

## Spatiotemporal Analysis of Multi-layer Soil Moisture Deficit and Its Influencing Factors in the Eastern Helan Mountain Oasis (Postprint)

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### Abstract

In the Helan Mountain eastern foothills oasis, acclaimed as the “Jiangnan beyond the Great Wall,” soil moisture constitutes a critical limiting factor for ecological conservation and high-quality socioeconomic development. Utilizing 10-layer soil moisture data (0-100 cm) and employing methods such as spatiotemporal trend analysis and partial regression analysis, this study conducts a multidimensional analysis of the spatiotemporal distribution, evolutionary characteristics, and influencing factors of soil moisture deficit in the Helan Mountain eastern foothills oasis, thereby facilitating an in-depth understanding of the correlations and interactive influences of soil moisture variations across different soil depths in this region. The results demonstrate that over the past two decades, the degree of soil moisture deficit in each layer has exhibited an intensifying trend. With increasing soil depth, soil moisture across layers in the northern and southern oasis areas displays multidimensional spatial distribution patterns of deficit→surplus→deficit→surplus→deficit and deficit→surplus→deficit, respectively, along with multidimensional spatiotemporal evolution trends of wetting→drying→wetting and wetting→drying. The influences of precipitation (PRE) and atmospheric saturated vapor pressure deficit (VPD) on soil moisture across layers gradually attenuate, the influence of temperature (TMP) initially intensifies then attenuates, while the influence of normalized difference vegetation index (NDVI) progressively intensifies. Collectively, soil moisture across different depths and its influencing factors manifest regular, multidimensional spatiotemporal variation characteristics; soil moisture in the 0-10 cm layer is strongly positively influenced by PRE, whereas soil moisture in the 10-30 cm and 30-100 cm layers are strongly negatively influenced by TMP and NDVI, respectively.

## Full Text

# Spatio-temporal Analysis of Multi-layered Soil Moisture Deficit and Its Influencing Factors in the Oases at the Eastern Foothill of Helan Mountains

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**Abstract:** In the oases at the eastern foothill of Helan Mountains, renowned as the “Jiangnan on the Frontier,” soil moisture constitutes a critical limiting factor for ecological conservation and high-quality socio-economic development. Based on ten-layer soil moisture data (0–100 cm), this study employs spatiotemporal trend analysis and partial regression analysis to conduct multidimensional investigations of the spatiotemporal distribution, evolution characteristics, and influencing factors of soil moisture deficit in this region. This approach facilitates deeper understanding of the correlations and interactive effects of moisture changes across different soil depths. Results demonstrate that the degree of soil moisture deficit across all layers has intensified over the past two decades. With increasing soil depth, the northern and southern oases exhibit distinct multidimensional spatial distribution patterns—specifically, deficit-surplus-deficit-surplus-deficit and deficit-surplus-deficit, respectively. The regions also display spatiotemporal evolution trends of wetting-drying-wetting and wetting-drying. The influence of precipitation (PRE) and atmospheric saturation vapor pressure deficit (VPD) on soil moisture across layers gradually weakens with depth, whereas temperature (TMP) shows a pattern of initially strengthening then weakening influence, and the normalized difference vegetation index (NDVI) exhibits gradually strengthening influence. Overall, soil moisture at different depths and its influencing factors demonstrate regular, multidimensional spatiotemporal variation patterns. The 0–10 cm layer is strongly positively influenced by PRE, while the 10–30 cm and 30–100 cm layers are significantly negatively affected by TMP and NDVI, respectively.

