Spatiotemporal Variation Characteristics and Main Driving Factors of Soil Moisture in the Qilian Mountains: Postprint

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Abstract

Soil moisture is crucial for vegetation growth and terrestrial ecosystems, particularly playing a decisive role in the provision of ecosystem services by mountain forest ecosystems in arid and semi-arid regions. Using remote sensing soil moisture data, this study investigated the temporal dynamics and spatial variation characteristics of soil moisture in the Qilian Mountains region from 2017 to 2021 based on trend analysis, correlation analysis, and the geographic detector method, analyzing the influence of mean annual temperature, mean annual precipitation, Normalized Difference Vegetation Index (NDVI), slope gradient, aspect, and elevation on the spatiotemporal variation of soil moisture. The results show that: (1) Soil moisture in the Qilian Mountains region exhibited relatively stable changes from 2017 to 2021 (trend slope of 0.000018), but with large interannual fluctuations (coefficient of variation of 0.183). (2) Soil moisture during the growing season (May–October) showed significant spatial differences (0.068–0.214), and influenced by the East Asian monsoon, the overall soil moisture presented a trend of being higher in the east and lower in the west. (3) Both correlation analysis and geographic detector results indicate that precipitation and NDVI play a dominant role in the spatiotemporal variation of soil moisture, with explanatory power (q) of 0.761 and 0.722, respectively, both above 70%, while topographic factors have a minor effect with q values less than 0.1. The influences of various environmental factors on the spatial distribution of soil moisture in the Qilian Mountains show significant differences and exhibit interaction effects, presenting two-factor enhancement and nonlinear enhancement relationships. The research findings can provide a scientific basis for the formulation of ecological protection policies and measures in the Qilian Mountains region, promoting ecological environmental conservation in this area.

Full Text

Preamble

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Analysis of Spatiotemporal Variation Characteristics and Main Driving Factors of Soil Moisture in the Qilian Mountains

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Abstract

Soil moisture is crucial for vegetation growth and terrestrial ecosystems, particularly in determining the provision of ecosystem services by mountain forest ecosystems in arid and semiarid regions. Using remote sensing soil moisture data, this study investigates the temporal dynamics and spatial differentiation of soil moisture in the Qilian Mountains from 2017 to 2021 through trend analysis, correlation analysis, and geographical detector methods. The analysis focuses on the impacts of mean annual temperature, mean annual precipitation, normalized difference vegetation index (NDVI), slope, aspect, and elevation on the spatiotemporal variation of soil moisture. The results reveal three key findings: (1) Soil moisture in the Qilian Mountains remained relatively stable during 2017–2021, with a trend slope of 0.000018, though interannual fluctuations were substantial, as indicated by a coefficient of variation of 0.183. (2) During the growing season (May–October), soil moisture exhibited significant spatial variability (0.068–0.214 cm^3/cm^3), showing an overall pattern of higher moisture in the east and lower in the west, influenced by the East Asian monsoon. (3) Both correlation analysis and geographical detector results demonstrate that precipitation and NDVI dominate the spatiotemporal variation of soil moisture, with explanatory power (q-values) of 0.761 and 0.722, respectively, both exceeding 70%. In contrast, topographic factors showed minimal influence, with q-values below 0.1. Environmental factors significantly affected the spatial distribution of soil moisture with notable differences among factors and interactive effects, manifesting as two-factor enhancement and nonlinear enhancement relationships. These findings provide a scientific basis for formulating ecological protection policies and measures for the Qilian Mountains, promoting ecological conservation in the region.

