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

Authors: Shouye Xue; Guocan Wu

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We highly appreciate the editor and anonymous reviewers for the very helpful and insightful comments that lead to the significant improvement this manuscript. We have checked our work carefully according to these comments and made the requested changes. In the revised version, the Results and Discussion sections were reorganized for improving clarity. Some quantitative summery was added to the Abstract and Conclusion sections. We also added Figure 6 for reflecting the results on annual scale and Figures S1 and S2 in revised manuscript for reflecting the accuracy of the copula functions.

Below we indicate the comments and use blue font for our responses. The corresponding revised texts are also used blue font in the revised version of our manuscript.

#Editior

Notification to the authors:

1) In the "Data availability" section, please consider indicating the doi numbers (where available) instead of weblinks.

Response: Revised.

2) For the section "Author contribution", please use initials only for the authors instead of full names.

Response: Revised.

3) Most figures (also supplement figures) are very pixelated. Please provide figure images with a better quality.

Response: Thanks, the pixelated figures have been replaced.

4) You uploaded a supplement file but do not mention the supplement in the manuscript text. Please consider mentioning the supplement file as reads might otherwise not be aware of the supplementary material.

Response: Thanks, some sentences have been added to reference the supplementary material.

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 for reflecting the results on annual scale and Figures S1 and S2 in revised manuscript for reflecting the accuracy of the copula functions. We hope that the following point to point response can address your concerns.

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.

"Accordingly, the ridge regression models for precipitation amount, precipitation frequency, evapotranspiration, and soil moisture can be used 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." (Lines 109-114)

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. S1), as shown in the supplementary file. Then the Kendall's tau correlation was calculated between precipitation and soil moisture with time lags ranging from 0 to 12 months (Fig. S2). The lag corresponding to the maximum absolute correlation was identified as the optimal lag." (Lines 259-265)

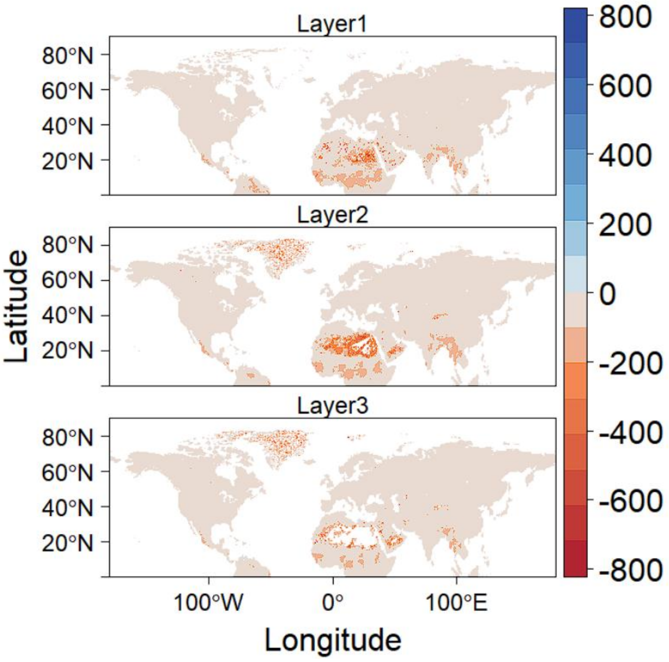

Fig. S1 The AIC value for each grid in the selection of copula function.

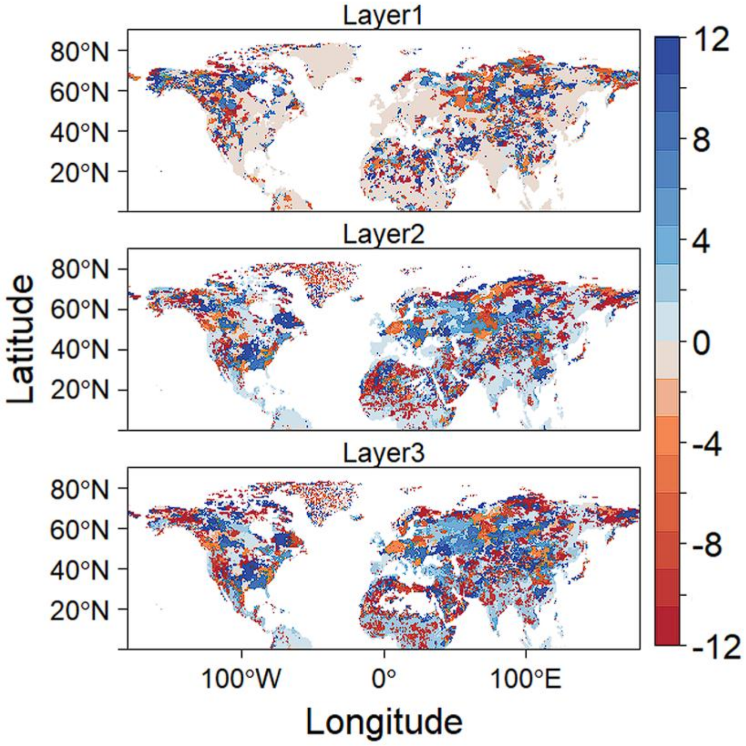

Fig. S2 The estimated number of lagged month for each grid in the the Kendall's tau correlation.