**Key words:** standardized soil moisture index; soil moisture deficit; spatiotemporal variability; multidimensional structure; oases at the eastern foothill of Helan Mountains

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Soil moisture, as a fundamental component of soil, represents one of the most critical variables in terrestrial systems. Its dynamics play a vital role in material

cycling and energy flow among the atmosphere, vegetation, and groundwater, fundamentally determining plant distribution and growth patterns in arid and semi-arid environments. Soil moisture deficiency adversely affects agricultural production and vegetation ecosystems, with particularly pronounced impacts in water-scarce arid and semi-arid regions. Previous research has revealed that in the desert steppe of eastern Ningxia, located in arid and semi-arid zones, increasing vegetation coverage leads to excessive soil moisture utilization, resulting in deep soil moisture depletion and intensified soil moisture deficit. In the Hedong Sandy Land of Ningxia, the vertical distribution of soil moisture exhibits distinct stratification characteristics influenced by both climate and vegetation. In the loess region of southern Ningxia, soil moisture is most strongly affected by meteorological factors, showing a decreasing then increasing trend over the study period. These studies have profoundly revealed the dynamic characteristics of soil moisture across different regions of Ningxia.

However, under the combined influence of multiple environmental factors such as precipitation, temperature, soil properties, and vegetation coverage, the distribution characteristics and controlling factors of soil moisture at different spatiotemporal scales and depths show significant variations, consequently exerting differential impacts on plant growth and crop yield. The extremely complex relationships among soil moisture layers pose substantial challenges for large-scale, high-resolution, dynamic monitoring of multi-layer soil moisture. Currently, common soil moisture observation methods include field measurements, remote sensing inversion, and model simulation. Field measurement data are constrained by observation duration, station density, and spatial representativeness, limiting the temporal frequency and spatial continuity of related studies. Remote sensing inversion and model simulation have enabled research to transition from point-based to area-based investigations, facilitating studies on large-scale soil moisture spatiotemporal patterns. However, existing long-term soil moisture datasets currently suffer from coarse spatial resolution, and most related research focuses on surface soil characteristics, with relatively few multidimensional spatiotemporal analyses of large-scale, multi-layer soil moisture.

The SMCI dataset, developed based on measured soil moisture and ERA5-Land data, demonstrates considerable potential for high-quality, high spatiotemporal resolution, multi-layer soil moisture research. This study utilizes this dataset combined with spatiotemporal analysis methods to investigate the multidimensional spatiotemporal distribution and evolution characteristics of soil moisture in the oases at the eastern foothill of Helan Mountains across horizontal and vertical scales. Furthermore, to address multicollinearity issues in correlation and multiple regression analyses of soil moisture influencing factors, we constructed a spatial partial regression analysis method to objectively reveal the multidimensional correlations and interactive effects of influencing factors on soil moisture at different depths. The findings will enhance understanding of soil drought mechanisms and evolution patterns, mitigate negative impacts of drought on socio-economic production and ecological environments, and promote the development of new productive forces in ecological conservation and management of

the Yellow River Basin.

## 1. Study Area

The oases at the eastern foothill of Helan Mountains (104°26' -106°98' E, 36°65' -39°39' N) extend from Huinong District in Shizuishan City in the north to Shapotou District in Zhongwei City in the south. Bounded by Qingtongxia, the region comprises the Yinchuan Plain and Weining Plain. Located in the inland northwest and the upper-middle reaches of the Yellow River, the area features a temperate continental climate with cold winters and hot summers. The multi-year average precipitation is less than 200 mm, while evaporation reaches 1600 mm. The region is characterized by drought, scarce precipitation, limited surface water resources, and water scarcity, representing a typical arid oasis area. Benefiting from the topographic effects of Helan Mountains and abundant water-soil resources from the Yellow River, irrigated agriculture has developed here for two millennia, creating the productive “Jiangnan on the Frontier” landscape and establishing the region as an important agricultural area and ecological protection barrier in northwestern China.

