Postprint: Study on the Relationship Between Soil Moisture Content and Topographic-Vegetation Factors in Different Dune Types in the Tengger Desert

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Abstract

Soil moisture constitutes the primary ecological limiting factor in sandy regions, with its distribution being influenced by numerous factors including climate, topography, and vegetation. This study comprehensively analyzed the distribution characteristics of soil moisture at different positions and depths across three types of sand dunes (fixed dunes, semi-fixed dunes, and mobile dunes) in the Shapotou area of the Tengger Desert, and examined its relationships with topographic-vegetation factors using variance analysis and redundancy analysis (RDA). The results demonstrated that: (1) Soil moisture within the 0-300 cm profile across different dune types increased with depth, with surface soil moisture exhibiting greater variability than middle and deep layers. (2) No significant differences in soil moisture were observed among different positions or depths on fixed dunes, whereas the windward slopes and dune bases of semi-fixed and mobile dunes exhibited higher soil moisture than leeward slopes and dune crests. (3) Soil moisture on fixed dunes was less influenced by topographic-vegetation factors compared to semi-fixed and mobile dunes, with the primary factors affecting fixed dune soil moisture being slope aspect, elevation difference, and shrub abundance. (4) Topographic-vegetation factors showed negative correlations with soil moisture in the majority of semi-fixed and mobile dunes within the study area. This study elucidates the distribution patterns of soil moisture in the Tengger Desert and its relationships with topographic-vegetation factors, providing valuable guidance for developing appropriate windbreak and sand fixation measures and establishing scientifically sound vegetation-based sand fixation models.

Full Text

Soil Moisture Content and Topographic-Vegetation Factors in Different Types of Dunes in the Tengger Desert

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Abstract: Soil moisture is a major ecological limiting factor in desert regions, and its distribution is influenced by numerous factors including climate, topography, and vegetation. This study investigated three types of sand dunes (fixed dunes, semi-fixed dunes, and mobile dunes) in the Shapotou area of the Tengger Desert. Using analysis of variance (ANOVA) and redundancy analysis (RDA), we conducted a comprehensive analysis of soil moisture distribution characteristics across different dune positions and depths, and examined their relationships with topographic and vegetation factors. The results show that: (1) Soil moisture at 0–300 cm depth increased with depth across all dune types, with greater fluctuation in surface layers compared to middle and deep layers. (2) No significant differences in soil moisture were observed among different positions of fixed dunes, while windward slopes and dune bottoms of semi-fixed and mobile dunes exhibited higher soil moisture than leeward slopes and dune tops. (3) Soil moisture in fixed dunes was less influenced by topographic-vegetation factors compared to semi-fixed and mobile dunes; the main factors affecting soil moisture in fixed dunes were slope aspect, elevation difference, and shrub abundance. (4) Most topographic-vegetation factors showed negative correlations with soil moisture in semi-fixed and mobile dunes. These findings reveal the distribution patterns of soil moisture in the Tengger Desert and its relationship with vegetation factors, providing valuable guidance for developing appropriate windbreak and sand fixation measures and establishing scientifically sound vegetation-based sand stabilization models.

Keywords: Tengger Desert; soil moisture; topographic factor; vegetation factor; redundancy analysis (RDA)

Introduction

Desertification represents one of the most severe environmental challenges facing humanity today. China is among the countries most severely affected by desertification, with the fifth national desertification monitoring survey indicating that desertified land in China covers 2.6116×10^{6} km^{2}, accounting for 27.20% of the country's total land area and 5.23% of global desertification area. Desert ecosystems constitute the primary type of arid and semi-arid ecosystems in China, playing crucial roles in maintaining ecosystem stability and enhancing ecosystem service functions. Soil moisture serves as the driving force behind vegetation patterns and ecological processes in desert ecosystems, controlling key processes such as plant growth, vegetation succession, and landscape distribution. Investigating soil moisture in desert areas contributes to understanding hydrological processes in sandy regions and establishing quantitative links between ecological processes.

Analyzing the distribution characteristics of soil moisture in different sandy areas and their relationships with topography and vegetation is essential for systematically understanding soil moisture distribution patterns and provides a foundation for implementing windbreak and sand fixation projects and vegetation construction and management across different regions. Current international research on the effects of topographic-vegetation factors on soil moisture in sandy ecosystems primarily employs geographic information systems (GIS) and geostatistical principles to comprehensively assess regional soil moisture conditions. For example, Abuhashim et al. [5] combined soil water erosion parameters to evaluate locations vulnerable to soil erosion. Fijakowska [6] calculated topographic factor values (slope length and gradient) for soil loss equations and analyzed total least squares factor values, proposing methods for assessing least squares factor values within homogeneous areas such as farmland. However, due to influences from climate, topography, and vegetation distribution, the distribution characteristics and influencing factors of soil moisture are highly complex. Existing studies demonstrate that topographic and vegetation factors are primary influences on soil moisture, with topographic factors serving as the main carriers of climatic and vegetation influences, while vegetation factors directly affect soil moisture through plant water use.

