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Spatially heterogeneous pathways linking atmospheric dryness to deep soil moisture

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E-mail: hans.chen@chalmers.se**Keywords:** vapor pressure deficit, soil moisture, atmospheric drying, global warming, vegetationSupplementary material for this article is available [online](#)

Abstract

Atmospheric vapor pressure deficit (VPD) has intensified under global warming, yet its influence on soil moisture across depths remains unclear. Using multiple global monthly soil moisture datasets spanning the past decades, we combined pairwise and conditional Granger causality analyses to disentangle pathways linking VPD to surface (0–28 cm, surface soil moisture (SSM)) and deep (28–100 cm, deep soil moisture (DSM)) soil moisture. We identify widespread statistical directional dependence from VPD to both SSM and DSM, whereas the reverse relationships from soil moisture to VPD are comparatively weak. Across global land areas, we identified significant VPD–DSM relationships that remained after conditioning on SSM, here termed SSM-independent pathways, which were concentrated mainly in the mid- to high-latitude regions of the Northern Hemisphere and dominated in most forest and savanna ecosystems. Regions with SSM-independent pathways exhibit significantly higher vegetation greenness and evapotranspiration than neighboring SSM-mediated regions. Our findings reveal spatially heterogeneous patterns of land–atmosphere coupling and suggest an important role for vegetation-mediated water use in linking VPD to DSM variability.

1. Introduction

Atmospheric vapor pressure deficit (VPD)—an indicator of atmospheric evaporative demand—has increased markedly under ongoing global warming since the 1980s, as near-surface air humidity has increased more slowly than the exponentially rising atmospheric saturation vapor pressure (Ficklin and Novick 2017, Yuan *et al* 2019, Fang *et al* 2022, Zhong *et al* 2025a). Elevated VPD strongly constrains plant physiological processes, including stomatal conductance, transpiration, photosynthesis, and ecosystem carbon uptake (Novick *et al* 2016, Grossiord *et al* 2020, López *et al* 2021, Zhong *et al* 2023). Beyond these physiological effects, VPD has been identified as a key driver of atmospheric evaporative demand (Gebrechorkos *et al* 2025). As a result, increases in VPD are commonly associated with soil-moisture depletion through enhanced terrestrial water loss (Penman 1948, McVicar *et al* 2012,

Massmann *et al* 2019). Concerns over soil-moisture depletion are not limited to the near surface. Recent evidence suggests that drought conditions in deeper soil layers have intensified over the past four decades and may become increasingly persistent during the 21st century (Guan *et al* 2025). Understanding how atmospheric drying is linked to moisture changes below the surface is therefore increasingly important for assessing drought development and ecosystem vulnerability.

Although rising VPD is widely expected to enhance evapotranspiration and thereby deplete soil moisture (Seneviratne *et al* 2010), soil-moisture anomalies can in turn influence near-surface atmospheric conditions by regulating evapotranspiration and surface energy partitioning (Zhou *et al* 2019), giving rise to land–atmosphere feedbacks. The directional relationship between VPD and soil moisture is therefore not necessarily one-way. Moreover, these relationships may differ substantially with soil depth.

Changes in upper soil moisture tend to respond rapidly to atmospheric forcing and closely track variations in atmospheric evaporative demand or drought metrics (Dai 2013, Berg *et al* 2017), whereas deeper soil moisture generally exhibits greater persistence and delayed responses (Wu *et al* 2002, Wu and Dickinson 2004, Wang and Shi 2019). However, it remains unclear how rising VPD is linked to moisture changes in deep soil layers globally.

The linkage between atmospheric dryness and deep soil moisture (DSM) can be decomposed into two distinct pathways: indirectly through surface soil moisture (SSM) or directly bypassing SSM. In the indirect SSM-mediated pathway, enhanced atmospheric evaporative demand first depletes SSM, with the resulting moisture anomaly subsequently propagating into deeper soil layers with increasing delay and attenuation (Wu *et al* 2002, Wu and Dickinson 2004, Gupta and Karthikeyan 2024). Such vertical propagation could be shaped by soil hydraulic properties (Caplan *et al* 2019, Delval *et al* 2025). Alternatively, an SSM-independent statistical pathway may occur when VPD be coupled with DSM without being transmitted entirely through contemporaneous SSM. Such a relationship could partly reflect vegetation-mediated root-zone processes, as deep-rooted vegetation can sustain transpiration during surface drying by directly accessing deeper soil-water reservoirs (Lauenroth *et al* 2014, Christina *et al* 2017, Chitra-Tarak *et al* 2018, 2021, Goulden and Bales 2019). Given that global vegetation greening has substantially altered evapotranspiration (Yang *et al* 2023) and soil drought (Li *et al* 2022, Liu *et al* 2025a), vegetation may further modulate the relative prevalence of these two pathways. Yet it remains a major knowledge gap which pathway dominates regionally and whether spatial differences are systematically associated with vegetation activity.

Disentangling these relationships requires an approach that goes beyond pairwise correlation and can test directional predictive relationships while accounting for potential intermediary variables. Conditional Granger causality (Hamilton 1994, Chen *et al* 2006) provides such a framework and has been widely used to investigate directional dependencies in Earth-system and climate-vegetation time series (Green *et al* 2017, Claessen *et al* 2019, Feng *et al* 2022). Conditional Granger causality tests whether past values of one variable enhance the prediction of another beyond what can be achieved using the target variable's own history and other conditioning variables. Such relationships represent directional predictive dependencies and should not be interpreted as evidence of direct physical causation.

Here, we applied conditional Granger causality to test whether VPD retains predictive information for DSM after accounting for SSM at the global scale. If the VPD–DSM relationship is no longer detected after conditioning on SSM, we classify it as

an SSM-mediated pathway; if it persists, we classify it as an SSM-independent pathway. Because direct long-term observations of DSM remain sparse at the global scale, large-scale assessments necessarily rely on reanalysis and reconstructed soil-moisture products (Dorigo *et al* 2021, Sungmin and Orth 2021). We used ERA5-Land reanalysis together with two global soil-moisture datasets to systematically assess pairwise and conditional Granger-causal relationships between VPD and SSM and DSM, following the same depth classification as Guan *et al* (2025). Furthermore, we examined how vegetation modulates the coupling between VPD and DSM. Together, these analyses characterize spatial variation in VPD–soil-moisture predictability and its potential ecosystem correlates, with implications for drought assessment, ecosystem resilience, and land-surface modeling.