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. (lines 403-417)

"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."

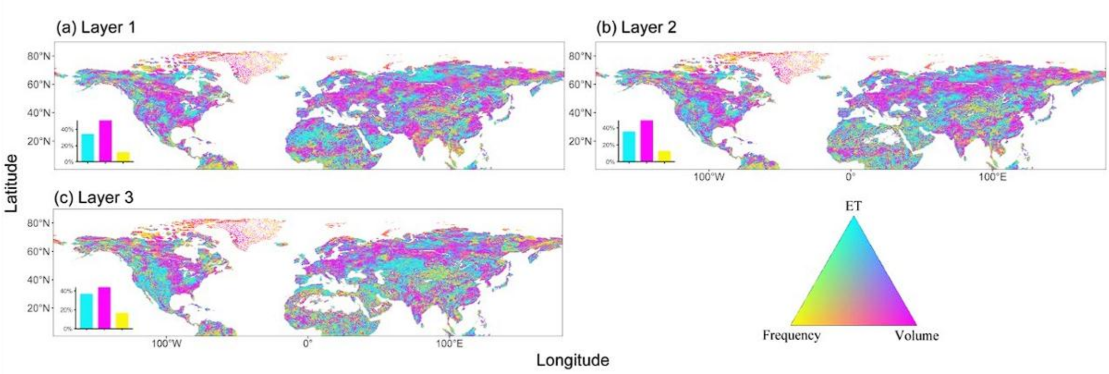

Fig. 6 Ternary map of factors controlling soil moisture at annual scale, for the period 2000 to 2019. The bottom-left histogram in the subgraph represents the proportion of grid cells where one variable exerts strong univariate control (with a regression coefficient greater than 75% of the total sum 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. (Lines 426-481)

"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. S3, S4).