Keywords: spatiotemporal variation; soil moisture; geographical detector; Qilian Mountains

Introduction

Soil moisture constitutes a vital component of soil and represents a critical element in global energy cycling, directly impacting food security, human health, and ecosystem functions. As a key link and driving force for material and energy transfer among different Earth surface spheres, soil moisture regulates the spatial patterns and processes of terrestrial surface systems. It controls surface water and heat fluxes and influences the partitioning of available land energy into sensible and latent heat fluxes, making it an essential variable in hydrology, meteorology, ecology, agriculture, and climate change research. Soil moisture is also a key factor affecting water regulation services in mountain ecosystems and reflects plant water utilization and atmospheric-soil-plant interactions through ecological processes such as infiltration, runoff, and evapotranspiration. Soil moisture exhibits high variability and nonlinearity in both temporal and spatial dimensions, necessitating in-depth understanding of its spatiotemporal dynamics and environmental driving factors for effective soil and water conservation, ecological restoration, and watershed water resource management under climate change.

Soil moisture detection methods fall into two categories: traditional methods and remote sensing techniques. Traditional approaches such as oven-drying, neutron probes, and frequency domain reflectometry offer high measurement accuracy but suffer from limitations including low spatiotemporal resolution, high cost, and operational complexity, making them suitable only for small-scale studies. In contrast, microwave remote sensing technology has become an effective tool for large-scale dynamic environmental monitoring due to its all-weather detection capability, penetration advantages, and continuous observation features. Microwave remote sensing directly retrieves soil moisture by exploiting the significant dielectric constant differences between dry soil and liquid water. Based on sensor operation modes, it can be classified into passive and active types: passive microwave remote sensing retrieves water content by receiving microwave radiation signals emitted from the soil surface, while active microwave remote sensing analyzes radar backscatter coefficients. Optical remote sensing primarily relies on multispectral data from Landsat/MODIS to indirectly reflect soil moisture conditions through drought indices or vegetation indices, though its effectiveness is constrained by cloud cover and illumination conditions.

The spatiotemporal differentiation of soil moisture is driven by multiple coupled factors, with mechanisms categorized into climate-driven and underlying surface response types. Climate systems dominate the dynamic balance of soil moisture through hydrological processes including precipitation input, temperature regulation, and evapotranspiration output. Underlying surface attributes construct multi-scale water redistribution mechanisms through vegetation, slope, soil properties, terrain, and land use types. Revealing these interaction effects on soil moisture transport pathways enables better modeling of soil moisture spatiotemporal distribution.

The Qilian Mountains, located on the northeastern edge of the Tibetan Plateau between 94°52 –103°09 E and 36°26 –40°01 N, constitute a series of mountains and valleys in China's northwest arid and semiarid regions. Serving as the origin of inland rivers including the Heihe, Shiyang, and Shule Rivers, the region functions as a critical "mountain water tower" ecosystem. Situated at the intersection of three major plateaus—the Tibetan Plateau, the Mongolian-Xinjiang Plateau, and the Loess Plateau—the Qilian Mountains exhibit complex topography and hydrothermal conditions that create significant regional differences in soil moisture spatiotemporal variation. The region experiences combined influences from monsoon systems and the Tibetan Plateau circulation. The central-eastern area features a continental semiarid alpine grassland climate, while the western area has a continental semiarid desert climate. Winter Mongolian high pressure dominates dry and cold air masses, while summer Tibetan thermal low pressure and the East Asian monsoon jointly drive moist airflows, with mean annual precipitation of 250–500 mm decreasing from southeast to northwest. Vegetation shows distinct vertical distribution patterns, transitioning from desert grassland and mountain grassland to mountain forest grassland, alpine shrub meadow, alpine meadow, and alpine sparse vegetation with increasing elevation. According to the Second Glacier Inventory, the Qilian Mountains contain 2,849 glaciers covering 1,597.81 km^2, which are facing accelerated retreat under global warming.

Previous studies have extensively investigated soil moisture spatiotemporal variation and influencing factors in the Qilian Mountains. For instance, Che et al. found that soil temperature in the western Qilian Mountains grasslands showed small amplitude variation while soil moisture fluctuated significantly, with a quadratic spatial distribution function and linear temporal trend. Hu et al. confirmed in the Pailugou watershed that soil temperature and moisture along vertical profiles and growing season progression exhibited nonlinear variation patterns of initial increase followed by decrease. However, due to limitations from complex high-altitude terrain and sampling conditions, existing studies have mostly focused on local point observations, with systematic analysis of regional-scale soil moisture heterogeneity and its dominant controlling factors remaining scarce.