2. Materials and methods

2.1. Data

Atmospheric and land-surface variables were obtained from the ERA5-Land reanalysis dataset for 1980–2023 (Muñoz-Sabater *et al* 2021). The ERA5-Land variables used in this study include hourly near-surface (2 m) air temperature and dew point temperature, and volumetric soil moisture across three layers (0–7 cm, 7–28 cm, 28–100 cm). Additionally, we used monthly total precipitation, surface solar radiation, and total evaporation. Soil moisture was separated into SSM (0–28 cm) and DSM (28–100 cm) layers to explicitly capture vertical heterogeneity (Guan *et al* 2025). SSM was calculated as a thickness-weighted average (Zhong *et al* 2025a) of the soil layers at 0–7 cm and 7–28 cm. Monthly evaporation from the Global Land Evaporation Amsterdam Model (GLEAM) (Miralles *et al* 2025) was additionally used to evaluate the robustness of the evaporation-related results.

Unless otherwise noted, results shown in the main text are based on ERA5-Land soil moisture. Given that ERA5-Land soil moisture is model-derived rather than based on direct observations, we further incorporated two additional soil moisture datasets for comparative and robustness analyses. The first was a temporally harmonized GLDAS soil moisture dataset based primarily on GLDAS-2.1 Noah simulations (Rodell *et al* 2004). We used GLDAS-2.1 as the primary GLDAS product because it provides multi-layer soil moisture fields from 2000 onward, which allows the construction of surface and DSM layers consistent with our ERA5-Land analysis. GLDAS-2.2 (Li *et al* 2019) Daily Catchment simulations provide root-zone soil moisture constrained by GRACE terrestrial water storage anomalies and were therefore used here as a reference for bias correction over the overlapping period (2003–2023). Specifically, we

bias-corrected daily GLDAS-2.1 soil moisture against GLDAS-2.2 root-zone soil moisture using quantile delta mapping independently for each grid cell, thereby reducing systematic differences between the two products while preserving the temporal variability of GLDAS-2.1. The corrected daily fields were then aggregated to monthly means, covering 2000–2023.

The second additional product was soil moisture via random forest regression (SMRFR) (Liu *et al* 2025b), a global multilayer soil moisture dataset generated using random forest from multi-source data, also covering 2000–2023. For consistency with the ERA5-Land analysis, the original GLDAS and SMRFR soil layers were converted into two integrated layers (0–28 cm and 28–100 cm) using depth-weighted averaging, representing SSM and DSM. For spatial consistency, all analyses were restricted to the intersection of grid cells where both SSM and DSM were available and exhibited detectable temporal variability across ERA5-Land, GLDAS, and SMRFR (figure S1). Detectable variability was defined from the temporal standard deviation, 95th–5th percentile range, and seasonal amplitude, using product-specific 5th-percentile thresholds calculated across initially valid grid cells; a grid cell was retained when both the first two metrics, or the seasonal amplitude, exceeded their respective thresholds. Areas excluded from this domain were mainly located in glacier-covered, arid, or high-elevation cold regions. Detailed descriptions of all three soil moisture datasets and the construction of the common valid soil-moisture domain are provided in supplementary methods 1.

Vegetation greenness was represented by the PKU global inventory modeling and mapping studies normalized difference vegetation index (NDVI) dataset (Li *et al* 2023), which spans 1982–2022 and was selected because its temporal coverage is broadly consistent with the period analyzed using ERA5-Land. Land cover information from the 2023 MODIS land cover product was used as a fixed biome classification to stratify the analysis across major biomes. Here, savannas were defined to include both Woody Savannas and Savannas, while shrublands comprised closed Shrublands and open Shrublands. Soil texture was characterized using the static ERA5 soil type field, which represents the soil classification used by the ECMWF land surface scheme to parameterize soil hydraulic properties. This field includes seven classes: coarse, medium, medium fine, fine, very fine, organic, and tropical organic soils, with non-land grid cells excluded.

All gridded datasets were resampled to a common $0.5^\circ \times 0.5^\circ$ grid before analysis using bilinear interpolation, except for categorical variables, including land cover and soil type, which were aggregated based on the majority class within each grid cell. VPD was first calculated at the hourly scale using hourly air temperature and dew-point temperature to account for the influence of diurnal temperature

variability on VPD estimates (Zhong *et al* 2025a, 2025b). VPD, SSM, and DSM were subsequently aggregated from their native temporal resolutions to monthly means before analyses. Prior to the correlation and Granger causality analyses, all variables were de-seasonalized by subtracting their monthly climatology (i.e. the long-term mean for each calendar month), and the resulting anomalies were linearly detrended to remove long-term trends.

2.2. Calculation of VPD

Hourly VPD (hPa) was calculated using the following formula (Murray 1967, Buck 1981):

$$\text{VPD} = \text{SVP} - \text{AVP} \quad (1)$$

$$\text{SVP} = 6.1078 \times e^{\frac{a \times T_a}{T_a + b}} \quad (2)$$

$$\text{AVP} = 6.1078 \times e^{\frac{a \times T_{\text{dew}}}{T_{\text{dew}} + b}}. \quad (3)$$

Here, SVP is the saturated vapor pressure calculated based on the air temperature (T_a) in degrees Celsius, AVP is the actual vapor pressure in hPa, and T_{dew} is the dew point temperature in degrees Celsius. The parameters a and b were taken from empirical studies (Murray 1967, Allen 1998). For $T_a \geq 0^\circ\text{C}$, $a = 17.269$ and $b = 237.3^\circ\text{C}$; for $T_a < 0^\circ\text{C}$, $a = 21.875$ and $b = 265.56^\circ\text{C}$.

2.3. Granger causality analysis

To quantify the directional interaction between VPD and soil moisture, we applied pairwise Granger causality analysis (Granger 1969). Granger causality assesses whether past values of one variable (X ; e.g. VPD or SSM) provide statistically significant information for predicting another variable (Y ; e.g. SSM or VPD) beyond the information contained in its own past. Specifically, we estimated and compared two autoregressive models. The restricted model includes only lagged values of Y up to lag p :

$$Y_t = \sum_{k=1}^p \alpha_k Y_{t-k} + \varepsilon_{1t} \quad (4)$$

where α_k denotes the regression coefficient associated with the lagged terms of Y , and ε is the model residual term.