Domestic research has primarily focused on soil moisture distribution in different communities and water use efficiency among different populations. For instance, Zhang Junhong [10] analyzed soil moisture characteristics in *Artemisia ordosica* communities with different degrees of stabilization, precipitation recharge to soil moisture, and the effects of biological soil crusts on precipitation redistribution, while also examining the role of soil moisture in community succession. However, few studies have investigated the effects of topographic and vegetation factors on soil moisture at small scales. Therefore, this study employed transect data to examine three dune types (fixed, semi-fixed, and mobile dunes) in the Shapotou area of the Tengger Desert, investigating the influence of topographic-vegetation factors on soil moisture across different positions (windward slope, leeward slope, dune top, and dune bottom) and depths to elucidate the governing relationships between these factors and soil moisture.

1 Study Area Overview

The study area is located in the Shapotou region at the southeastern edge of the Tengger Desert, geographically positioned between 37°30 –40°10 N and 102°20 – 105°55 E, with an elevation of 1200–1400 m and a total area of approximately 5922.4 km^2. The region has an average annual temperature of approximately

10.0 °C, with winter minimum temperatures reaching -25.1 °C and summer maximum temperatures up to 38.1 °C. Average annual precipitation is 176.5 mm, while annual evaporation reaches 1500–2000 mm. The average annual wind speed is 2.9 $m \cdot s^{-1}$, with approximately 120 sandstorm days per year and 3264 hours of annual sunshine. The soil substrate consists of loose, infertile drifting sand, with main soil types being sierozem and aeolian sandy soil. Gravimetric soil moisture content ranges between 0.5% and 3.0%. Vegetation cover reaches 15%–20% on fixed and semi-fixed dunes, with relatively dense plant growth on fixed dunes dominated by shrubs, semi-shrubs, and herbaceous plants. Common xerophytic shrubs include *Caragana korshinskii*, *Artemisia ordosica*, *Caragana microphylla*, *Calligonum arborescens*, and *Atraphaxis bracteata*. Mobile dunes have almost no vegetation cover.

2 Methods

2.1 Experimental Design

In May 2021, three representative experimental plots were established on fixed, semi-fixed, and mobile dunes in the Shapotou area, each encompassing different dune positions (windward slope, leeward slope, dune top, and dune bottom). The fixed dune plot was located in the Hongwei area (104°46 01 E, 37°27 00 N), while the semi-fixed dune plot was in the Changliushui area (104°46 12 E, 37°27 26 N), and the mobile dune plot was also in the Changliushui area (104°46 12 E, 37°27 26 N). Each plot measured 40 m × 140 m and was divided into 4 m × 4 m quadrats, totaling 350 quadrats for fixed dunes, 350 for semi-fixed dunes, and 280 for mobile dunes (due to differences in plot size).

Soil moisture sampling points were selected within each plot, with additional sampling points in areas with significant topographic relief. Ten quadrats from each plot were chosen as representative samples. A total of 140 soil moisture sampling points were established across all plots. Soil moisture was measured using the soil auger method at six depth intervals: 0–5 cm, 5–15 cm, 15–25 cm, 25–35 cm, 35–50 cm, and then every 20 cm from 50 cm to 300 cm, with measurements taken three times.

Herbaceous quadrats of 50 cm × 50 cm were established within each 4 m × 4 m quadrat to survey herbaceous cover, herbaceous abundance, and litter. Additionally, every shrub within each quadrat was tagged to measure height, crown diameter (east-west and north-south directions), and shrub cover and abundance within the quadrat. Real-time kinematic (RTK) positioning was used to locate each shrub and quadrat vertex, obtaining latitude, longitude, and elevation data. Topographic factors including slope gradient, slope aspect, and elevation difference were calculated for each quadrat using the positioning data. The experimental design flowchart is shown in [Figure 2: see original paper].

2.2.1 Soil Moisture Classification

Previous studies indicate that herbaceous plants in the study area primarily utilize soil moisture in the 0–40 cm layer, while roots of sand-fixing shrubs are distributed within 40–200 cm depth, with approximately 90% of shrub roots concentrated in the 0–40 cm layer. Therefore, this study classified soil moisture into three layers: surface layer (0–40 cm), middle layer (40–200 cm), and deep layer (200–300 cm) to investigate their effects on herbaceous and shrub growth.

