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Title: A Study of the Dependence between Soil Moisture and Precipitation in different Ecoregions of the Northern Hemisphere

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We highly appreciate the anonymous reviewer for the very helpful and insightful comments that lead to the significant improvement of the quality of this manuscript. We have checked our work carefully according to these comments and made the requested changes. For point to point response, we indicate the comments and use blue font for our responses.

Anonymous Referee #1

The study investigates the relationship between soil moisture and precipitation, but a lot needs to be clarified. First, it is stated in the abstract that soil moisture is jointly affected by precipitation and evapotranspiration, but there is no description of evapotranspiration in the abstract. Secondly, the respective roles of Ridge regression models and Bayesian generalized non-linear multivariate multilevel models in attribution need to be explained. What causes the differences in dependencies between land cover types? How do these differences come about? There is no consensus on what common features these land covers have. Finally, the effects on seasonal scales and interannual scales look more like the usual conclusions, and it is not clear that this work finds something new based on these traditional results.

Response: Thanks for your thorough review, and we appreciate for your insightful comments. In the response, we have highlighted the major findings of the study, reorganized the logical flow among the three key components, and revised both the Results and Discussion sections. Additionally, we have added Figure 6 reflecting the results on annual scale and Figures S3 and S4 reflecting the accuracy of the copula functions. We hope that the revised version can lead to significant improvement of the manuscript.

I suggest a major revision. Please see my comments below:

Major Comments

1. In the introduction, the linear or nonlinear relationship here is a model for estimating soil moisture by precipitation, whereas copula is a distribution function, they should not be compared together. Ridge regression is an important method in the abstract, but it is not mentioned in the introduction. What role does ridge regression play?

Response: This study employs the joint distribution of precipitation and soil moisture to capture their nonlinear relationship. The copula function is a multivariate statistical method that can describe the dependency relationships between multiple variables through their joint distribution as a compound event. The statistic Kendall's τ

generated form the copula function can be served as an effective measurement, if the relationship between precipitation and soil moisture is nonlinear. Therefore, copula function approach is used to investigate the nonlinear dependence between precipitation and soil moisture in this study. We have added further clarification on this point in the manuscript.

Ridge regression is used in this study to quantify the relative influence of precipitation amount, precipitation frequency, and evapotranspiration on soil moisture. We have included a corresponding explanation in the introduction.

“This study established ridge regression models for precipitation amount, precipitation frequency, evapotranspiration, and soil moisture to quantify the relative influence of precipitation and evapotranspiration on soil moisture. As an improvement of the least squares estimation method, it can handle the multi-collinearity problems of the covariates, although it is usually biased.”

2. In the material and method, the joint probability of copula considers soil moisture and precipitation, ridge regression considers precipitation and evapotranspiration to predict soil moisture, Bayesian generalized non-linear multivariate multilevel models consider GPP, LST, and temperature to predict soil moisture and precipitation, what is the relationship between these three methods that seem to be simply spliced together. Why choose these models and how accurate are they in the simulation?

Response: Previous studies have found a negative correlation between precipitation and soil moisture; however, such findings often lack spatial generality. To address this, the first part of our study establishes a joint distribution to capture the nonlinear monotonic relationship (dependence) between precipitation and soil moisture, confirming the consistent presence of this negative dependence across multiple temporal scales. The second part investigates how changes in precipitation characteristics influence the control exerted by precipitation and evapotranspiration on soil moisture. A ridge regression model is constructed to quantify whether the observed negative dependence between precipitation and soil moisture across different regions is primarily driven by precipitation or by evapotranspiration. This model has a particular focus on the strength of evapotranspiration, which is treated as a driving factor. The third part explores the roles of air temperature, land surface temperature, and GPP in modulating the dependence between precipitation and soil moisture, and identifies region-specific patterns. The Bayesian nonlinear multivariate multilevel model is particularly employed in this study, since it can accurately capture both individual and interactive effects of multiple drivers on the regulation of precipitation–soil moisture relationships.