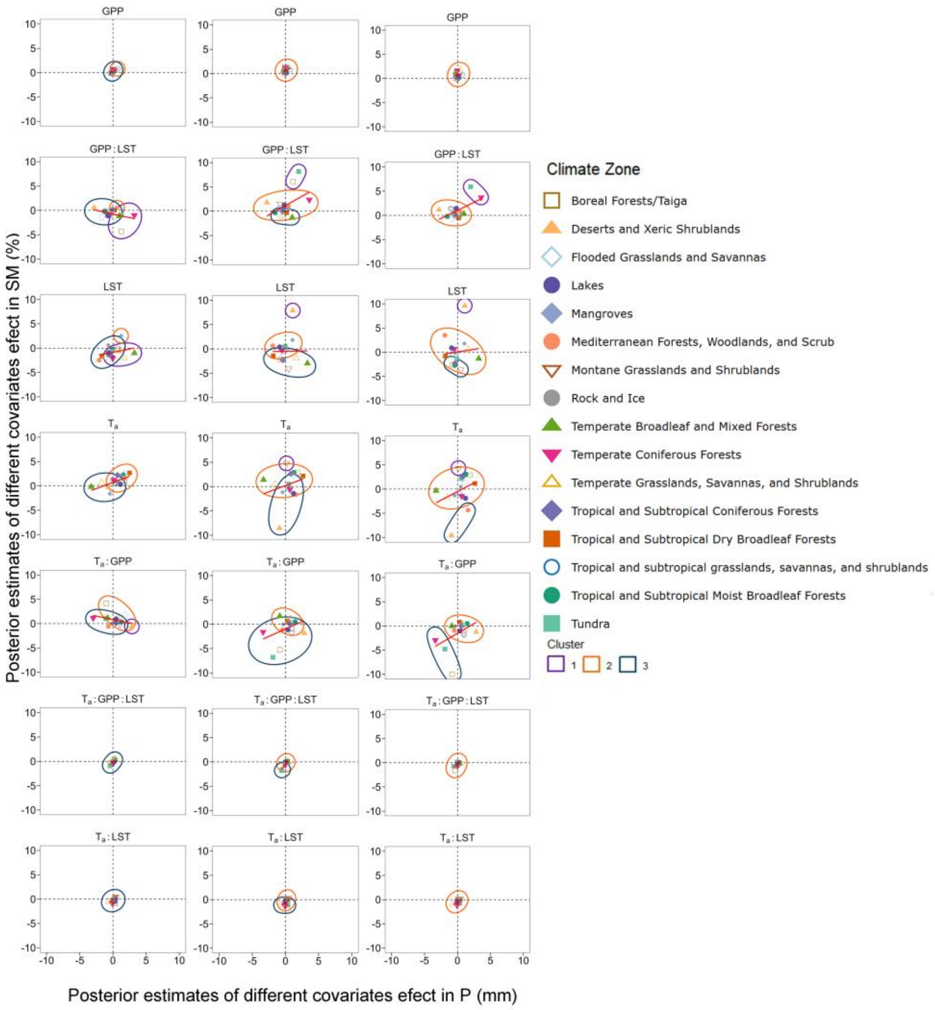

Fig. 7 Posterior estimates of the covariate variables of the Bayesian generalized non-linear multivariate multilevel model, built using monthly data. The columns represent soil depths of 0 to 7 cm, 7 to 28 cm, and 28 to 100 cm. Red lines indicate linear regressions of precipitation and soil moisture 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.

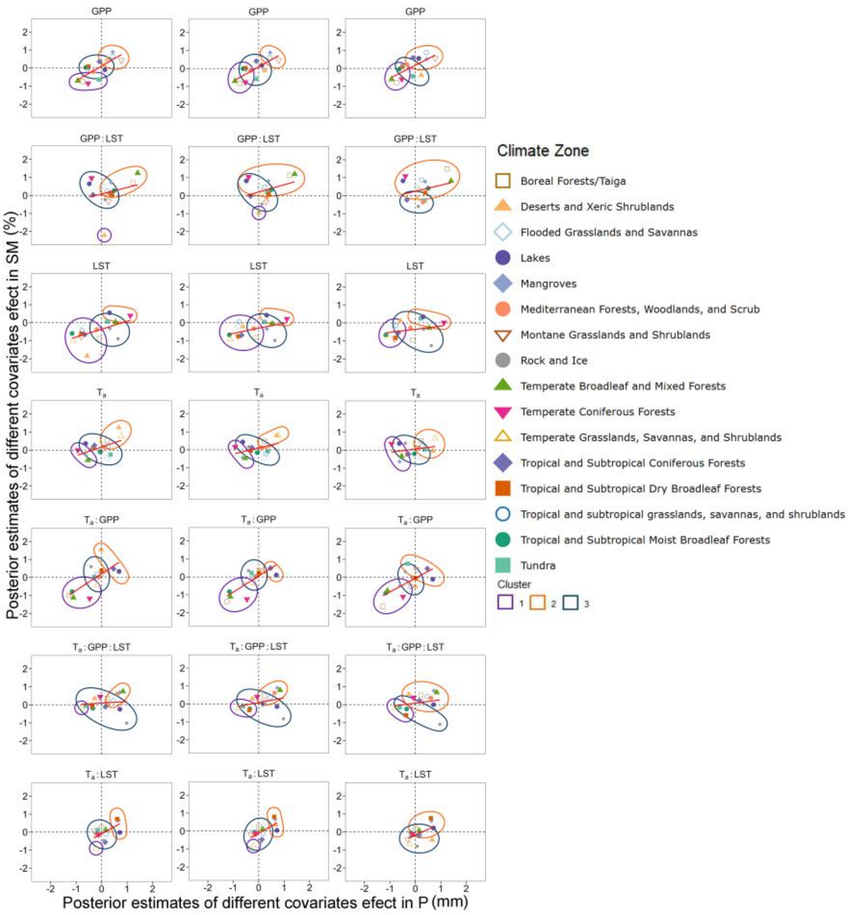

Fig. 8 Posterior estimates of the covariate variables of the Bayesian generalized non-linear multivariate multilevel model, built using annual data. The columns represent soil depths of 0 to 7 cm, 7 to 28 cm, and 28 to 100 cm. Red lines indicate linear regression of precipitation and soil moisture across 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. (Lines 484-519)

"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." (Lines 550-551)

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. (Lines 523-582)

"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.

“This kind of nonlinear and asymmetric correlation is generally referred to as ‘dependence’.” (Lines 77-78)

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 sentence was deleted in revised manuscript.

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

Response: Revised.

Reference

Berauer, B.J., P.A. Wilfahrt, M.A.S. Arfin-Khan, P. Eibes, A. Von Heßberg, J. Ingrisch, M. Schloter, M.A. Schuchardt, and A. Jentsch. 2019. Low resistance of montane and alpine grasslands to abrupt changes in temperature and precipitation regimes. *Arctic, Antarctic, and Alpine Research*. 51:215-231.

Buxbaum, C.A.Z., and K. Vanderbilt. 2007. Soil heterogeneity and the distribution of desert and steppe plant species across a desert-grassland ecotone. *Journal of Arid Environments*. 69:617-632.

Chen, G., Q. Wang, and T. Chen. 2025. Dominant effect and threshold response of soil moisture on global vegetation greening in the 21st century. *CATENA*. 254:109008.

