaldo, A.: Evaluating nitrate removal and travel times in a bare deciduous forest soil through a column tracer experiment, *Catena*, 258, 109204, 2025.
- Clapp, R. B. and Hornberger, G. M.: Empirical equations for some soil hydraulic properties, *Water resources research*, 14, 601-604, 1978.
- Fu, C. S., Wang, G. L., Goulden, M. L., Scott, R. L., Bible, K., and Cardon, Z. G.: Combined measurement and modeling of the hydrological impact of hydraulic redistribution using CLM4.5 at eight AmeriFlux sites, *Hydrology and Earth System Sciences*, 20, 2001-2018, 10.5194/hess-20-2001-2016, 2016.
- Miele, F., Benettin, P., Wang, S., Retti, I., Asadollahi, M., Frutschi, M., Mohanty, B., Bernier-Latmani, R., and Rinaldo, A.: Spatially explicit linkages between redox potential cycles and soil moisture fluctuations, *Water Resources Research*, 59, e2022WR032328, 2023.
- Rawls, W. J., Brakensiek, D. L., and Saxton, K.: Estimation of soil water properties, *Transactions of the ASAE*, 25, 1316-1320, 1982.
- Zhang, D., Madsen, H., Ridler, M. E., Kidmose, J., Jensen, K. H., and Refsgaard, J. C.: Multivariate hydrological data assimilation of soil moisture and groundwater head, *Hydrology and Earth System Sciences*, 20, 4341-4357, 2016.