To ensure model accuracy, the MCMC samples were extracted from the Bayesian model and the Rhat values was computed for convergence diagnostics. Furthermore, to ensure the statistical soundness of the selected copula function, we calculated the Akaike Information Criterion (AIC) and time lag for each grid and use it to verify the appropriateness of the chosen copula function and time lag.

The relevant information on model accuracy has been included in the Appendix as follows. The related sentences were added to the manuscript.

"To address the potential delayed response of soil moisture to precipitation, lagged correlation analysis was conducted. For each grid cell, the AIC value was calculated to select copula function (Fig. S3), then the Kendall's tau correlation was calculated between precipitation and soil moisture with time lags ranging from 0 to 12 months (Fig. S4). The lag corresponding to the maximum absolute correlation was identified as the optimal lag."

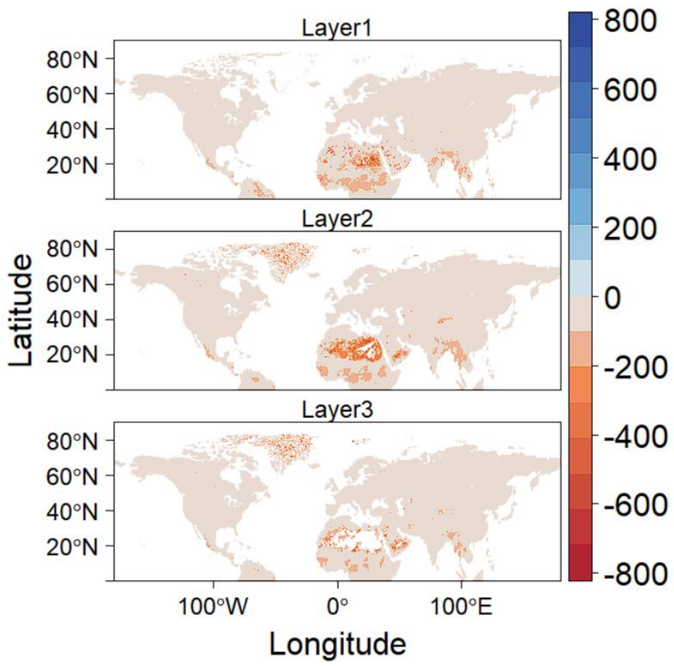

Fig. S3 The AIC value for each grid in the selection of copula function.

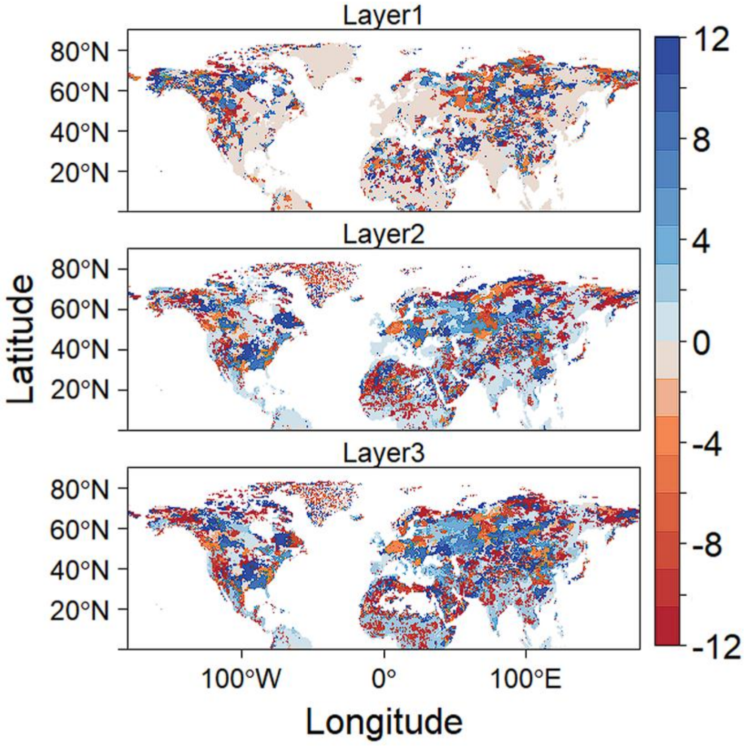

Fig. S4 The estimated number of lagged month for each grid in the the Kendall's tau correlation.