The unrestricted model includes both lagged values of Y and lagged values of X as predictors:

$$Y_t = \sum_{k=1}^p \beta_k Y_{t-k} + \sum_{k=1}^p \gamma_k X_{t-k} + \varepsilon_{2t} \quad (5)$$

where β_k and γ_k are the regression coefficients associated with the lagged terms of Y and X , respectively. The null hypothesis is that X does not Granger-cause Y ($H_0: \gamma_1 = \gamma_2 = \dots = \gamma_p = 0$). Granger causality

from X to Y was inferred if the null hypothesis was rejected at the 5% significance level (F -test).

Conditional Granger causality (Hamilton 1994, Chen *et al* 2006) was further applied to test whether past VPD provided additional predictive information for DSM after conditioning on lagged SSM. Specifically, we extended the pairwise Granger causality framework by including SSM as an additional covariate (Z) in the restricted model:

$$Y_t = \sum_{k=1}^p \alpha_k Y_{t-k} + \sum_{k=1}^p \delta_k Z_{t-k} + \varepsilon_{3t} \quad (6)$$

as well as in the unrestricted model:

$$Y_t = \sum_{k=1}^p \beta_k Y_{t-k} + \sum_{k=1}^p \gamma_k X_{t-k} + \sum_{k=1}^p \zeta_k Z_{t-k} + \varepsilon_{4t} \quad (7)$$

where δ_k and ζ_k denote the regression coefficients associated with the lagged terms of Z . Granger causality from X_t to Y_t was established if the lagged terms of X_t remained jointly significant after controlling for Z_t . We adopted linear Granger causality to provide a straightforward and consistent framework for comparing lagged directional dependencies across multiple datasets and grid cells at the global scale. The analysis is intended to characterize broad-scale spatial patterns rather than the full functional form of local land–atmosphere interactions.

2.4. Pathway classification

To distinguish whether the influence of VPD on DSM is mediated through SSM or operates independently of it, we employed a Granger causality pathway attribution framework. We first evaluated the pairwise Granger causality between VPD and DSM to identify their overall directional association. We then conducted conditional Granger causality analyses by including SSM as a conditioning variable, thereby explicitly accounting for SSM dynamics. If significant pairwise Granger causality from VPD to DSM lost significance after conditioning on SSM, the effect was classified as an SSM-mediated pathway. Conversely, if the relationship remained significant after conditioning, it was classified as an SSM-independent pathway. Grid cells showing significant conditional Granger causality in the absence of significant pairwise VPD-to-DSM causality were not assigned to either pathway.

2.5. Neighbor-paired comparative analysis

To identify local environmental characteristics associated with the two VPD–DSM pathways, we compared immediately adjacent grid cells classified as SSM-mediated and SSM-independent. Adjacency was defined using the four cardinal neighboring cells. For each neighboring pair, we extracted the multi-year mean air temperature, precipitation, incoming solar radiation, NDVI and evaporation and calculated

the difference as the value in the SSM-independent cell minus that in the SSM-mediated cell. This local pairing reduced confounding by broad-scale climatic and geographical gradients.

Because neighboring pairs were spatially auto-correlated and some grid cells contributed to multiple pairs, we applied a spatial-block sign-flip permutation test (Winkler *et al* 2014, 2015, Radersma and Sheldon 2015) and spatial-block bootstrap confidence intervals (Lahiri and Zhu 2006). Neighboring pairs were grouped into spatial blocks according to their midpoint coordinates, and the analysis was repeated using $2.5^\circ \times 2.5^\circ$, $5^\circ \times 5^\circ$, and $10^\circ \times 10^\circ$ blocks to assess sensitivity to block size. All pairwise differences within the same block were randomized jointly to retain local spatial dependence. Full details are provided in supplementary methods 2.

3. Results

We first examined the pairwise relationships among monthly VPD, SSM and DSM using lagged Pearson correlation analysis. For each grid cell, correlations were calculated within a ± 6 month lag window, and the maximum absolute correlation and its corresponding lag were retained. Positive lag values indicate that variations in the first variable temporally precede those in the second at the selected dominant lag, whereas negative lag values indicate the reverse temporal ordering. VPD showed a strong negative correlation with both SSM and DSM, with mean correlation coefficients of -0.59 and -0.40 , respectively (figure 1(a)). Similar relationships were also found when soil moisture was derived from GLDAS (figure S2) and SMRFR (figure S3). Based on ERA5-Land soil moisture, 96.6% of the study domain showed a dominant zero-lag relationship between VPD and SSM, whereas only 14.2% of the domain showed a dominant zero lag for VPD–DSM (figure 1(b)). Instead, a one-month lag dominated the monthly VPD–DSM relationship, accounting for 69.9% of the study domain. Thus, VPD–DSM generally exhibited a longer lag than VPD–SSM. This depth-dependent delay is physically plausible because near-SSM can respond relatively rapidly to atmospheric forcing, whereas deeper soil moisture generally integrates hydrological and vegetation-related influences over longer timescales through processes such as vertical soil–water redistribution, drainage, and root water uptake.

To assess whether this contrast was sensitive to temporal aggregation, we repeated the lagged correlation analysis using daily ERA5-Land data and grouped the resulting lags into monthly-equivalent classes for direct comparison (figure S4). Although the daily analysis showed a broader lag distribution and a greater contribution from the 0 month class for VPD–DSM than the monthly analysis, the