This study aims to: (1) analyze regional-scale spatiotemporal differentiation characteristics of surface soil moisture; (2) investigate the coupling mechanisms of multiple environmental factors on soil moisture; and (3) identify the dominant controlling factors for surface soil moisture spatial distribution in the mountain system. The findings will deepen understanding of alpine mountain water cycle processes and provide theoretical support for ecological environmental protection in the Qilian Mountains.

Data and Methods

Study Area Overview

The Qilian Mountains are situated at the intersection of the Tibetan Plateau, the Mongolian-Xinjiang Plateau, and the Loess Plateau, forming a natural boundary among the three major plateaus. The region's complex geomorphology and hydrothermal conditions create significant regional differences in soil moisture spatiotemporal variation. Located on the northeastern edge of the Tibetan Plateau in northeastern Qinghai Province and western Gansu Province, the mountains serve as the source of inland rivers and provide critical "mountain water tower" ecosystem functions. The region lies at the junction of climate systems, influenced by both monsoon and Tibetan Plateau circulation. The central-eastern area exhibits a continental semiarid alpine grassland climate, while the western area shows a continental semiarid desert climate. Winter Mongolian high pressure dominates dry and cold air masses, while summer Tibetan thermal low pressure and the East Asian monsoon jointly drive moist airflows, with mean annual temperature of approximately 0°C and precipitation of 250–500 mm decreasing from southeast to northwest. Vegetation shows distinct vertical distribution, transitioning from desert grassland, mountain grassland, and mountain forest grassland to alpine shrub meadow, alpine meadow, and alpine sparse vegetation with elevation. According to the Second Glacier Inventory data, the Qilian Mountains contain 2,849 glaciers covering 1,597.81 km^2, which are facing accelerated retreat under global warming.

Data Sources

Soil moisture data were obtained from the 0.05° daily soil moisture dataset for the Qilian Mountains region, provided by the National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn). This dataset was derived by downscaling the SMAP L3 passive microwave 36 km resolution soil moisture product (SMAP L3 Radiometer Global Daily 36 km Grid Soil Moisture) using a random forest optimization downscaling model coupled with wavelet analysis. Mean annual precipitation, temperature, and NDVI data were obtained from the National Earth System Science Data Center (www.geodata.cn). The 30 m ASTER GDEM data were acquired from the National Tibetan Plateau Science Data Center. All data were processed using ArcGIS 10.8 software, clipped to the study area, and resampled to 0.05° spatial resolution using Kriging interpolation and nearest-neighbor methods.

Research Methods

Geographical Detector The geographical detector is a statistical method for exploring spatial differentiation characteristics and driving forces of geographic elements, proposed by Wang et al. It comprises four components: factor detection, interaction detection, risk detection, and ecological detection.

Factor Detection: The factor detector calculates the explanatory power (q-value) of each influencing factor to quantitatively analyze its impact on soil moisture spatial differentiation in the Qilian Mountains:

$$q = 1 - \frac{1}{N\sigma^2}\sum_{i=1}^{L} N_i\sigma_i^2$$

where q ranges from [0, 1]; N_i and N represent the number of units in layer i and the entire region, respectively; and σ_i^2 and σ^2 represent the variance of Y values in layer i and the entire region, respectively.

Interaction Detection: Interaction detection identifies whether the combined effect of two factors on soil moisture spatial differentiation is enhanced or weakened. If the q-value of the interaction exceeds the q-value of either single factor, it indicates two-factor enhancement. If the interaction q-value exceeds the sum of the two individual q-values, it indicates nonlinear enhancement.