2.2.2 Calculation of Topographic Factors

Elevation Difference Calculation: RTK-measured geodetic coordinates of each point were converted to Cartesian coordinates. The elevation difference for each point was defined as its altitude minus the minimum altitude of the entire plot. Let z represent the elevation difference of the i-th vertex; the elevation difference for each quadrat equals the average elevation difference of its four vertices.

Slope Gradient Calculation: Using the horizontal coordinates and elevation differences of each quadrat's vertices, slope gradient and aspect were calculated. Let (i, j) represent grid dimensions, y the quadrat unit length, and Δ the diagonal length. The unit normal vector n of each quadrat is calculated as:

$$n = \frac{1}{\sqrt{1+u^2+v^2}}(-u, -v, 1)$$

where u and v are the inclination angles at point z. The slope gradient (slope) is the angle between vector n and the z-axis, calculated as:

$$\text{slope} = \tan^{-1}\sqrt{u^2+v^2}$$

Slope Aspect Calculation: Slope aspect is the angle between the projection of vector n on the horizontal plane and the x-axis (pointing south). For square grids, the calculation method is as follows:

If u > 0 and v < 90°, then = $\tan^{-1}$(v/u) indicates an eastward direction; if v < 0, it indicates east-north direction; if v > 0, it indicates east-south direction.

If u < 0 and v < 90°, then = 180° + $\tan^{-1}$(v/u) indicates a westward direction; if v < 0, it indicates west-north direction; if v > 0, it indicates west-south direction.

If u = 0 and v < 0, then = 90° indicates a northward direction; if v > 0, then = 270° indicates a southward direction.

2.2.3 Redundancy Analysis (RDA)

RDA is a constrained ordination method first proposed to analyze relationships between explanatory and response variables by selecting environmental variables with high explanatory power to reveal causes of data variation. In RDA ordination diagrams, quadrats are plotted as points at their corresponding coordinates, while species variables appear as vectors originating from (0,0) and pointing to species score coordinates. The direction of vectors indicates the direction of species abundance increase. Explanatory variable scores are similarly represented as vectors, where vector length indicates the strength of correlation between quadrat species distribution and environmental factors, and the angle between vectors and constrained axes indicates the strength of correlation with ordination axes. Small angles suggest strong relationships, while orthogonal angles indicate no correlation.

3 Results

3.1 Variation Characteristics of Soil Moisture with Depth

Soil moisture across the three dune types increased gradually with depth and stabilized. The order of average soil moisture was: mobile dunes > semi-fixed dunes > fixed dunes. The fluctuation degree of soil moisture was greatest in the surface layer (0–40 cm), gradually decreasing and stabilizing with increasing depth. Moreover, the fluctuation degree of soil moisture in semi-fixed and mobile dunes was significantly higher than in fixed dunes [Figure 3: see original paper].

3.2 Distribution Characteristics of Soil Moisture in Different Dune Positions

Soil moisture at 0–300 cm depth on mobile dunes was significantly higher than on leeward slopes and dune tops, with greater fluctuation on mobile dune leeward slopes and tops compared to semi-fixed dunes [Figure 4: see original paper].

3.3 Distribution of Surface, Middle, and Deep Layer Soil Moisture in Different Dune Positions

To further determine the distribution patterns of surface, middle, and deep layer soil moisture across different positions on various dune types, one-way ANOVA and multiple comparisons were conducted [Figure 5: see original paper].

Surface Layer (0–40 cm): No significant differences were observed among different positions on fixed dunes. On semi-fixed and mobile dunes, windward slopes and dune bottoms showed higher surface soil moisture than leeward slopes and dune tops. Specifically, on semi-fixed dunes, the order was: dune bottom > windward slope > leeward slope dune top, with significant differences between windward slope and leeward slope/dune top, and between dune bottom and leeward slope/dune top. On mobile dunes, the order was: dune bottom > windward slope > leeward slope, with significant differences among all positions.

Middle Layer (40–200 cm): No significant differences were found among positions on fixed dunes. On semi-fixed and mobile dunes, windward slopes and dune bottoms showed higher middle layer soil moisture than leeward slopes and dune tops. On semi-fixed dunes, the order was: dune bottom > windward slope > leeward slope dune top, with significant differences between windward slope and leeward slope/dune top, and between dune bottom and leeward slope/dune top. On mobile dunes, the order was: dune bottom > windward slope > leeward slope dune top, with significant differences between windward slope and leeward slope/dune top, and between dune bottom and leeward slope/dune top.