3. In Section 3.1, for example in northwest Africa, why is there a negative dependence between the soil moisture at the first layer and precipitation while a positive dependence between the soil moisture at the second layer and precipitation, and what causes the difference between the different layers? Is there any connection

between the result expressed by λU/λL and Kendall's tau, and why do many grids have no value in the result expressed by λU/λL?

Response: In this study, different copula methods were applied to construct the joint distribution across different grid cells. However, we selected the method with high goodness-of-fit, even though some of these copula functions do not support the estimation of λU and λL. Therefore, the Kendall's τ as the primary indicator was emphasized and the calculation of λU and λL could be omitted in regions where the applied method does not support their estimation.

The results in Sections 3.2 and 3.3 further indicated that the variation in correlation across different soil depths is driven by multiple factors, including air temperature, vegetation root distribution, and ecosystem characteristics. In the joint distribution framework, Kendall's τ characterizes the overall monotonic relationship of the full time series, while λU and λL represent tail dependence under extreme conditions, capturing the dependence between precipitation and soil moisture during extreme drought or extreme wetness.

4. In Section 3.1, the monthly scale and annual scale are used, but in Section 3.2, the monthly scale and seasonal scale are used, so it is recommended to unify the comparison scale.

Response: Thanks for your suggestion. The results of annual scale have been added in Section 3.2 as follows.

"At the annual scale, precipitation amount exerts a dominant influence across all three soil depth layers, accounting for more than 40% of the total area (Fig. 6). The spatial extent of areas dominated by precipitation amount, precipitation frequency, and evapotranspiration remains largely consistent with that observed at the monthly scale. The regions dominated by precipitation frequency are still primarily located in high-latitude areas, particularly in Greenland and the northern parts of Canada, although no distinct ecological zone patterns are observed in these areas. Regions dominated by precipitation amount are mainly distributed across boreal forests, temperate grasslands, savannas and shrublands, temperate broadleaf and mixed forests, as well as tropical and subtropical moist broadleaf forests. In temperate regions, soil moisture is primarily controlled by precipitation amount due to moderate temperatures and limited rainfall, making substantial precipitation is essential for soil moisture replenishment. In contrast, tropical and subtropical regions experience high temperatures and intense evapotranspiration, requiring substantial precipitation to maintain a water balance."

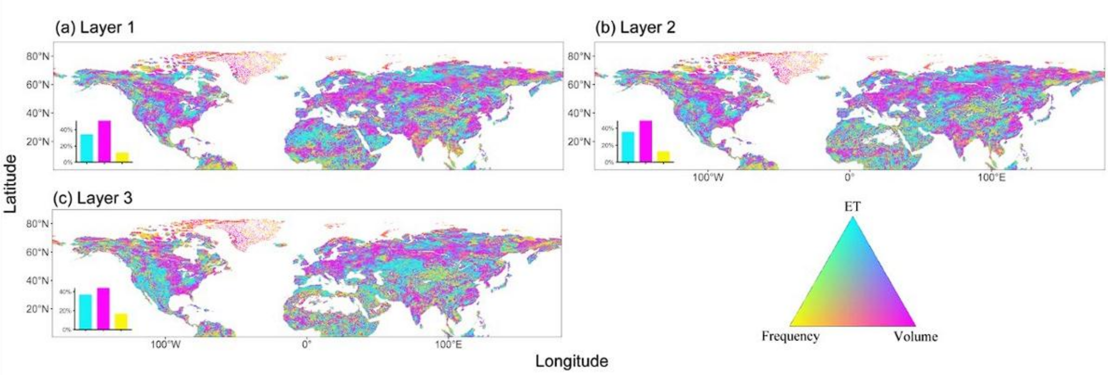

Fig. 6 Ternary map of factors controlling soil moisture at annual scale, for the period 2000 to 2019. The bottom-left histogram in the subgraph represents the proportion of grid cells where one variable exerts strong univariate control (with a regression coefficient greater than 75% of the total sum of the three variables), suggesting that soil moisture was predominantly controlled by that specific variable.