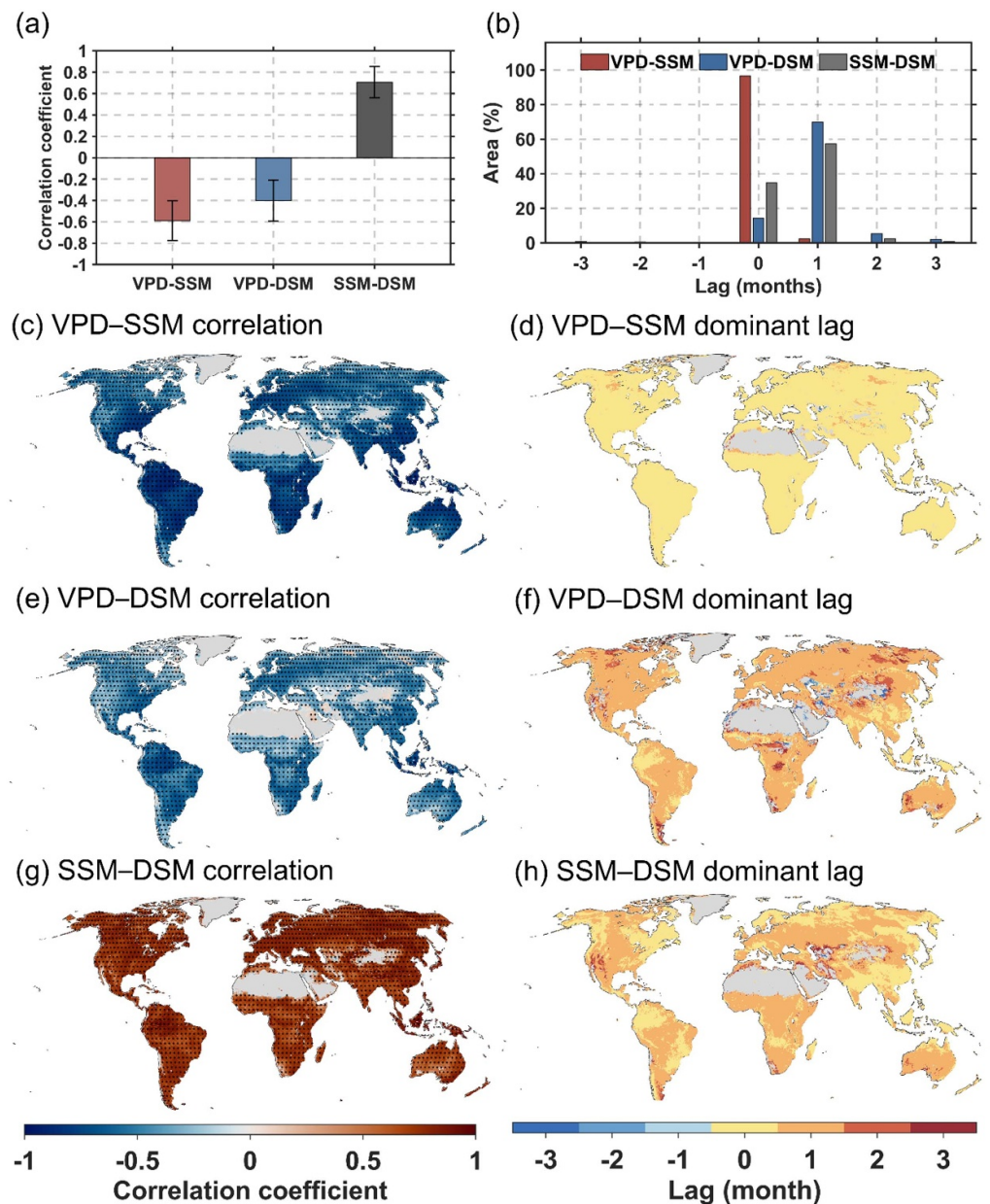


Figure 1. Pairwise Pearson correlations between atmospheric vapor pressure deficit (VPD), surface soil moisture (SSM), and deep soil moisture (DSM) during 1980–2023 in ERA5-Land. (a) Spatial mean correlation at the dominant lag; error bars show ± 1 standard deviation of the correlation values. (b) Percentage of the study domain at each dominant lag value. (c–h) Spatial distributions of correlation coefficients at the lag of maximum absolute correlation and the corresponding lags within a ± 6 month window for VPD and SSM (c and d), VPD and DSM (e and f), and SSM and DSM (g and h). Black dots mark areas where correlations are significant at the $p < 0.05$ level. Positive lag values indicate that variations in the first variable lead those in the second, whereas negative values indicate the opposite.

dominant VPD–SSM relationship remained substantially more synchronous than VPD–DSM. A similar tendency toward longer lags was also evident for SSM–DSM. These results indicate that the longer lag associated with DSM is a consistent feature across temporal resolutions, while the predominance of a one-month lag in the monthly analysis is partly influenced by temporal aggregation and soil-moisture persistence. Accordingly, the VPD–DSM lag should be interpreted as a delayed statistical association rather than direct evidence of vertical soil-water propagation. This lagged association does not by itself isolate

the underlying physical mechanism or distinguish transpiration-mediated processes from other persistent or slowly varying hydroclimatic influences.

We next applied pairwise Granger causality analysis to examine the directional relationships among monthly VPD, SSM, and DSM over the period 1980–2023. Guided by the lagged correlation results, which indicate that most responses occur within three months (figure 1(b)), the Granger causality tests were conducted using a maximum lag of three months. The analysis reveals strong statistical coupling within the soil column. Significant Granger-directional

dependence from SSM to DSM is detected across most (97.9%) of the study domain, whereas the reverse directional dependence from DSM to SSM is detected across approximately 50.0% of the domain (figure 2(c)). Significant Granger-directional relationships from VPD to SSM were detected over 60.1% of the study domain, with pronounced signals in northern and eastern North America, northern South America, central and Southern Africa, Europe, northern Asia, southern China, and northeastern Australia (figure 2(a)). Granger-directional relationships from VPD to DSM were detected over an even larger fraction of the study domain, encompassing 88.7%.

In contrast, Granger-directional relationships from soil moisture to VPD were detected over substantially smaller areas. Significant Granger dependence from SSM and DSM to VPD is found in only 25.1% and 20.3% of the study domain, respectively. A qualitatively similar asymmetry is also evident when soil moisture is derived from GLDAS (figure S5) and SMRFR (figure S6), and when maximum Granger lag lengths of 1, 6, and 12 months are applied to ERA5-Land (figure S7), with significant Granger causality from VPD to both SSM and DSM consistently occurring over more extensive areas than the reverse relationships. These results indicate a pronounced asymmetry in statistical directional dependence, with VPD showing more widespread predictive relationships with both SSM and DSM than soil moisture does with VPD. The regional heterogeneity in these relationships may reflect spatial differences in hydroclimatic conditions, vegetation water use, soil properties, and soil-moisture memory, which can modulate the timing and persistence of land-surface responses.