Deep Layer (200–300 cm): No significant differences were observed among positions on fixed and semi-fixed dunes. On mobile dunes, windward slopes and dune bottoms showed higher deep layer soil moisture than leeward slopes and dune tops, with the order: dune bottom > windward slope > leeward slope dune top, and significant differences between dune top and dune bottom/windward slope.

3.4 RDA Analysis of Soil Moisture and Topographic-Vegetation Factors

Based on detrended correspondence analysis (DCA), the gradient length of the first axis was less than 3.0, indicating linear relationships suitable for RDA analysis. The RDA results are presented in .

For fixed dunes, the first and second ordination axes had eigenvalues of 0.08 and 0.03, respectively, with correlation coefficients of 0.69 and 0.51 between axes and factors. The first two axes cumulatively explained 15.2% of soil moisture variation, indicating weak linear relationships between ordination axes and factors that poorly reflect correlations between soil moisture and topographic-vegetation factors.

For semi-fixed dunes, the first and second ordination axes had eigenvalues of 0.12 and 0.05, with correlation coefficients of 0.85 and 0.80, respectively. The first two axes cumulatively explained 24.6% of soil moisture variation, indicating credible RDA results with good linear relationships reflecting soil moisture-topographic-vegetation correlations.

For mobile dunes, the first and second ordination axes had eigenvalues of 0.15 and 0.07, with correlation coefficients of 0.88 and 0.83, respectively. The first two axes cumulatively explained 31.2% of soil moisture variation, also indicating credible results with good linear relationships.

The RDA ordination diagram [Figure 6: see original paper] shows that for fixed dunes, significant topographic-vegetation factors affecting soil moisture were slope aspect, elevation difference, and shrub abundance. For surface soil moisture, herbaceous cover, biomass, litter, and herbaceous abundance showed positive correlations, while slope gradient, elevation difference, shrub cover, and shrub abundance showed negative correlations. For middle layer soil moisture, slope aspect, herbaceous abundance, and herbaceous cover showed positive correlations, while slope gradient, elevation difference, and shrub abundance showed negative correlations. For deep layer soil moisture, slope aspect, herbaceous abundance, herbaceous cover, shrub cover, and shrub abundance showed positive correlations, while slope gradient, elevation difference, and biomass showed negative correlations.

For semi-fixed dunes, significant factors were slope aspect, slope gradient, and elevation difference. For surface soil moisture, litter showed positive correlations, while slope aspect, elevation difference, herbaceous cover, biomass, shrub cover, and herbaceous abundance showed negative correlations. For middle layer soil moisture, litter showed positive correlations, while slope aspect, slope gradient, elevation difference, herbaceous abundance, herbaceous cover, shrub abundance, shrub cover, and biomass showed negative correlations. For deep layer soil moisture, litter, shrub cover, and herbaceous cover showed positive correlations, while slope aspect, slope gradient, elevation difference, shrub abundance, and shrub cover showed negative correlations.

For mobile dunes, significant factors were slope gradient, shrub abundance, and biomass. For surface soil moisture, shrub cover and shrub abundance showed positive correlations, while slope aspect, slope gradient, elevation difference, biomass, litter, herbaceous abundance, and herbaceous cover showed negative correlations. For middle layer soil moisture, herbaceous abundance showed positive correlations, while slope aspect, slope gradient, elevation difference, biomass, shrub cover, and shrub abundance showed negative correlations. For deep layer soil moisture, herbaceous abundance, litter, and herbaceous cover showed positive correlations, while slope aspect, slope gradient, elevation difference, shrub abundance, and shrub cover showed negative correlations.

4 Discussion

4.1 Variation Characteristics of Soil Moisture at Different Depths

Soil moisture in fixed, semi-fixed, and mobile dunes of the Tengger Desert increased gradually with depth, with the greatest fluctuation in surface layers and decreasing fluctuation with depth, eventually stabilizing. This aligns with findings from Li Lujun et al. [2]. The primary reason is that surface soil moisture is influenced by evapotranspiration, precipitation, herbaceous abundance and cover, biomass, and soil crust development, with particularly high surface evaporation in sandy areas causing greater fluctuation. Middle and deep layer soil moisture is mainly affected by precipitation intensity and water uptake by sand-fixing plant roots, with weaker connections to surface evaporation, resulting in smaller fluctuations.