Dette, H., K.F. Siburg, and P.A. Stoimenov. 2013. A Copula-Based Non-parametric Measure of Regression Dependence. *Scandinavian Journal of Statistics*. 40:21-41.

Graham Emily, B., A. Garayburu-Caruso Vanessa, R. Wu, J. Zheng, R. McClure, and D. Jones Gerrad. 2024. Genomic fingerprints of the world’s soil ecosystems. *mSystems*. 9:e01112-01123.

Jarvis, N.J. 2011. Simple physics-based models of compensatory plant water uptake: concepts and eco-hydrological consequences. *Hydrol. Earth Syst. Sci.* 15:3431-3446.

Kouki, K., K. Luojus, and A. Riihelä 2023. Evaluation of snow cover properties in ERA5 and ERA5-Land with several satellite-based datasets in the Northern Hemisphere in spring 1982–2018. *The Cryosphere*. 17:5007-5026.

Koukoula, M., C.S. Schwartz, E.I. Nikolopoulos, and E.N. Anagnostou. 2021. Understanding the Impact of Soil Moisture on Precipitation Under Different Climate and Meteorological Conditions: A Numerical Sensitivity Study Over the CONUS. *Journal of Geophysical Research: Atmospheres*. 126:e2021JD035096.

Lamprecht, A., P.R. Semenchuk, K. Steinbauer, M. Winkler, and H. Pauli. 2018. Climate change leads to accelerated transformation of high‐elevation vegetation in the central Alps. *New Phytologist*. 220:447-459.

Lockwood, M., G. Worboys, and A. Kothari. 2006. Managing Protected Areas: A Global Guide. Earthscan, London, Sterling.

Olson, D., and E. Dinerstein. 1998. The Global 200: A Representation Approach to Conserving the Earth's Most Biologically Valuable Ecoregions. *Conservation Biology*. 12:502-515.

Pepin, N.C., E. Arnone, A. Gobiet, K. Haslinger, S. Kotlarski, C. Notarnicola, E. Palazzi, P. Seibert, S. Serafin, W. Schöner, S. Terzago, J.M. Thornton, M. Vuille, and C. Adler. 2022. Climate Changes and Their Elevational Patterns in the Mountains of the World. *Reviews of Geophysics*. 60:e2020RG000730.

Prior, L.D., D. Eamus, and G.A. Duff. 1997. Seasonal and Diurnal Patterns of Carbon Assimilation, Stomatal Conductance and Leaf Water Potential in <emph type="2">Eucalyptus tetrodonta</emph> Saplings in a Wet–Dry Savanna in Northern Australia. *Australian Journal of Botany*. 45:241-258.

Qing, Y., S. Wang, Z.-L. Yang, and P. Gentine. 2023. Soil moisture−atmosphere feedbacks have triggered the shifts from drought to pluvial conditions since 1980. *Communications Earth & Environment*. 4:254.

Sala, O.E., and W.K. Lauenroth. 1985. Root Profiles and the Ecological Effect of Light Rainshowers in Arid and Semiarid Regions. *The American Midland Naturalist*. 114:406-408.

shen, S., S. Ye, C. Cheng, C. Song, J. Gao, J. Yang, L. Ning, K. Su, and T. Zhang. 2018. Persistence and Corresponding Time Scales of Soil Moisture Dynamics During Summer in the Babao River Basin, Northwest China. *Journal of Geophysical Research: Atmospheres*. 123:8936-8948.

Siebielec, S., G. Siebielec, A. Klimkowicz-Pawlas, A. Gałązka, J. Grządziel, and T. Stuczyński. 2020. Impact of water stress on microbial community and activity in sandy and loamy soils. *Agronomy*. 10:1429.

Stocker, B.D., S.J. Tumber-Dávila, A.G. Konings, M.C. Anderson, C. Hain, and R.B. Jackson. 2023. Global patterns of water storage in the rooting zones of vegetation. *Nature Geoscience*. 16:250-256.

Straffelini, E., J. Luo, and P. Tarolli. 2024. Climate change is threatening mountain grasslands and their cultural ecosystem services. *CATENA*. 237:107802.

Taylor, H.M., and B. Klepper. 1979. The Role of Rooting Characteristics in the Supply of Water to Plants11Journal Paper J-8906 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa, Project No. 1941, and Technical Paper 4673 of the Oregon State University Agricultural Experiment Station, Pendleton, Oregon. *In* Advances in Agronomy.

Vol. 30. N.C. Brady, editor. Academic Press. 99-128.

Tomlinson, K.W., L. Poorter, F.J. Sterck, F. Borghetti, D. Ward, S. de Bie, and F. van Langevelde. 2013. Leaf adaptations of evergreen and deciduous trees of semi-arid and humid savannas on three continents. *Journal of Ecology*. 101:430-440.

Vidana Gamage, D.N., A. Biswas, and I.B. Strachan. 2020. Scale and location dependent time stability of soil water storage in a maize cropped field. *CATENA*. 188:104420.