5. There are too many descriptions in section 3.3, and scatters of different land cover types in figures 6 and 7 are not clear. The large number of listed results makes it difficult to distinguish the commonalities and differences between different land cover types, and why there are differences between different soil layers. Part of the discussion should be summarized in the results, and the discussion should add references.

Response: Thanks for your comment. Section 3.3 has been re-written and Figures 6 and 7 has been re-plotted as follows, which were numbered as Figures 7 and 8 in the revised version.

"3.3 Drivers of negative dependencies between soil moisture and precipitation

For each model in this study, four MCMC chains were used for iterative sampling. The sampling results demonstrated that the chains for both the monthly and annual scales were well-distributed in the parameter space, with no noticeable trends or drifts, indicating convergence to the target posterior distribution. The convergence was considered satisfactory, with all models yielding a Rhat value below 1.05 (Fig. S1, S2).

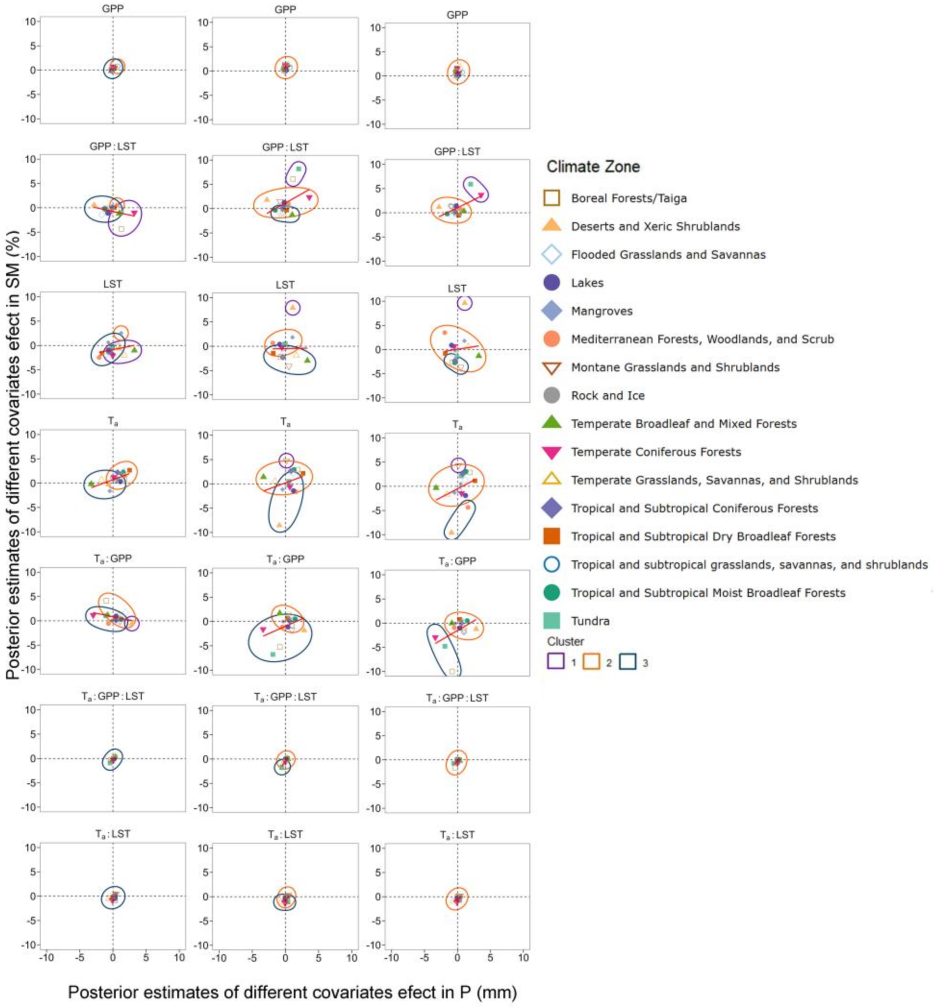

Fig. 7 Posterior estimates of the covariate variables of the Bayesian generalized non-linear multivariate multilevel model, built using monthly data. The columns represent soil depths of 0 to 7 cm, 7 to 28 cm, and 28 to 100 cm. Red lines indicate linear regressions of precipitation and soil moisture across all ecoregions, with cluster groups represented by three circles.

The negative dependence in the surface layer across the Northern Hemisphere was primarily driven by the interactions between GPP:LST and T_a:GPP (Fig. 7). It shows that the regression trend line crosses quadrants II and IV. The negative relationship driven by GPP:LST was predominantly concentrated in quadrant IV, where increased precipitation lead to decreased soil moisture in the boreal forest, tundra, temperate coniferous forest, and temperate broadleaf mixed forest. The negative dependence driven by T_a:GPP was mainly found in quadrant II, with distributions in deserts and xeric shrublands, boreal forests, montane grasslands and shrublands, temperate broadleaf mixed forests, and tundra. For the middle soil layer, GPP:LST drove a negative dependence in tropical and subtropical grasslands, savannas, shrublands, and tropical and subtropical coniferous forests. T_a and T_a:GPP drove in Mediterranean forests, woodlands, and scrub, as well as in temperate grasslands, savannas, and shrublands. The mixed effects of T_a:GPP:LST and T_a:LST had minimal impact across all ecological zones, with all estimates concentrated near the origin and only two clusters observed.