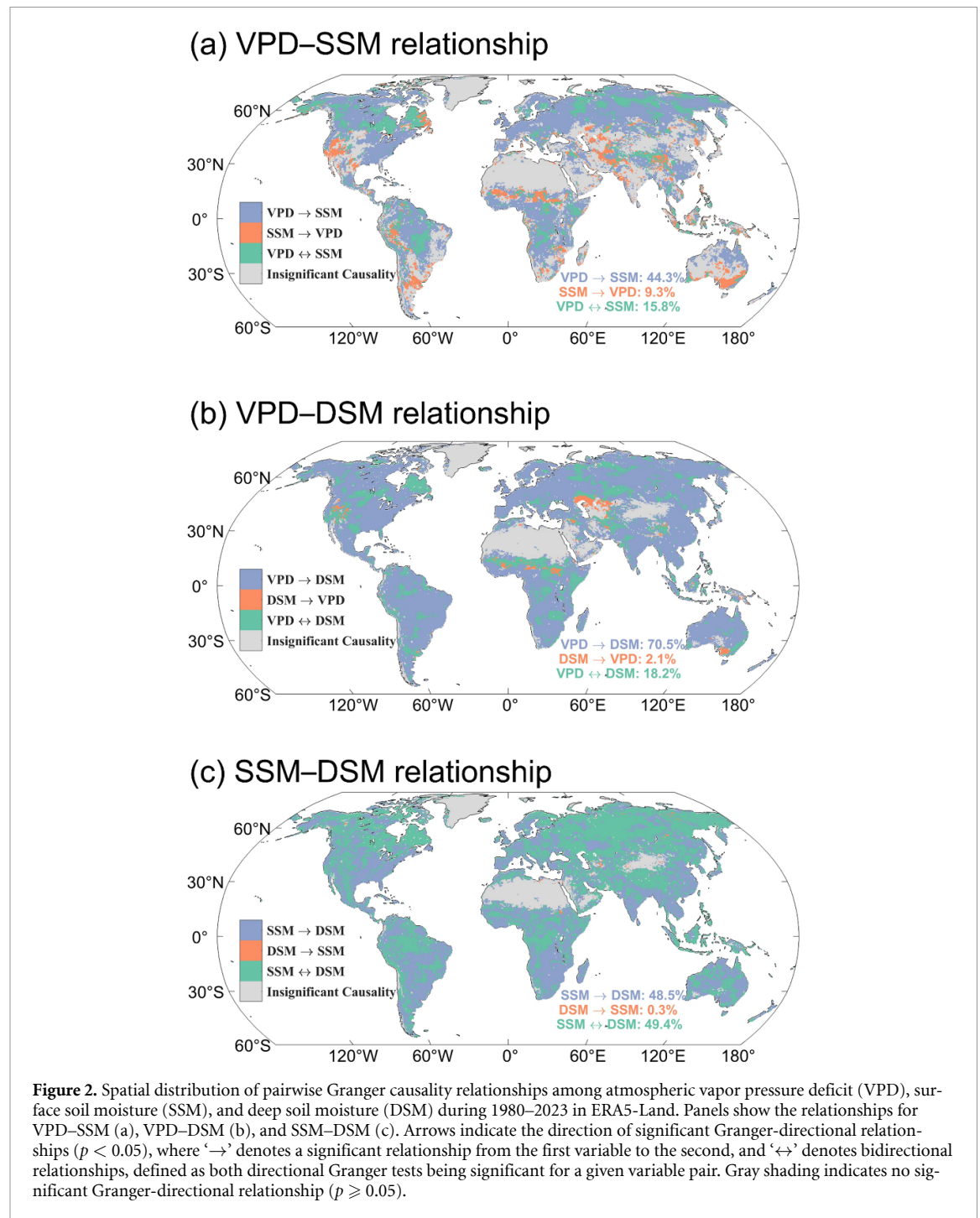
These pairwise results indicate widespread statistical directional dependence from VPD to DSM, detected across approximately 90% of the study domain. To distinguish whether this relationship is mediated by SSM or operates independently, we conducted conditional Granger causality analyses in which SSM was included as a conditioning variable. After conditioning on lagged SSM, the lagged VPD terms remained jointly significant for DSM over 46.2% of the study domain (figure 3(a)). These SSM-independent relationships were concentrated predominantly in the mid- to high-latitude regions of the Northern Hemisphere, indicating that a substantial fraction of the VPD–DSM linkage cannot be fully explained by SSM variability alone. A broadly similar spatial pattern, characterized by the widespread distribution of this SSM-independent pathway in the mid- to high-latitude Northern Hemisphere, is also reproduced when soil moisture is derived from GLDAS (figure S8(a)) and SMRFR (figure S9(a)). Using ERA5-Land soil moisture, this spatial partitioning remained largely unchanged when precipitation, air temperature, and solar radiation were additionally controlled for (figure S10(a)), and was also

robust to maximum Granger lag lengths of 1, 6, and 12 months (figure S11).

Based on ERA5-Land soil moisture, the statistical directional dependence from VPD to DSM detected by pairwise Granger causality was no longer significant after accounting for SSM across 42.5% of the study domain, which we classified as an SSM-mediated pathway. These pathways were mainly concentrated in low- to mid-latitude regions, highlighting pronounced spatial heterogeneity in the statistical coupling between VPD and DSM variability.

Given that the SSM-independent pattern appears to largely coincide with temperate and boreal forests, we further examined the relative spatial dominance of SSM-independent and SSM-mediated pathways across different biome types (figure 3(b)). SSM-independent pathways account for larger area fractions in most forest and savanna ecosystems, including evergreen needleleaf forests (ENF, 79.2%), deciduous broadleaf forests (DBF, 64.4%), and mixed forests (MF, 86.3%), as well as in savannas (SAV, 64.4%). An exception is evergreen broadleaf forests (EBF, 43.0%), where SSM-mediated pathways occupy a larger fraction of the area. A broadly similar pattern, with more widespread SSM-independent pathways in most forest biomes and savannas, is also evident when soil moisture is derived from GLDAS (figure S8(b)) and SMRFR (figure S9(b)). In the baseline ERA5-Land analysis, SSM-mediated pathways were more prevalent in shrublands, grasslands, and croplands (figure 3(b)). The biome-level area fractions remained broadly similar across maximum Granger lag lengths of 1, 6, and 12 months (figure S11). The broad spatial pattern also persisted when precipitation, air temperature, and solar radiation were additionally controlled for, although the biome-level fractions showed some sensitivity to the expanded conditioning set, including increased SSM-independent fractions in shrublands and grasslands (figure S10(b)). Further analysis by ERA5 soil type shows that the relative fractions of SSM-independent and SSM-mediated pathways are generally comparable in coarse, medium, and medium-fine soils, with a slight tendency toward larger SSM-independent fractions, whereas fine-textured soils show a higher SSM-mediated fraction (figure S12).