Wang, G., Y. Li, H. Hu, and Y. Wang. 2008. Synergistic effect of vegetation and air temperature changes on soil water content in alpine frost meadow soil in the permafrost region of Qinghai-Tibet. *Hydrological Processes*. 22:3310-3320.

Xue, S.-Y., H.-Y. Xu, C.-C. Mu, T.-H. Wu, W.-P. Li, W.-X. Zhang, I. Streletskaya, V. Grebenets, S. Sokratov, A. Kizyakov, and X.-D. Wu. 2021. Changes in different land cover areas and NDVI values in northern latitudes from 1982 to 2015. *Advances in Climate Change Research*. 12:456-465.

Xue, S., and G. Wu. 2023. Sensitivities of Vegetation Gross Primary Production to Precipitation Frequency in the Northern Hemisphere from 1982 to 2015. *Remote Sensing*. 16:21.

Yadav Brijesh, K., S. Mathur, and A. Siebel Maarten. 2009. Soil Moisture Dynamics Modeling Considering the Root Compensation Mechanism for Water Uptake by Plants. *Journal of Hydrologic Engineering*. 14:913-922.

Yang, L., G. Sun, L. Zhi, and J. Zhao. 2018. Negative soil moisture-precipitation feedback in dry and wet regions. *Scientific Reports*. 8:4026.

Zhong, F., S. Jiang, A.I.J.M. van Dijk, L. Ren, J. Schellekens, and D.G. Miralles. 2022. Revisiting large-scale interception patterns constrained by a synthesis of global experimental data. *Hydrol. Earth Syst. Sci.* 26:5647-5667.

Anonymous Referee #2

The authors examine the dependences between soil moisture and precipitation, and their drivers across the northern hemisphere. They find substantial negative dependences, which are mostly attributed to evapotranspiration and vegetation conditions. The topic is intriguing and the methodology interesting. However, I think this paper could benefit from refinement in areas like novelty declaration, method justification, presentation quality, and enhanced supporting evidence for conclusions. Therefore, I would recommend a major revision.

Response: We sincerely thank you for your valuable comments. Based on your suggestions, the Results and Discussion sections were reorganized for improving clarity. Some quantitative summery was added to the Abstract and Conclusion sections. Figure 2 was re-plotted and Figures S1 and S2 in revised manuscript were added for considering the time lag. We hope that the following point to point response can address your concerns.

1. Below are major concerns that expect to authors to address in the revised manuscript. The authors need to identify the research gaps and specify any novel findings or methodology not reported in earlier studies. Negative correlations between soil moisture and precipitation and their causes have previously been identified, a fact acknowledged by the authors (Line 66-73). The authors seem to claim their novelty in terms of climate change and climate extremes (Line 101-106). However, I find the two points only loosely related to this study.

Response: Thanks for your comment. We have rewritten the related sentences to identify the research gaps and specify novel in Abstract and Introduction as follows.

"Recently, negative correlations between soil moisture and precipitation have been observed in Northern Hemisphere ecosystems. However, the driving mechanisms of this negative correlations as well as how soil moisture is influenced by precipitation and evapotranspiration, remain unclear. This study analyzes the dependence between soil moisture and precipitation in different ecoregions to explore the driving mechanisms and regional patterns." (Lines 18-24)

“Although previous studies have identified the mechanisms of soil moisture variation across different time scales (shen et al., 2018; Vidana Gamage et al., 2020), the interaction among precipitation, evapotranspiration and soil water under climate change may have changed over different time scales. The dependence of soil moisture to precipitation and its interactions with evapotranspiration under conditions of climate change require further investigation.” (Lines 104-109)

Shen, S., and Coauthors, 2018: Persistence and Corresponding Time Scales of Soil Moisture Dynamics During Summer in the Babao River Basin, Northwest China. Journal of Geophysical Research: Atmospheres, 123, 8936-8948.

Vidana Gamage, D. N., A. Biswas, and I. B. Strachan, 2020: Scale and location dependent time stability of soil water storage in a maize cropped field. CATENA, 188, 104420.

2. There is a lack of quantitative summary of the findings throughout the paper, especially in the abstract and conclusion sections. For instance, the authors should indicate the proportion of positive/negative correlations across various soil layers/ecoregions and quantify the contribution of controlling factors.

Response: Thanks for your suggestion. We have revised abstract and conclusion, and the quantitative summary was added.

“……The nonlinear negative dependencies of soil moisture to precipitation were revealed. The monthly scale negative dependence proportion reached 19.2%, 0.7%, and 2.3%, while the annual scale was 3.0%, 4.0%, and 8.6%, respectively.” (Lines 27-29)

“……The results suggest that, the negative dependence proportion reached 19.2%, 0.7%, and 2.3% at monthly scale,, while it was 3.0%, 4.0%, and 8.6% at annual scale, respectively, for the three soil layers.” (Lines 618-620)

3. The Results and Discussion section reads too imbalance. Currently, there is a lack of reasoning of the findings shown in the Results section, making the results a bit dull to read. The reasoning in Discussion is too spread and redundant, causing readers having to flip between the two sections. Also, I think a schematic diagram might help.