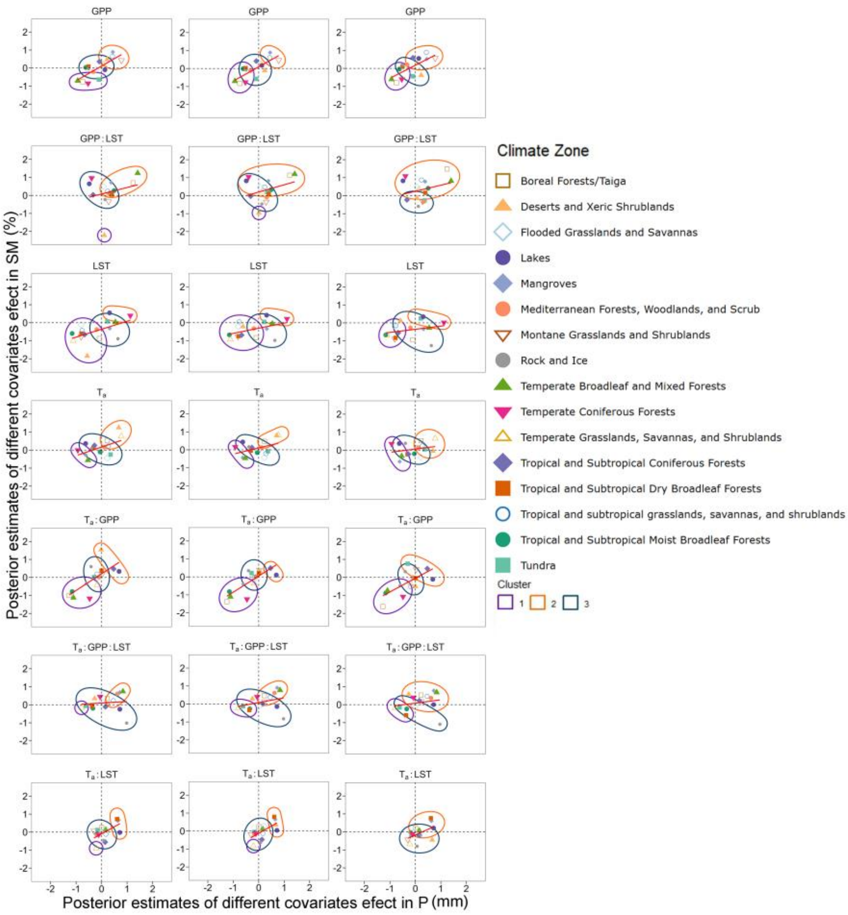

Fig. 8 Posterior estimates of the covariate variables of the Bayesian generalized non-linear multivariate multilevel model, built using annual data. The columns represent soil depths of 0 to 7 cm, 7 to 28 cm, and 28 to 100 cm. Red lines indicate linear regression of precipitation and soil moisture across all ecoregions, with cluster groups represented by three circles.

Interannual negative dependence was primarily observed in the montane grasslands and shrublands region, where GPP:LST drove this pattern across all three soil layers. All other variables lead to positive dependence (Fig. 8). The long-term trend in the annual-scale Bayesian model revealed strong patterns, with the most significant difference compared to the monthly scale being the influence of T_a:GPP:LST and T_a:LST, where different ecological zones exhibited substantial variation. Among the multiple variables, T_a drove the most negative dependence, with the greatest differences observed between ecological zones. In the surface layer, LST alone drove the negative dependence in the mangrove, rock, and ice regions. T_a drove the negative dependence in tropical and subtropical coniferous forests, lakes, and rock and ice regions. In the middle soil layers, the negative dependence driven by T_a was in temperate forests, arid shrublands, and flooded grasslands and savannas, while it driven by T_a:GPP was in tropical and subtropical moist broadleaf forests. The negative dependence driven by T_a:LST was fully distributed in quadrant IV. This pattern was observed in regions such as the montane grasslands and shrublands, tropical and subtropical coniferous forests, tropical and subtropical grasslands, savannas, and shrublands; and rock and ice regions. The strongest drivers of negative dependence in the deep layers were GPP:LST and T_a. The negative dependence driven by GPP:LST was found in the rock and ice regions, Mediterranean forests, woodlands, and scrub, as well as tundra and temperate coniferous forests in quadrant II. The negative dependence driven by T_a was observed in rock and ice regions, lakes, and temperate coniferous forests in quadrant II, and flooded grasslands and savannas in quadrant IV."