Ecological Detection: Ecological detection compares whether the effects of different factors on soil moisture spatial distribution are significantly different, using F-statistics for testing:

$$F = \frac{N_x(N_x - 1) \times SSW_x}{N_y(N_y - 1) \times SSW_y}$$

where N_x and N_y represent the sample sizes of two factors, and SSW_x and SSW_y represent the sum of within-layer variances formed by stratification of the two factors.

Indicator Selection: Based on previous research experience, this study selected seven natural factors affecting soil moisture variation. Using the optimal parameter geographical detector model in R language, optimal classification methods and numbers were calculated to avoid subjective bias from traditional manual classification. Data processing included: mean annual temperature and slope were classified into 5 categories using quantile method; mean annual precipitation and elevation were classified into 6 categories using natural breaks; NDVI and aspect were classified using standard deviation method.

Results and Analysis

Temporal Variation Characteristics of Soil Moisture

Intra-annual Variation Analysis of intra-annual variation characteristics of soil moisture in the Qilian Mountains from 2017 to 2021 shows that monthly-scale soil moisture fluctuated between 0.092–0.138 cm^3/cm^3. In spring, as temperature gradually increased, snowmelt contributed to soil moisture replenishment, making spring snowmelt an important water source. Additionally, phase transformation during freeze-thaw processes contributed to seasonal soil moisture variation. In May, the East Asian monsoon brought precipitation that formed a synergistic effect with alpine meltwater, maintaining soil moisture at high levels. In autumn, attenuated water vapor transport from westerlies combined with soil freezing processes caused sharp reductions in soil moisture content, while winter maintained low stable values.

Inter-annual Variation Soil moisture in the Qilian Mountains showed relatively stable interannual variation from 2017 to 2021, with an average value of 0.114 cm^3/cm^3. The minimum average value occurred in 2017 at 0.108 cm^3/cm^3, while the maximum occurred in 2019 at 0.138 cm^3/cm^3, likely due to abundant precipitation that year. Subsequently, soil moisture content showed a continuous declining trend, reaching 0.112 cm^3/cm^3 by 2021. The coefficient of variation was 0.183, indicating substantial interannual fluctuation. The trend slope was 0.000018, suggesting relatively stable change during this period, which has important reference value for ecological balance and water resource management in the region.

Soil moisture content varied significantly across different elevation gradients, though the variation trend was similar. In high-altitude areas, soil moisture content was generally lower with smaller variation amplitude, while low-altitude areas showed higher moisture content with larger variation amplitude. Overall, soil moisture content was highest in the 2,987–3,452 m elevation range and higher in the 3,452–3,888 m range than other elevations. Soil moisture content in different elevation zones of the Qilian Mountains showed consistent trends from 2017 to 2021, with relatively stable moisture in mid-elevation zones (2,987–3,888 m), while high and low elevation areas showed greater fluctuations, indicating more sensitive responses to climate change.

Spatial Variation Characteristics of Soil Moisture

During the growing season (May–October), soil moisture in the Qilian Mountains exhibited a stable spatial pattern of higher moisture in the east and lower in the west, with annual mean values fluctuating between 0.120–0.129 cm^3/cm^3. The spatial distribution showed significant differences, with the most pronounced spatial heterogeneity occurring in 2019. Trend analysis revealed significant wetting trends concentrated in the eastern regions and some western local areas, highly coupled with monsoon water vapor transport paths and terrain uplift effects. The overall spatial distribution showed higher moisture in the east and lower in the west, influenced by the East Asian monsoon.

Correlation Analysis

Pearson Correlation Analysis Pearson correlation analysis examined relationships between environmental factors and soil moisture. Soil moisture showed significant positive correlations with mean annual temperature, mean annual precipitation, and NDVI ($P < 0.01$). The correlation coefficient with mean annual precipitation was 0.761, while with NDVI it was 0.722. However, except for precipitation and NDVI, correlation coefficients between other environmental factors and soil moisture did not exceed 0.5. Further spatial analysis revealed very strong positive correlations between soil moisture and precipitation (correlation coefficient up to 0.761) and between soil moisture and NDVI (0.722), confirming the vegetation-water positive feedback mechanism under hydrothermal coupling. Soil moisture and temperature also showed positive correlation, though weaker than precipitation, suggesting temperature increase may enhance soil moisture but with less direct impact, possibly regulated by evaporation and other factors.