The order of soil moisture across different dune types was: mobile dunes > semi-fixed dunes > fixed dunes. This occurs because semi-fixed and mobile dunes have loose soil texture favorable for precipitation infiltration. After precipitation events, a dry sand layer 3–5 cm thick quickly forms on the surface, inhibiting soil moisture evaporation. Additionally, these dunes have sparse sand-fixing vegetation (including biological soil crusts), resulting in lower plant water consumption and minimal runoff, allowing most precipitation to infiltrate. In contrast, fixed dunes have higher vegetation cover, greater fine particle content, more compact soil texture, and well-developed biological soil crusts, which increase surface water resistance and reduce precipitation infiltration while exhibiting higher plant water consumption.

4.2 Relationships Between Soil Moisture and Topographic-Vegetation Factors

Vegetation type and cover differences on dune surfaces are important factors affecting soil moisture content. This study demonstrates that surface soil moisture in fixed dunes is primarily influenced by herbaceous abundance, biomass, herbaceous cover, and litter, while deep layer soil moisture is mainly affected by slope aspect and shrub cover, consistent with findings from Ma Fengyun et al. [15]. This is because herbaceous plants have shallow root systems primarily affecting surface soil moisture, while shrubs have deeper roots influencing deep layer moisture. Moreover, soil moisture at different depths in fixed dunes was less affected by topographic-vegetation factors than in semi-fixed and mobile dunes.

Significant topographic-vegetation factors affecting soil moisture in fixed dunes included slope aspect (negative), elevation difference (negative), and shrub abundance (negative). Therefore, shrub abundance should be maintained within certain eco-hydrological thresholds to preserve ecosystem health. Herbaceous cover and abundance showed positive relationships with soil moisture at all depths in fixed dunes, emphasizing the need for herbaceous plant protection and prevention of inappropriate human activities such as grazing that could damage the ecosystem.

For semi-fixed and mobile dunes, most topographic-vegetation factors showed negative correlations with soil moisture. If these dunes significantly impact normal production activities, scientifically sound sand fixation measures should be implemented to promote stabilization. If they do not affect production activities, preserving their original landform types indirectly protects desert water resources and benefits scientific management of regional water cycles.

This study found no significant differences in soil moisture among different positions or depths on fixed dunes, with higher fluctuation on windward slopes. For semi-fixed and mobile dunes, soil moisture was highest at dune bottoms and windward slopes, consistent with Wang Rui et al. [14]. These patterns result from local topography influencing vegetation distribution, which in turn affects biological soil crust and soil horizon development. Soil crust development effectively improves water retention capacity, with thicker crusts and soil horizons showing stronger water-holding capacity. Dune bottoms develop moss-dominated crusts with the thickest crusts and soil horizons; windward slopes have mixed moss and algal crusts of intermediate thickness; leeward slopes are dominated by algal crusts with thinner crusts and soil horizons; dune tops are similar to leeward slopes with local “activated patches.” Consequently, soil water content follows the order: dune bottom > windward slope > leeward slope dune top.

Therefore, sand barriers should be installed at appropriate positions on windward slopes of fixed dunes to prevent activation and transformation into semi-fixed or mobile dunes. For semi-fixed and mobile dunes, sand barriers should first be installed on windward slopes to prevent sand burial and erosion hazards. If straw checkerboards are used for sand fixation, they and the planted sand-fixing vegetation can be denser on windward slopes and dune bottoms than on leeward slopes and dune tops, thereby accelerating ecological restoration.

5 Conclusions

This study investigated soil moisture distribution characteristics across different positions and depths on three dune types in the Shapotou area of the Tengger Desert, and analyzed relationships with topographic-vegetation factors. The research advances beyond previous studies limited to single dune types by examining multiple dune types, positions, and depths. The main conclusions are:

1. Soil moisture at 0–300 cm depth increased with depth across all three dune types, with greater fluctuation in surface layers than in middle and deep layers.
2. No significant differences in soil moisture were observed among different positions or depths on fixed dunes, though windward slopes showed higher fluctuation. Soil moisture on windward slopes and dune bottoms of semi-fixed and mobile dunes was higher than on leeward slopes and dune tops.
3. Soil moisture in fixed dunes was less influenced by topographic-vegetation factors than in semi-fixed and mobile dunes. The main factors affecting soil moisture in fixed dunes were slope aspect, elevation difference, and shrub abundance. Most topographic-vegetation factors showed negative correlations with soil moisture in semi-fixed and mobile dunes.

These results provide scientific basis for protecting and utilizing sand-fixing vegetation ecosystems and establishing scientifically sound windbreak and sand fixation measures. Future sand-fixing vegetation construction should comprehensively consider dune type, position-specific soil moisture differences, and relationships between soil moisture and topographic-vegetation factors to implement site-appropriate vegetation restoration. Further research should explore scientifically sound sand fixation models by integrating eco-hydrological processes across different positions on various dune types.

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