Some of the discussion has be moved the results, and the references have been added to the discussion. Please see our responses to the following comments.

6. The first paragraph in Section 4.1 repeats the results, which should add references to compare and explain why this is the case. The second paragraph of the discussion is more like an introduction to land cover types but does not explain why.

Response: Thanks for your suggestion. Section 4.1 has revised as follows:

"4.1 Characteristics of negative dependence areas

In this study, joint distributions of precipitation and soil moisture were constructed using Kendall's τ to characterize the nonlinear relationship. Consistent with previous findings, we observed a negative dependence between precipitation and soil moisture, particularly in arid and semi-arid regions (Qing et al., 2023; Yang et al., 2018). At the monthly scale, τ values in surface layer were stronger, indicating that seasonal dynamics—such as intermittent rainfall events followed by rapid soil moisture loss through evapotranspiration—likely drive the observed negative correlation. On the annual scale, the negative dependence may instead reflect long-term climate feedbacks. In high-latitude regions, for example, Arctic amplification and permafrost thawing can decouple precipitation inputs from effective soil moisture retention, leading to persistent moisture deficits despite increasing precipitation trends. Regions showing negative dependence between precipitation and soil moisture are primarily distributed in arid, semi-arid and cold high-latitude climates. Representative ecosystems include deserts and xeric shrublands, montane grasslands and shrublands, and Arctic tundra. Despite their climatic differences, these ecosystems share key ecohydrological traits, including limited precipitation input, strong evapotranspiration demand, sparse vegetation cover, and low soil moisture retention capacity.