### 2.1 Data Sources

Multi-layer, high spatiotemporal resolution soil moisture data were extracted from the SMCI v1.0 dataset. This dataset uses ERA5-Land high-quality soil moisture data as a benchmark, incorporating 2940-layer soil moisture observations, leaf area index, land cover type, topography, and soil properties as covariates, obtained through machine learning methods and validated to have high accuracy. Temperature (TMP) and precipitation (PRE) data were extracted from the ERA5-Land dataset; atmospheric saturation vapor pressure deficit (VPD) data were extracted from the TerraClimate dataset; and normalized difference vegetation index (NDVI) data were extracted from the MODIS dataset. The bilinear interpolation method, suitable for relatively smooth surfaces and widely applied with high precision and quality, was used to resample all raster data to 1 km × 1 km resolution. The study period spanned 2000–2020. Additionally, using 2000–2020 ERA5-Land soil moisture data for validation, parameters including the coefficient of determination ( $R^2$ ) and root mean square prediction error were employed to assess the applicability and accuracy of SMCI data in the study area. Data sources and preprocessing details are provided in Table 1.

[Figure 1: see original paper] Schematic diagram of the study area

Data sources and pre-processing process

#### 2.2.1 Standardized Soil Moisture Index

Due to the spatial heterogeneity of precipitation, evapotranspiration, and other factors affecting soil moisture, significant differences exist in soil moisture across

different regions and depths. Consequently, comparative analysis based on raw soil moisture values introduces bias. The Standardized Soil Moisture Index (SSMI) is a standardized index constructed from historical soil moisture data, offering simple calculation and suitability for regional soil moisture monitoring and comparative analysis. For each soil layer  $j$  ( $j \in [1,10]$ ), SSMI $_j$  characterizes the degree of soil moisture deficit, with formulas detailed in the literature. SSMI $_j < 0$  indicates soil moisture below normal, representing a deficit state (drought), where lower values signify stronger moisture deficit; SSMI $_j > 0$  indicates soil moisture above normal, representing a surplus state (wetness), where higher values signify greater moisture surplus.

### 2.2.2 Spatiotemporal Trend Analysis

The Theil-Sen Median method was applied to SSMI $_j$  for pixel-by-pixel analysis at the raster scale, yielding trend values ( $\beta$ ) to determine the intensity and nature of soil moisture changes. This non-parametric statistical trend calculation method offers robust computation, high efficiency, and insensitivity to outliers and measurement errors, with formulas detailed in the literature.  $\beta < 0$  indicates a drying trend, where lower values signify stronger moisture deficit trends;  $\beta > 0$  indicates a wetting trend, where higher values signify stronger moisture surplus trends.

To enhance the accuracy and reliability of trend analysis, the Mann-Kendall test was subsequently employed to assess the significance of soil moisture trends, generating test statistics ( $Z$ ). The calculation process is detailed in the literature.  $Z > 0$  indicates an increasing trend, while  $Z < 0$  indicates a decreasing trend. Setting significance level  $\alpha$ , if  $|Z| > Z_{1-\alpha/2}$ , the null hypothesis is rejected, indicating a significant trend ( $P < 0.05$ ).

### 2.2.3 Spatiotemporal Partial Regression Analysis

Partial regression analysis was conducted pixel-by-pixel for SSMI $_j$  and its influencing factors (PRE, TMP, VPD, NDVI) to eliminate multicollinearity effects among variables and reveal the primary influencing factors and their differences across soil depths. The calculation process involves:

First, using PRE as the independent variable ( $P$ ) and TMP, VPD, NDVI as dependent variables ( $T, V, N$ ), a regression equation is established:  $P = \beta T + \beta V + \beta N + \epsilon$ , where  $\beta$  represents regression coefficients and  $\epsilon$  represents the unexplained portion of  $P$  by  $T, V, N$ .

A new variable  $P'$  is defined as  $P$  minus the predicted values from this regression ( $P' = P - (\beta T + \beta V + \beta N)$ ), representing  $P$  after controlling for the effects of  $T, V, N$ .

Similarly, using SSMI $_j$  as the dependent variable ( $S$ ) and  $T, V, N$  as independent variables, a regression equation is established:  $S = \beta' T + \beta' V + \beta' N + \epsilon'$

e, where  $\beta'$  represents regression coefficients and e represents the unexplained portion of S by T, V, N.