To further examine environmental contrasts between these two pathway types, we conducted a neighbor-paired comparative analysis across 17 736 pairs of adjacent grid cells (figure 4). For each paired location, multi-year mean air temperature, precipitation, incoming solar radiation, NDVI, and evaporation were compared using paired Student's *t*-tests. The paired comparisons reveal no statistically significant differences ($p \geq 0.05$) in mean air temperature, precipitation, and incoming solar radiation between the two pathway types, indicating that the spatial separation of pathways is not attributable to systematic differences in background



climate forcing. In contrast, both NDVI and evaporation are significantly higher ($p < 0.05$) in regions characterized by the SSM-independent pathway than in their neighboring SSM-mediated counterparts. This pattern remained unchanged when the pairing distance was relaxed to 100 km, with significantly higher NDVI and evaporation in SSM-independent grid cells ($p < 0.05$; figure S13). Spatial robustness was further assessed using spatial-block sign-flip permutation tests and spatial-block bootstrap confidence intervals. Across block sizes of 2.5° , 5° , and 10° , both NDVI and evaporation remained consistently higher in SSM-independent than in SSM-mediated grid

cells, with permutation p values < 0.05 and bootstrap 95% confidence intervals excluding zero (figure S14). Replacing ERA5-Land evaporation with GLEAM evaporation yielded the same pattern across all three block sizes (figure S15). These results show that SSM-independent pathways are spatially associated with higher vegetation greenness and evapotranspiration.

4. Discussion

Our study provides a global assessment of how VPD is coupled to soil moisture variability at different

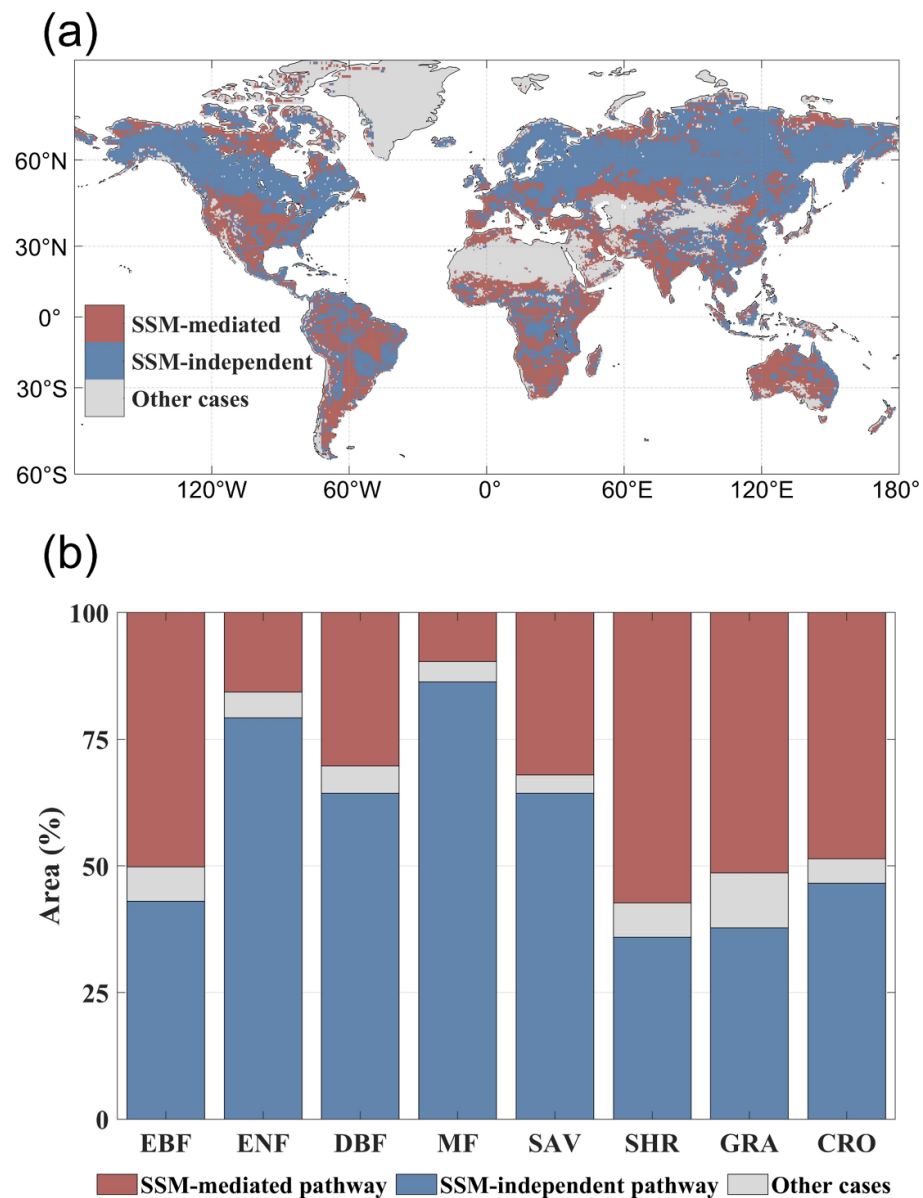
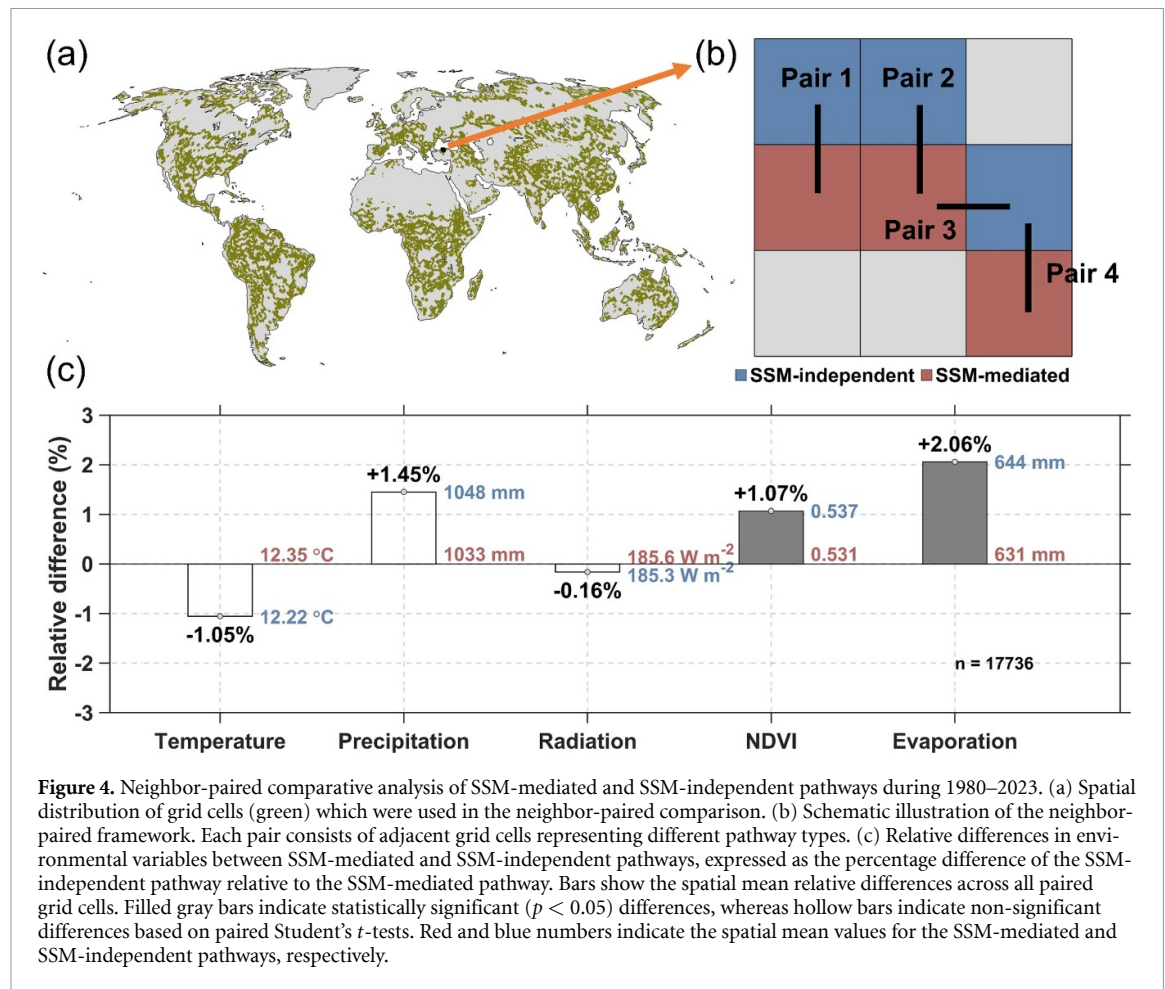