Response: We appreciate your comment about the readability of the manuscript. We have substantially revised the structure of the Results and Discussion sections to enhance logical flow and readability. In particular, we have reorganized subsection 4.3 based on the driving mechanisms and strengthened the interpretation of our findings directly within the Results section to reduce redundancy. We hope these changes can address your concerns effectively.

4. The ridge regression and Section 3.2 seem off topic, as the main scope is to study the dependences between precipitation and soil moisture as well as their drivers. As a key driver of the dependences, why ET is not added to the Bayesian model. The soil property, another key controlling factor according to the authors, is also not considered in the Bayesian model as well (Line 116).

Response: The ridge regression model was established to quantify the driving intensity of precipitation-evapotranspiration on soil water, which is a complementary analysis for joint distribution. Considering evapotranspiration is generally correlated with soil moisture and air temperature, while soil moisture is used as the dependent variable in the Bayesian model, air temperature and ground temperature are considered as driving factors. So it is not necessary to consider ET as the driving factor separately. Soil factors include many factors such as soil depth, soil texture, etc., and this study mainly explores the dependence in different depths. These were further explained in Section 4.3 in the revised version.

"Additionally, other variables such as wind patterns and topography may also influence the negative dependence between precipitation and soil moisture. Soil properties—such as texture, organic matter content, and hydraulic conductivity—represent another set of important controls that were not explicitly included in the current Bayesian models. While this study provides a foundational analysis of the negative dependencies across different ecoregions, future research should explore these additional environmental factors to gain a more comprehensive understanding of the mechanisms underlying precipitation–soil moisture interactions." (Lines 604-611)

5. The authors should justify their use of eco-region boundaries over the more well-known climate region, e.g., Köppen climate classification system.

Response: Ecoregions are divided based on an integrated consideration of vegetation types, soils, substrate, and climate. Compared to climate zones, they can better capture the heterogeneity of regional water feedback processes. Therefore, ecoregion boundaries were used instead of climate zones. The explanation for this choice was added in the revised manuscript.

"In this study, the ecoregion boundaries rather than Köppen climate zones were used to investigate the spatial patterns of precipitation–soil moisture feedbacks. Ecoregions are divided based on a combination of factors including vegetation types, soil characteristics, substrate, and climate conditions. This multi-factor approach allows ecoregions to better reflect ecological and hydrological processes than classifications based solely on climate variables. Since soil moisture dynamics and their feedbacks with precipitation are strongly influenced by vegetation structure, root systems, and edaphic properties, the ecoregions can provide a more mechanistic and spatially relevant framework for our analysis." (Lines 207-215)

6. The dependence between soil moisture and precipitation might not be concurrent, and could have a lag time. There are little consideration and discussion of this point.

Response: We appreciate your insightful comment regarding the potential non-concurrent relationship between precipitation and soil moisture, and we fully agree with this point.

In the revised version, we have re-evaluated the dependence between precipitation and soil moisture by incorporating time-lagged effects. Specifically, for each grid cell, a maximum lag of up to 12 months was used to calculate the lagged correlation between precipitation and soil moisture. Then the optimal lag for each grid cell was determined by identifying the time lag that yielded the maximum Kendall's tau within this 0–12 month window. To assess model adequacy, the Akaike Information Criterion (AIC) was calculated for each lag.

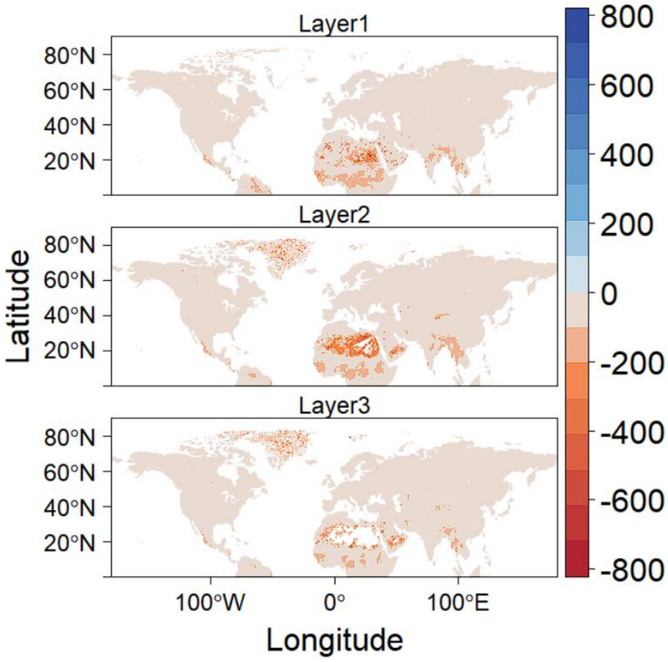

Fig. S1 The AIC value for each grid in the selection of copula function.