A new variable S' is defined as S minus the predicted values from this regression ( $S' = S - (\beta' T + \beta' V + \beta' N)$ ), representing S after controlling for the effects of T, V, N.

Finally, using S' as the dependent variable and P' as the independent variable, a partial regression equation is established:  $S' = aP' + b$ , where a is the partial regression coefficient and b is a constant. The partial regression coefficient reflects the influence degree of PRE on SSMIj after controlling for other variables. Larger coefficients indicate stronger effects of PRE on SSMIj, and vice versa. This process is repeated to establish partial regression equations between SSMIj and each influencing factor, reflecting their respective impacts.

### 3.1 SMCI Data Validation Analysis

SMCI data from 0-10 cm, 10-20 cm, and 20-30 cm layers were arithmetically averaged to create 10-30 cm layer data, and 30-100 cm layer data were similarly generated. Monthly soil moisture data from the ERA5-Land dataset for corresponding layers were then extracted. Cross-validation was performed by plotting scatter diagrams between the two datasets.

Scatter plots for 0-10 cm, 10-30 cm, and 30-100 cm layers show  $R^2$  values of 0.72, 0.74, and 0.70, respectively. Overall, SMCI data demonstrate good accuracy across different soil layers in the study area.

[Figure 2: see original paper] Cross validation of two types of multi-layered soil moisture data

### 3.2.2 Multi-layer Soil Moisture Spatial Structure Characteristics

In the oases at the eastern foothill of Helan Mountains, the 0-30 cm layer exhibits drought characteristics across most areas, except for slightly wetter conditions in Dawukou and Huinong districts in the north. The moisture deficit is particularly severe in Shapotou District. As soil depth increases, the degree of moisture deficit gradually improves, with moisture surplus areas gradually expanding. The 30-50 cm layer shows weaker moisture deficit, while the 70-80 cm layer displays wetting characteristics. Overall, with increasing soil depth, soil moisture in the northern Yinchuan Plain transitions from deficit to surplus, while the southern Weining Plain shows a deficit-surplus-deficit pattern.

### 3.2.3 Multi-layer Soil Moisture Spatiotemporal Evolution Trend

Although the 0-30 cm layer exhibits high moisture deficit, it has shown a wetting trend in recent years, with overall improvement in moisture deficit conditions.

As soil depth increases, the soil drying trend gradually intensifies. The 30–60 cm layer shows a strong drying trend across most areas except central Yinchuan Plain. The 60–100 cm layer shows improved drying trends in Yinchuan Plain, while Weining Plain continues to exhibit drying trends.

[Figure 3: see original paper] Temporal structure of multi-layered soil moisture in the oases at the eastern foothill of Helan Mountains

[Figure 4: see original paper] Multi-dimensional spatial structure of multi-layered soil moisture

[Figure 5: see original paper] Multi-dimensional spatio-temporal evolutionary structure of multi-layered soil moisture

### 3.3.1 Multi-dimensional Analysis of Soil Moisture and PRE

Based on the above analysis, three layers were selected (0–10 cm, 10–30 cm, and 30–100 cm, denoted as surface, shallow, and deep layers) to investigate correlations and interactive effects among influencing factors across different depths. In the surface layer, PRE shows positive correlations across the oases, with strong positive correlations in most areas except western Shapotou District. In the shallow layer, positive correlations weaken compared to the surface layer. In the deep layer, correlations further weaken, with most areas transitioning to no correlation or weak negative correlations except Yinchuan Plain. Overall, as soil depth increases, the strong positive effect of PRE gradually weakens: in southern Yinchuan Plain, it decreases from a very strong positive effect at the surface to a strong positive effect in the deep layer; in other areas, it decreases from a relatively strong positive effect at the surface to no effect or weak positive effect in the deep layer.