Figure 3. SSM-mediated and SSM-independent Granger-directional pathways from atmospheric vapor pressure deficit (VPD) to deep soil moisture (DSM) during 1980–2023. (a) Spatial distribution of SSM-mediated and SSM-independent pathways. (b) Area fractions of SSM-mediated and SSM-independent pathways across major biomes. Biomes include evergreen broadleaf forest (EBF), evergreen needleleaf forest (ENF), deciduous broadleaf forest (DBF), mixed forest (MF), savannas (SAV), shrublands (SHR), grasslands (GRA), and croplands (CRO).

depths. Our analyses reveal that VPD–DSM coupling is not governed by a single, universal mechanism, but rather reflects spatially heterogeneous combinations of SSM-mediated and SSM-independent pathways, whose relative importance varies systematically across regions and biomes. The lagged correlation analysis reveals a clear depth-dependent temporal structure in soil moisture responses to VPD. Variations in VPD are closely linked with SSM, whereas their association with DSM emerges with a longer delay. However, this temporal contrast should not be interpreted as evidence that VPD exerts a stronger control on SSM than DSM. SSM is highly sensitive to other short-term atmospheric forcings, particularly precipitation (Berg *et al* 2017, Guan *et al* 2025). In contrast, the

linkage between VPD and DSM, while often indirect and delayed, may operate through a broader set of land–atmosphere interaction pathways. Higher VPD increases atmospheric evaporative demand, but the resulting transpiration response depends on stomatal regulation, plant hydraulic characteristics, and soil-water availability (Massmann *et al* 2019, Grossiord *et al* 2020). Where deeper soil water remains available, vegetation can access water stored below the surface layer and sustain transpiration during surface drying (Fan *et al* 2017, Miguez-Macho and Fan 2021, Stocker *et al* 2023). Recent multilayer soil-moisture analyses further show that enhanced atmospheric evaporative demand, sustained evapotranspiration, and plant water uptake can contribute to deeper-soil depletion



and the development of whole-profile drought (Gu *et al* 2026). Such processes provide a physically plausible pathway through which VPD may remain statistically linked to DSM without the relationship being fully mediated by SSM variability. The higher evapotranspiration observed in SSM-independent regions in our neighbor-paired analysis is consistent with this interpretation.

Our Granger-based asymmetry should not be interpreted as evidence for intrinsically weak feedbacks from soil moisture to VPD. Soil moisture can modify near-surface temperature and humidity through evapotranspiration, surface-energy partitioning, and boundary-layer development, thereby feeding back on VPD (Santanello *et al* 2018, Zhou *et al* 2019). Model experiments further show that these soil-moisture–atmosphere feedbacks can substantially influence ecosystem carbon uptake through associated temperature and VPD anomalies (Green *et al* 2019, Humphrey *et al* 2021). This apparent contrast largely reflects methodological differences: Granger causality evaluates whether past variations in one variable provide additional predictive information for another, whereas land–atmosphere coupling experiments are designed to quantify physical feedbacks. Moreover, our monthly analysis may underrepresent rapid or contemporaneous feedback

processes that are not readily captured by lag-based Granger causality.

Our findings show that SSM-independent pathways linking VPD to DSM occur predominantly in the mid- to high-latitude regions of the Northern Hemisphere. This spatial pattern is consistent with widespread increases in evapotranspiration at northern high latitudes, driven partly by vegetation greening and an increasing contribution of plant transpiration to total evapotranspiration (Yang *et al* 2023). SSM-independent pathways are also more prevalent in most forest and savanna ecosystems, consistent with the possibility that vegetation access to subsurface water contributes to VPD–DSM coupling. Where roots access deeper soil layers, DSM can sustain transpiration during surface drying, providing a plausible route through which atmospheric evaporative demand can be linked to DSM through root-water uptake (Lauenroth *et al* 2014, Schlaepfer *et al* 2017). An exception occurs in EBF where SSM-independent pathways are less prevalent. Some tropical trees can rely substantially on shallow soil water (Sohel *et al* 2021, Alencar *et al* 2023), although deep-water uptake can become important during dry periods (Hasselquist *et al* 2010, Fan *et al* 2017). This diversity in water-use strategies may contribute to the comparatively greater importance

of SSM-mediated pathways in these ecosystems. Moreover, the increased SSM-independent fractions in shrublands and grasslands after additional climatic conditioning (figure S10(b)) indicate that biome identity alone cannot be used as a direct proxy for rooting depth or depth-specific water uptake. Shrublands can also contain woody vegetation capable of accessing subsurface water. We therefore interpret the biome-level patterns as being consistent with, rather than direct evidence of, vegetation-mediated deep-water use.