Significance test results showed that correlations between soil moisture and precipitation, NDVI, and temperature passed the 0.01 significance test only in small eastern areas, with large regions showing non-significant correlations.

Geographical Detector Analysis Geographical detector analysis quantified environmental factors' effects and their interactions. Among the studied factors, precipitation and NDVI most significantly affected soil moisture temporal variation, with q-values of 0.761 and 0.722, respectively, substantially higher than other factors. Except for 2017 when NDVI was the dominant factor, precipitation was the primary influencing factor in all other years.

The q-values for elevation, mean annual temperature, slope, and aspect were relatively low, indicating minimal individual effects on soil moisture. Among topographic factors, elevation showed the highest q-value (0.087), while aspect showed the lowest (0.032). Therefore, precipitation is the dominant factor determining soil moisture spatial distribution.

Interaction detection revealed that all factors showed interactive effects on soil moisture, presenting two-factor enhancement and nonlinear enhancement relationships, indicating that soil moisture spatial differentiation in the Qilian Mountains results from combined effects of multiple factors. Compared with single-factor effects, q-values increased significantly in two-factor interactions, with the strongest interactions occurring between: mean annual temperature   precipitation ($q = 0.891$), mean annual precipitation   NDVI ($q = 0.878$), and mean annual precipitation   elevation ($q = 0.851$), all exceeding 85% explanatory power. These results demonstrate significant combined effects of precipitation, temperature, and NDVI on soil moisture.

Ecological detection confirmed significant differences among factors' effects on soil moisture spatial distribution, indicating each factor influences soil moisture spatial patterns uniquely, with these differences being statistically meaningful.

Environmental Factor Variation Analysis

Precipitation Precipitation in the Qilian Mountains showed strong seasonal consistency with soil moisture variation. Monthly precipitation increased continuously from January, reaching maximum values in July–August (80.12 mm) and minimum values in December (0.73 mm). Precipitation showed dramatic increases in June and decreases in September. Interannual variation showed an initial increase, then decrease, then increase again, peaking at 366.72 mm in 2019 and reaching minimum values of 332.58 mm in 2017. Spatial distribution showed clear east-west gradients, decreasing from east to west.

Temperature Mean monthly temperature gradually increased from January, reaching maximum values in July (9.02°C) and minimum values in January (−16.76°C). The region experienced subzero temperatures for five months. Temperature showed significant variation from January to July, with slight increases in November. Interannual variation was relatively small, fluctuating between −3.87°C and −3.24°C.

NDVI Intra-annual vegetation coverage in the Qilian Mountains was good during the growing season, related to increased precipitation and temperature. NDVI reached minimum values in January (0.206) and maximum values in August (0.688), then continuously decreased. Interannual variation was small, ranging 0.206–0.688. Spatial distribution decreased from east to west, with vegetation mainly distributed in low-elevation areas of the central-eastern region with favorable water-heat combinations.

Discussion

The Qilian Mountains serve as a natural boundary among the Tibetan Plateau, Mongolian-Xinjiang Plateau, and Loess Plateau. Complex geomorphology and hydrothermal conditions create significant regional differences in soil moisture spatiotemporal variation. This study systematically analyzed soil moisture variation characteristics and influencing factors from 2017 to 2021, revealing significant temporal dynamics and spatial heterogeneity.