[Figure 6: see original paper] Spatially partial regression coefficients of multi-layered soil moisture and PRE

### 3.3.2 Multi-dimensional Analysis of Soil Moisture and TMP

In the surface layer, TMP shows positive correlations across the oases, with particularly strong correlations in Weining Plain. In the shallow layer, correlations remain positive but weaken compared to the surface layer. In the deep layer, correlations further weaken, with most areas transitioning to no correlation or weak negative correlation except Yinchuan Plain. Overall, as soil depth increases, the initially weak positive effect of TMP in northern Yinchuan Plain and Weining Plain transforms into a strong negative effect in the shallow layer, then reverts to no effect or weak positive effect in the deep layer. In southern Yinchuan Plain, the strong positive effect at the surface transforms into a strong negative effect in the shallow layer, further weakening to a weak negative effect in the deep layer.

[Figure 7: see original paper] Spatially partial regression coefficients of multi-layered soil moisture and TMP

### 3.3.3 Multi-dimensional Analysis of Soil Moisture and VPD

In the surface layer, VPD shows strong negative correlations in southern Yinchuan Plain, with weak negative or weak positive correlations in other areas. In the shallow layer, negative correlations increase. In the deep layer, negative correlations weaken, with most areas transitioning to positive correlations. Overall, as soil depth increases, the strong negative effect of VPD in southern Yinchuan Plain gradually weakens from surface to deep layers, while in northern Yinchuan Plain and Weining Plain, the weak positive effect remains essentially unchanged.

[Figure 8: see original paper] Spatially partial regression coefficients of multi-layered soil moisture and VPD

### 3.3.4 Multi-dimensional Analysis of Soil Moisture and NDVI

In the surface layer, NDVI shows positive correlations across the oases, with particularly strong correlations in Weining Plain. In the shallow layer, positive correlations weaken in Weining Plain but strengthen in northern Yinchuan Plain. In the deep layer, positive correlations further weaken, with strong negative correlations dominating most areas except parts of Yinchuan Plain. Overall, as soil depth increases, the initially weak positive effect of NDVI in most areas transforms into a strong negative effect in the deep layer. In southern Yinchuan Plain, the strong positive effect at the surface transforms into a strong negative effect in the shallow layer, further weakening to a weak negative effect in the deep layer.

[Figure 9: see original paper] Spatially partial regression coefficients of multi-layered soil moisture and NDVI

In summary, the spatial distribution, evolution trends, and interactive effects with influencing factors of multi-layer soil moisture in the oases at the eastern foothill of Helan Mountains exhibit obvious correlations, differences, and regular multidimensional spatiotemporal patterns (Table 2).

Multi-dimensional spatio-temporal evolution characteristics of soil moisture and its influencing factors in the oases at the eastern foothill of Helan Mountains

## 4.1 Regional Comparative Analysis of Multi-dimensional Spatiotemporal Evolution Characteristics of Soil Moisture

Previous studies have shown that surface soil moisture increased on the Mongolian Plateau and upper Yellow River Basin during 2000–2020, while it decreased on the Qinghai-Tibet Plateau, in northern semi-arid regions, central-eastern

agricultural areas, the middle Yellow River Basin, and Shaanxi Province. The Loess Plateau also showed a slight decreasing trend, with intensified soil moisture drought in summer. The surface soil moisture in the oases at the eastern foothill of Helan Mountains similarly exhibited a strong drying trend, which only alleviated after 2010. This decreasing trend may result from combined effects of increasing vegetation water consumption and climate warming. Deep soil moisture on the Mongolian Plateau and in North China, particularly root-zone soil moisture below 100 cm, showed the most significant decrease, consistent with deep soil moisture changes in the study area.

## 4.2 Analysis of Influencing Factors and Their Correlations for Multi-layer Soil Moisture

Although soil moisture is influenced by multiple factors including climate, vegetation, soil, and topography, PRE exhibits the strongest impact on surface soil moisture of the Qinghai-Tibet Plateau, Shaanxi Province, and Mu Us Sandy Land. In the study area, PRE's positive effect is significantly stronger than other factors and gradually decreases with soil depth, similar to findings in central-eastern agricultural areas and the Mongolian Plateau. As the direct source of soil moisture, PRE contacts surface soil most directly, and rainfall infiltration positively affects surface soil moisture.