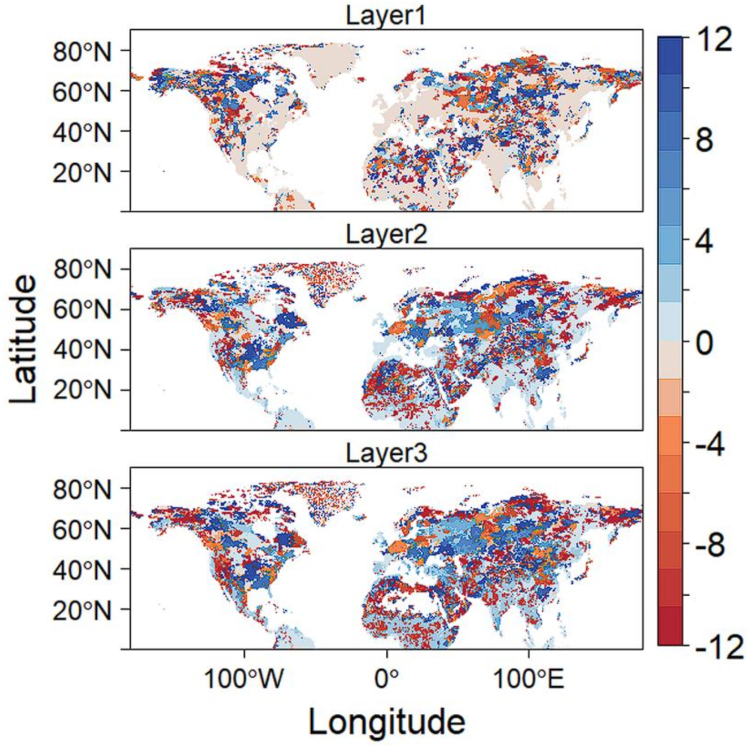

Fig. S2 The estimated number of lagged month for each grid in the the Kendall’s tau correlation.

The related text was added in revise manuscripts as follows.

“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. S1), as shown in the supplementary file.

Then the Kendall's tau correlation was calculated between precipitation and soil moisture with time lags ranging from 0 to 12 months (Fig. S2). The lag corresponding to the maximum absolute correlation was identified as the optimal lag." (Lines 259-265)

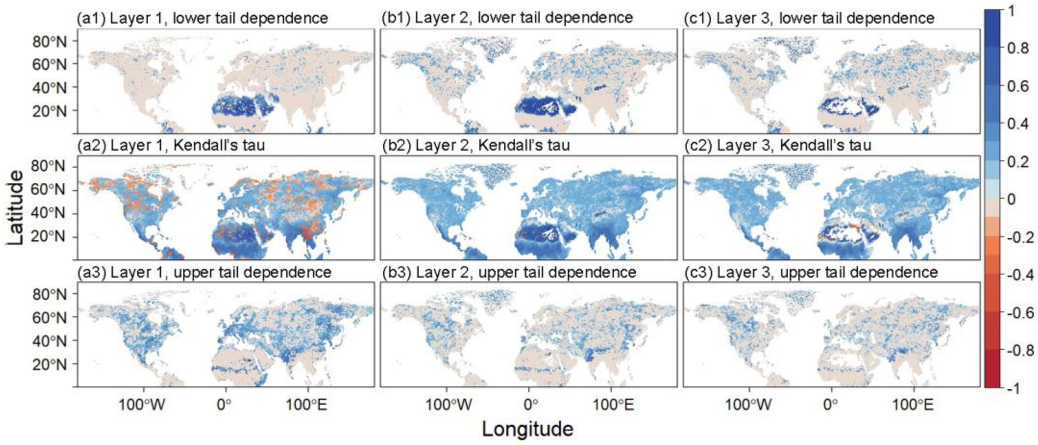

Fig. 2 Spatial distribution of Kendall's tau (τ), the upper tail dependence (λ_U), and the lower tail dependence (λ_L) on the 0.25 ° × 0.25 °grids between monthly precipitation volume and soil moisture with the time lag during 2000 to 2019. The three columns are for the soil moisture from depths of 0 to 7 cm, 7 to 28 cm, and 28 to 100 cm, respectively.