Precipitation is the direct water source for soil moisture in arid and semiarid regions and has decisive effects on soil moisture content and distribution. Its uneven spatiotemporal distribution drives soil moisture differentiation. Precipitation amount directly relates to soil moisture dynamic balance, affecting surface water and groundwater recharge, evaporation, and plant transpiration. In the Qilian Mountains, precipitation shows distinct wet/dry seasons and clear spatial patterns, decreasing from east to west, which matches soil moisture distribution patterns. The eastern Qilian Mountains, significantly influenced by the Asian monsoon, receive abundant precipitation from warm, moist air masses uplifted by terrain. With increasing elevation, temperature decreases and terrain steepens, enhancing monsoon uplift and rainfall, creating superior soil moisture conditions. The correlation coefficient between precipitation and soil moisture of 0.761 confirms precipitation as the dominant factor, consistent with findings by Che et al. and Hu et al.

Vegetation plays a crucial role in maintaining soil moisture in this important water source region. Root systems effectively capture and retain water, reducing evaporation losses. Canopy interception reduces surface runoff and promotes infiltration, enhancing water conservation functions. Vegetation growth and root activity improve soil structure and porosity, facilitating water penetration and storage. Vegetation coverage reduces surface temperature and solar radiation, decreasing evaporation rates and helping maintain soil moisture. Recent ecological restoration measures including returning farmland to forest and grassland have significantly increased vegetation coverage. Vegetation distribution shows an east-high, west-low pattern closely related to precipitation and soil moisture conditions. Eastern areas with lower elevation and abundant precipitation provide favorable conditions for vegetation growth and soil moisture retention.

Elevation indirectly affects soil moisture dynamics by influencing meteorological factors including precipitation, temperature, and radiation. It affects plant species distribution and thus soil moisture availability. During ablation periods, high-altitude areas receive more snowmelt water, while lower temperatures reduce evaporation and vegetation biomass decreases water consumption, facilitating soil moisture retention. The Qilian Mountains contain extensive glaciers that are accelerating retreat under global warming, particularly in central and eastern watersheds, releasing substantial water that significantly supplements soil moisture. Freeze-thaw processes also contribute to soil moisture increase through phase transformation. Temperature distribution shows clear patterns, decreasing with elevation and forming a spatial pattern of lower temperatures in the southwest and higher in the northeast. In areas with lush vegetation, relatively stable temperature changes benefit vegetation growth and ecosystem balance. However, lower temperatures in high-altitude areas may reduce photosynthetic rates and inhibit vegetation growth. In arid regions with relatively low soil moisture, temperature affects soil moisture changes mainly through evapotranspiration, with precipitation-vegetation interactions remaining the key factor for soil moisture maintenance.

Since 2000, northwest China's arid regions have shown significant warming and wetting trends, particularly accelerating after 2010, with the wetting trend expanding from Xinjiang to eastern Gansu, Qinghai, Ningxia, and Shaanxi. Increased precipitation is considered the main cause of wetting in northwest China's arid regions. This long-term climate change has profoundly affected regional precipitation patterns, providing important context for understanding soil moisture variation in the Qilian Mountains from 2017 to 2021.

Conclusions

This study analyzed spatiotemporal variation characteristics and driving factors of soil moisture in the Qilian Mountains from 2017 to 2021, reaching the following conclusions:

1. Soil moisture in the Qilian Mountains remained relatively stable during 2017–2021, with a trend slope of 0.000018, though interannual fluctuations were substantial (coefficient of variation = 0.183). Growing season (May–

October) soil moisture showed significant spatial variability (0.068–0.214 cm^3/cm^3), with an overall east-high, west-low spatial pattern influenced by the East Asian monsoon.

2. Correlation analysis and geographical detector results demonstrate that precipitation and NDVI dominate spatiotemporal soil moisture variation, with q-values of 0.761 and 0.722, respectively, both exceeding 70%. Topographic factors showed minimal influence ($q < 0.1$). Environmental factors significantly affected soil moisture spatial distribution with interactive effects, showing two-factor enhancement and nonlinear enhancement relationships.
3. The effects of precipitation and NDVI on soil moisture are direct and significant, while temperature and elevation influence soil moisture through interactions with precipitation and NDVI. The combined effects of precipitation, NDVI, and temperature on soil moisture are particularly pronounced, providing important insights for ecological protection and water resource management in the Qilian Mountains.

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