In deserts and xeric shrublands, annual precipitation typically falls below 250 mm, while evaporation consistently exceeds rainfall (Lockwood et al., 2006). Vegetation in these regions is dominated by shallow-rooted shrubs, which offer minimal resistance to post-rainfall moisture loss. As a result, soil moisture often declines rapidly following precipitation events, leading to a counterintuitive negative relationship between rainfall and moisture storage. Montane grasslands and shrublands, despite occurring in more topographically complex terrains, also experience dry climatic conditions characterized by low precipitation, high temperatures, and elevated VPD (Olson and Dinerstein, 1998). These factors enhance evapotranspiration, limiting the effectiveness of rainfall in replenishing soil moisture. Consequently, increases in precipitation may coincide with soil moisture decline due to enhanced moisture loss. In contrast, Arctic tundra ecosystems—such as those found in northern North America and Eurasia—are defined by cold temperatures, continuous permafrost, and moderate but ineffective precipitation. Frozen soils impede infiltration, causing much of the precipitation to be lost as surface runoff rather than retained in the soil profile. Dominant vegetation includes mosses, sedges, and dwarf shrubs with shallow root systems, further limiting water uptake and storage (Olson and Dinerstein, 1998; Xue et al., 2021)."

7. The meltwater discussed in 4.2 is even an important part of the abstract, but the meltwater is not used in the results. The discussion should be based on the main content of the results, and the discussion should also consider the geological conditions, such as karst landform, in addition to the influence of vegetation.

Response: We acknowledge the limitations of the ERA5-Land dataset in capturing snow and permafrost dynamics, particularly in high-latitude regions. These limitations could affect the accuracy of snowmelt estimation and its influence on soil moisture (Kouki et al., 2023). This study does not intend to discuss "meltwater", since the main objective is to investigate how changes in LST and T_a influence the phase of precipitation (e.g., rain vs. snow) and how these changes affect water availability.

We also agree with you that geological conditions such as karst topography may influence the spatial patterns of precipitation–soil moisture relationships. We have added some discussion in Section 4.2 in the revised version.

"The geological conditions, such Karst landforms can also influence the relationship between precipitation and soil moisture."

8. It is suggested that Section 4.3 be parted in different sections according to different mechanisms.

Response: Thanks for your suggestion. Section 4.2 and 4.3 were merged together and it has been rewritten and re-numbered as follows.

"4.2.1 Energy-Driven Mechanism: LST and T_a-Driven ET Dominance

Negative dependence between precipitation and soil moisture was observed across several dry and cold ecoregions, including deserts and xeric shrublands, montane grasslands and shrublands, tundra. These regions are generally characterized by low precipitation and GPP, limiting vegetation's ability to retain or utilize moisture effectively (Olson and Dinerstein, 1998; Xue and Wu, 2023). In arid ecosystems, shallow-rooted vegetation and high temperatures result in rapid soil moisture loss following rainfall. In montane environments, stronger warming trends (Pepin et al., 2022) and shallow-rooted vegetation (Stocker et al., 2023) further limit precipitation use, despite increased GPP under warming. Besides, the surface soil induced upward movement of soil water from the middle layer due to the osmotic and matric potential, further contributing to moisture depletion. In semi-arid grasslands, the interaction between soil texture and precipitation patterns further reinforces negative dependence. Brief rainfall events primarily moisten upper clay layers where grass roots concentrate (Sala and Lauenroth, 1985), while well-developed clay horizons restrict deep water percolation and shrub root expansion (Buxbaum and Vanderbilt, 2007). This physical confinement exacerbates water loss when increased GPP and LST enhance evapotranspiration from the shallow moistened zone, intensifying the precipitation-soil moisture decoupling. High temperatures can lead to surface soil sealing, preventing rainfall from effectively entering the root zone. Model simulations confirm that in flat arid regions (Koukoula et al., 2021), such soil barriers promote the "dry soil advantage"—where precipitation triggers runoff rather than infiltration.