"The copula analysis of monthly average soil moisture and total monthly precipitation volume revealed a clear negative dependence at all three soil depths (Fig. 2(a2, b2, c2)). The percentages of grid cells exhibiting negative dependence at these depths were 19.2%, 0.7%, and 2.3%, respectively. The negative dependence between precipitation and soil moisture is more prevalent in the surface soil layer, where the grid cells exhibiting are more widespread. In contrast, at the middle and deep soil layers, these negative dependence patterns are primarily confined to the margins of the Sahara desert, the montane grasslands and shrublands, and parts of the deserts and xeric shrublands regions. In the surface layer, the negatively dependent grid patches are more spatially scattered, mainly distributed across the tundra, montane grasslands and shrublands, deserts and xeric shrublands, as well as the tropical and subtropical moist broadleaf forests.

Regions exhibiting high λL values were primarily located in the deserts and xeric Shrublands, as well as in parts of India, where λL reached values as high as 0.99 (Fig.

2(a1, b1, c1)). With increasing soil depth, λL values gradually increased across the Eurasian continent. Similarly, λ_U exhibited a clear reduction in spatial extent with increasing soil depth, with the majority of these regions located in the temperate broadleaf and mixed forests and the southern margin of the Sahara desert. With increasing soil depth, λU values consistently decreased, resulting in a lack of clear correspondence between these regions and specific ecological zones (Fig. 2(a3, b3, c3))." (Lines 329-349)

7. I also have concerns about the time scale. I agree with reviewer #1 that the time scale (monthly, seasonal, annual) should be unified. Since the authors did not eliminate seasonal variations from monthly data, seasonal signals affect the monthly-scale results. The patterns and mechanisms during seasons appear clearer. I would suggest the authors to narrow the analyses by only focusing on one or two scales.

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

"At the annual scale, results are consistent with those at the monthly scale, with precipitation amount continuing to exert 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. In terms of spatial distribution, regions dominated by precipitation frequency are still primarily located in high-latitude areas, particularly in Greenland and the Queen Elizabeth Islands, 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 inputs 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.” (Lines 403-417)

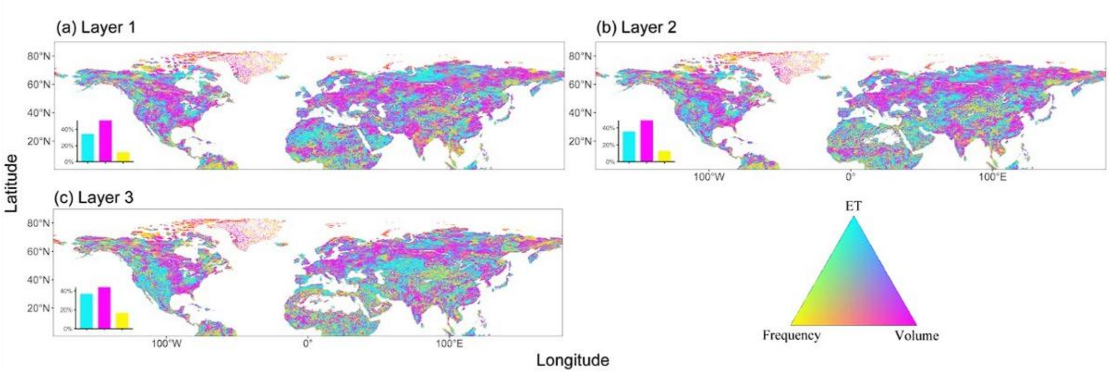

Fig. 6 Ternary map of factors controlling soil moisture at annual scale, for the period 2000 to 2019. The bottom-left histogram in the subgraph represents the proportion of grid cells where one variable exerts strong univariate control (with a regression coefficient greater than 75% of the total sum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

Minor comments:

1) Line 489: the “Arctic amplification” appears abruptly. How are the climate pattern associated with the dependences? Why not other climate patterns?

Response: Our intention means that, the heterogeneity in global warming among different regions can affects GPP and drives precipitation-soil water feedback. However, climate pattern are not the focus of this study, which aims to explore the driving characteristics of GPP, air temperature, and ground temperature in different regions.

2) Line 517-519: not clear, need rephrase.

Response: The sentence was deleted in revised manuscript.

3) Line 747-748: need quantitative measures to support this point.

Response: Revised.

“Evapotranspiration was the dominant driver of soil moisture dynamics during the growing season, with a regression coefficient proportion greater than 75%. In contrast, precipitation volume played a more significant role in the surface and middle layer of non-growing season, with areas under strong univariate control accounting for over 40% of the total area. Additionally, the influence of precipitation frequency on soil moisture increased with latitude, the proportion of the regression coefficient averaging from 36.5% to 91.3%, highlighting a shift in controlling factors across climatic gradients." (Lines 625-632)

4) Line 764-769: these reasoning needs quantitative support.

Response: Thanks for your suggestion. Since this point is not the focus of our study, we have revised this sentence in the manuscript to better reflect our reasonable speculation.

"A possible explanation is the long-term variability in precipitation and temperature, which may have influenced geomorphology, vegetation structure, and soil water retention capacity." (Lines 648-650)