When stratified by soil type, fine-textured soils show the highest fraction of SSM-mediated pathways, possibly reflecting their greater water-holding capacity and capillary retention, which may strengthen the coupling between surface and deeper soil moisture (figure S12). In contrast, organic soils show a distinctly lower fraction, potentially owing to their unique hydrological properties and the additional influence of groundwater and cryosphere processes. However, differences among soil types are generally less pronounced than those among vegetation types, indicating that pathway occurrence is more strongly differentiated among vegetation classes than among the broad soil classes considered here.

Across the three soil moisture products, SSM-independent pathways are consistently detected in mid- to high-latitude regions and across most forest ecosystems, indicating that this broad spatial pattern is not specific to a single dataset. However, the SMRFR-based analysis (figure S9(a)) shows fewer SSM-mediated pathways in low- to mid-latitude regions than ERA5-Land and GLDAS. This difference likely reflects how vertical soil moisture dynamics are represented across products. Compared with ERA5-Land and GLDAS, SMRFR shows a weaker monthly lagged relationship between SSM and DSM (figure S3(b)), consistent with a less explicit representation of delayed surface-to-DSM responses. Because SMRFR is based on random forest reconstruction using contemporaneous predictors, including vegetation indices, overlying-layer soil moisture, and other environmental covariates, without explicitly incorporating lagged predictors (Liu *et al* 2025b), SSM and DSM variations tend to appear more synchronous (figure S3), while pairwise Granger-causal relationships are more spatially fragmented (figure S6(c)). These features may weaken the apparent SSM-mediated pathway. Future machine-learning-based soil moisture reconstructions may therefore benefit from explicitly incorporating lagged predictors and temporal response structures to better preserve vertical soil moisture dynamics and land-atmosphere coupling signals.

The spatial heterogeneity identified in this study has important implications for drought monitoring and land surface modeling. Our results suggest that SSM alone may be insufficient to characterize subsurface drought dynamics, particularly in

regions with high vegetation activity and strong evapotranspiration. In such regions, ongoing vegetation greening may strengthen transpiration-driven water withdrawal from deeper soil layers. If vegetation dynamics are not adequately represented, the land surface models underlying widely used soil moisture products—such as HTESSEL in ERA5-Land and the Noah-based framework in GLDAS—may not fully capture SSM-independent statistical relationships between VPD and DSM. Several study limitations should also be acknowledged. Granger causality quantifies statistical directional dependence rather than establishing physical causation, and its causal interpretation depends on assumptions underlying time-series causal inference (Runge *et al* 2019). Because land-atmosphere interactions can be non-linear and state dependent, some predictive relationships may not be fully captured by our linear Granger framework (Papagiannopoulou *et al* 2017). Seasonal hysteresis in soil-moisture-evaporative-fraction relationships, including contrasts between surface and root-zone soil moisture and across land-cover types, may introduce additional state dependence that is not represented here (Khandare *et al* 2024). Moreover, the use of monthly data may obscure faster soil-plant-atmosphere interactions operating at sub-monthly timescales. Although mean temperature, precipitation, and radiation did not differ significantly between the two pathway types, differences in climate variability and extreme conditions may still modulate soil-plant-atmosphere interactions and thereby influence pathway classification.

An additional limitation is that the soil moisture products used here do not provide fully independent observations of DSM. DSM is inferred through model-based or reconstruction-based representations of vertical soil-water dynamics, and similarities in the underlying representations of soil-water transport and vegetation-soil interactions may contribute to the agreement across products. Moreover, SMRFR uses several predictors derived primarily from ERA5-Land, further limiting the independence of the cross-product comparison. Actual rooting depth and the vertical distribution of root-water uptake were not directly observed in this study. Moreover, the land surface models underlying ERA5-Land and GLDAS-2.1 represent rooting characteristics using vegetation-type-dependent parameterizations over fixed soil layers. These prescribed rooting schemes may differ from actual rooting depths and may not fully capture spatial, seasonal, species-level, or drought-induced variations in root distribution and water uptake. Such structural uncertainty may propagate into the simulated coupling between surface and deeper soil moisture and, consequently, into the inferred pathway classification. Soil hydraulic properties and groundwater interactions are also not explicitly constrained in our statistical analysis. Despite these limitations, the globally consistent patterns identified here

highlight the important role of ecosystem functioning in regulating how VPD signals propagate into the soil column.

5. Conclusions

By combining pairwise and conditional Granger causality analyses across multiple global soil moisture datasets, we identify widespread statistical directional dependence from VPD to both SSM and DSM, whereas the reverse relationships from soil moisture to VPD are comparatively less extensive. A substantial fraction of the directional relationships from VPD to DSM remain significant after conditioning on SSM, indicating that DSM variability cannot be explained solely by the downward propagation of SSM deficits. The spatial distribution of these pathways suggests a potential role for vegetation-mediated water use. SSM-independent pathways are most prevalent in mid- to high-latitude Northern Hemisphere regions and are more widespread in most forest and savanna ecosystems. Their association with higher vegetation greenness and evapotranspiration is consistent with the possibility that vegetation access to subsurface water contributes to VPD–DSM coupling. Given the ongoing increase in global vegetation greenness (Anniwaer *et al* 2026), our findings underscore the importance of incorporating dynamic vegetation information and improving representations of vegetation–soil interactions in land surface models, in order to enable more robust projections of future soil water availability and associated changes in the terrestrial water cycle.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Supplementary material available at <http://doi.org/10.1088/1748-9326/aeabbe/data1>.

Data and materials availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. These data are freely accessible from the following sources: The ERA5-Land dataset is from <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land>. The GLDAS dataset is from <https://doi.org/10.5067/SXAVCZFAQLNO> and <https://doi.org/10.5067/TXBMLX370XX8>. The SMRFR dataset is from <https://doi.org/10.6084/m9.figshare.27601035.v4>. The PKU GIMMS NDVI dataset is from <https://doi.org/10.5281/zenodo.8253971>. The MODIS Land Cover dataset is from <https://doi.org/10.5067/MODIS/MCD12C1.006>. The ERA5 soil type dataset is from <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means>. The GLEAM4.2a actual evaporation dataset is from www.gleam.eu.

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