The boreal forest and tundra ecosystems, often with permafrost, are temperature-limited systems. Precipitation often falls as snow, which accumulates on the surface. Then, a low LST can cause soil freezing, and the presence of surface withered litter may further insulate the soil, preventing timely moisture replenishment. Permafrost in these regions can lead to surface runoff of some precipitation, preventing effective infiltration into the soil. The geological conditions, such as Karst landforms can also influence the relationship between precipitation and soil moisture.

4.2.2 Biotic-Driven Mechanism: Vegetation Water Use and GPP Dominance

High-altitude ecosystems, especially in the Arctic and Qinghai–Tibetan Plateau, are increasingly affected by warming and variable precipitation (Lamprecht et al., 2018). These changes lead to reduced species abundance and increased GPP (Berauer et al., 2019). In montane grasslands and shrublands, species abundance negatively correlates with soil nutrients and microbial functions (Graham Emily et al., 2024). Rising LST and extreme precipitation reduce microbial biomass and release soil minerals (Siebielec et al., 2020), intensifying light competition and lowering ecosystem stability. Biodiversity loss decreases soil water capacity, with some of these regions at high risk of water erosion (Straffelini et al., 2024).

Soil moisture reduction in the surface and middle layer is mainly driven by root water uptake under high LST and GPP. Roots shift absorption to deeper layers during droughts (Yadav Brijesh et al., 2009). In dry seasons, plants in grasslands and shrublands retain leaves to support evaporative cooling (Prior et al., 1997), this strategy also seen in deserts and xeric shrublands, where winter precipitation and freezing reduce surface moisture. Even during rainfall, soil moisture may decline due to evapotranspiration, runoff, and plant uptake (Tomlinson et al., 2013), creating a negative precipitation–soil moisture relationship. Canopy interception also limits infiltration (Zhong et al., 2022). However, in high-latitude ecosystems like boreal forests and tundra, warming mitigates cold limitations, allowing precipitation to increase soil moisture, shifting the relationship to positive.

Negative dependence in mid-to-deep soil layers can occur when a single factor dominates, limiting ecosystem compensation (Jarvis, 2011; Taylor and Klepper, 1979). In contrast, positive dependence may arise from synergistic interactions between GPP and LST. Higher GPP can reflect deeper root systems or improved water-use efficiency, while increased LST may enhance soil moisture release and promote water availability together (Wang et al., 2008). This interaction may strengthen ecosystem feedbacks—e.g., higher GPP can improve soil structure through biomass and organic matter, boosting water retention (Chen et al., 2025). Such synergy can offset LST-driven evapotranspiration and enhance ecosystem resilience, particularly through freeze–thaw processes in cold regions."

Minor Comments

1. What does dependence mean?

Response: Nonlinear and asymmetric correlations in joint distributions are generally defined as dependence (Dette et al., 2013), we have explained it in manuscript as follows.

“In studies, this kind of nonlinear and asymmetric correlation is generally referred to as ‘dependence’.”

2. Line 287: What are the multivariate mixed effects, and why do these variables combine?

Response: Multivariate mixed effects refer to the interaction effect of multiple variables. Specifically, the environmental elements in the ecosystem can restrain and promote each other, and ultimately produce the same or opposite effects as the single variable drive. Therefore, this study considered the single effect of different driving factors and the multivariate interaction effect.

Line 519: The results about arid areas should be added after the reference to compare.

Response: The results about arid areas have revised as follows.

“For example, at the monthly scale, LST drives surface soil moisture in Mediterranean forests, woodlands and scrub to remain relatively stable despite an increase in precipitation. As well as T_a drives deep soil moisture in deserts and xeric shrublands. However this “drought advantage” accounts for only a small proportion in the results.”

Line 532: The figures in the results should be marked here.

Response: Revised.

Reference

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