The influence of TMP ranks second in the study area, transitioning from positive to strong negative effects with increasing soil depth, further indicating the layered complexity of soil moisture changes. Increased vegetation coverage reduces surface evaporation area, blocks direct solar radiation, lowers surface temperature, and reduces soil moisture loss. Additionally, enhanced root systems stabilize soil and effectively retain moisture, while vegetation-enriched soils with organic matter and microorganisms improve aggregate structure and water retention capacity. Therefore, NDVI has positive effects in the study area. However, studies show that vegetation transpiration in the Loess Plateau primarily utilizes deep root-zone soil moisture, making vegetation an important driver of soil moisture reduction. Increased vegetation coverage raises water demand, and extensive deep root systems consume substantial deep soil moisture through transpiration, strengthening the negative correlation between NDVI and deep soil moisture. Similar patterns occur in eastern Ningxia desert steppe and Hedong Sandy Land, where increased vegetation coverage consumes large amounts of deep soil moisture, intensifying deep soil moisture deficit.

VPD has strong negative effects on surface soil moisture in the study area. VPD is directly related to atmospheric moisture demand and affects surface soil moisture conduction and evapotranspiration. Higher VPD indicates greater atmospheric moisture deficit, making surface soil moisture more susceptible to loss through evapotranspiration. As soil depth increases, the negative correlation between VPD and soil moisture gradually weakens due to weaker atmospheric contact with deeper soils.

Overall, this study focuses on refined analysis of the internal connections and differences in spatiotemporal distribution and evolution trends of multi-layer soil moisture, revealing more detailed vertical variation characteristics through finer multi-layer soil moisture data compared to other studies. By constructing spatial partial regression models to eliminate multicollinearity among influencing factors at the pixel scale, this study objectively reveals influencing factors and their interactive effects on soil moisture at different depths. However, limitations include reliance on a single soil moisture product without extensive in-situ experimental validation, and lack of discussion on socio-economic and land use factors due to space constraints. Future research should employ multiple soil moisture products or model simulation methods like the Temperature Vegetation Dryness Index to improve data accuracy and representativeness, while simulating different climate change and human activity scenarios to explore future soil moisture changes and impacts.

## 5. Conclusions

- 1) The distribution characteristics, changing trends, and interactive effects with influencing factors of multi-layer soil moisture in the oases at the eastern foothill of Helan Mountains exhibit regular, multidimensional spatiotemporal evolution patterns. Temporally, the degree of soil moisture deficit across all layers intensified during 2000–2020. In multidimensional space, the 0–10 cm layer shows high moisture deficit, with Yinchuan Plain and Weining Plain displaying deficit-surplus-deficit patterns as depth increases. In multidimensional spatiotemporal terms, Yinchuan Plain and Weining Plain show wetting-drying-wetting and wetting-drying trends, respectively, with increasing soil depth.
- 2) In the oases at the eastern foothill of Helan Mountains, PRE has the strongest positive influence on 0–10 cm soil moisture, followed by positive effects from TMP in Weining Plain and VPD in Yinchuan Plain. NDVI has weak positive effects. With increasing soil depth, PRE's influence gradually weakens; TMP's influence shifts from positive to negative with gradually strengthening intensity; VPD's influence first strengthens then weakens; and NDVI's influence gradually increases. Both TMP and NDVI exert strong negative effects on 10–30 cm and 30–100 cm soil moisture, respectively.
- 3) Under global warming, VPD and soil moisture coupling relationships are increasingly important. In the study area, VPD has strong negative effects on soil moisture in Weining Plain and southern Yinchuan Plain, with gradually weakening influence as soil depth increases.

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*Note: Figure translations are in progress. See original paper for figures.*

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