Spatiotemporal Variation Characteristics of Soil Moisture During Vegetation Succession in Artificial Sand-Fixing Areas: Postprint

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Abstract

Taking the sandy lands at different vegetation succession stages (early, middle, late, and mature succession stages) in the artificial sand-fixation area on the eastern margin of the Kubuqi Desert as the research object, volumetric water content was measured in layered soils at depths of 0–180 cm at the top, middle, and bottom of windward slopes during the growing seasons of 2017 and 2018, to elucidate the spatiotemporal differentiation characteristics of desert soil moisture and its response to environmental factors. The results showed that: due to differences in precipitation, interannual variation existed in soil water content in the study area, with 2018 (8.8%) > 2017 (4.8%); affected by precipitation events and plant growth, the soil water content in all four sample plots exhibited stage-specific characteristics of a slow decline in the early growing season, a rapid increase after precipitation recharge during the peak growing period, and stable accumulation at the end of the growing season; the soil water content across different vegetation succession stages generally showed the pattern of early succession stage (7.3%) > mature stage (7.2%) > late stage (6.7%) > middle stage (5.9%); for all four sample plots, the middle of the windward slope had the lowest soil water content, while the water content at the slope top and bottom varied relative to each other across different succession stages; the soil water content in all four sample plots showed a dynamic trend of first decreasing and then increasing with soil depth; the water content in the surface 0–20 cm soil layer was significantly higher than in other layers, and an inflection point of moisture change existed in deep soils, representing the dry sand layer with the lowest water content, the depth of which varied under different succession stages or precipitation amounts. At the end of the growing season, after a season of consumption and recharge, soil water storage in the study area showed a positive balance, which could meet the water requirements for normal growth and succession of artificial sand-fixation vegetation.

Full Text

Preamble

Spatial and Temporal Variability of Soil Water Content During Vegetation Succession in Sand-Binding Areas

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Abstract

This study investigated the spatiotemporal dynamics of soil water content and its response to environmental factors in the eastern Hobq Desert, China. We measured volumetric soil water content at 0–180 cm depth during the growing seasons of 2017 and 2018 at the top, middle, and bottom of windward slopes across four vegetation succession stages (initial, middle, late, and mature). Results showed that: (1) Interannual variation in soil water content was driven by precipitation differences, with 2018 (8.8%) > 2017 (4.8%). (2) Influenced by precipitation events and plant growth, all four plots exhibited three distinct seasonal phases: a slow decline in early growing season, rapid increase after precipitation recharge during the vigorous growth period, and stable accumulation at the end of the growing season. (3) Soil water content across succession stages followed the pattern: initial stage (7.3%) > mature stage (7.2%) > late stage (6.7%) > middle stage (5.9%). (4) The middle windward slope position consistently showed the lowest water content across all stages, while top and bottom positions varied by succession stage. (5) Soil water content decreased then increased with depth, with the 0–20 cm surface layer significantly higher than deeper layers. An inflection point identified as a dry sand layer with minimal water content occurred at varying depths depending on succession stage and precipitation. At the end of the growing season, soil water storage showed positive balance, indicating sufficient water availability for vegetation growth and succession in the sand-binding area.

Keywords: sand-binding area; soil water content; vegetation succession; spatiotemporal variation; Hobq desert

Introduction

Soil moisture constitutes a critical component of terrestrial ecosystem water cycles and represents a fundamental requirement for plant growth and development [1]. In desert ecosystems particularly, soil water scarcity has become a limiting factor for ecological restoration and vegetation establishment, with water balance remaining the central concern of anthropogenic intervention activities and determining both ecosystem sustainability and plant community stability [2-3]. China has implemented extensive desertification control measures in arid and semi-arid sandy lands, along desert margins, and in oasis extension zones. Numerous practices have demonstrated that artificial planting promotes sand fixation, vegetation recovery, and microhabitat improvement, ultimately forming stable ecosystems that facilitate natural community succession [4-5]. During this process, ecohydrological cycling and feedback mechanisms within the vegetation-soil system create pronounced spatial heterogeneity in soil moisture, while temporal variations in climatic factors such as precipitation generate substantial interannual and seasonal heterogeneity [6-8].

Current research on spatiotemporal differentiation of soil moisture in arid and semi-arid regions includes studies on soil moisture characteristics of fixed dunes at the southern edge of the Gurbantunggut Desert [9], effects of soil moisture conditions on plant growth in alpine shrub sand-fixation areas [10], dynamic differences in soil moisture between dry and wet years in the Tengger Desert sand-binding region [11], responses of soil moisture variation to rainfall in desert steppe of semi-arid zones [12], and spatiotemporal variation coefficients of soil moisture in the Mu Us Sandy Land [13].

The Hobq Desert ranks as China' s seventh largest desert. Its eastern margin represents a vulnerable ecological transition zone from desert to grassland and cropland, characterized by complex terrain, frequent human activity, and severe landscape fragmentation. Existing research on soil moisture variation in this region includes Gu et al. [14] who analyzed soil moisture differences among various shelter forests, and Fu et al. [15] who evaluated soil moisture effectiveness in windbreak and sand-fixation forests. However, research on spatiotemporal dynamics of soil moisture during vegetation succession remains lacking, particularly regarding long-term continuous monitoring and the impacts of environmental factor variations on soil moisture. Using a space-for-time substitution approach, this study analyzes dynamic characteristics and influencing factors of desert soil moisture across different vegetation succession stages to reveal: (1) the effects of artificial planting-promoted vegetation restoration on desert soil moisture conditions; (2) responses of desert soil moisture to precipitation, seasonal variation, slope position, and soil depth; and (3) the supply-demand relationship between regional soil water storage and sand-fixation vegetation growth.

Materials and Methods

1.1 Study Area Overview

The study area is located in Jungar Banner, Ordos City, Inner Mongolia, representing typical desert landforms in the eastern Hobq Desert. The region experiences a temperate continental climate with concurrent heat and precipitation, featuring dry and windy springs/winters and hot summers/autumns with concentrated rainfall. Mean annual temperature ranges 6.1–7.2 °C, mean annual precipitation is 270.4 mm, mean annual evaporation reaches 2560.6 mm, and mean annual wind speed is 3.3 $\mathrm{m \cdot s^{-1}}$. Soils are predominantly aeolian sandy soils. Dominant plant species include *Salix cheilophila*, *Caragana intermedia*, *Hedysarum laeve*, *Artemisia ordosica*, *Salsola collina*, *Psammochloa villosa*, and *Agriophyllum squarrosum*.

1.2.1 Sample Plot Selection

Sample plots were classified based on establishment age and vegetation succession progression: (1) **Initial stage**: Established in 2015 on mobile sandy land using row-strip cuttings of *S. cheilophila* with 2 m row spacing. At measurement, *S. cheilophila* showed height of (68$±11)cmandcrownwidthof(45±$7) cm, with sparse annual herbs on the surface. (2) **Middle stage**: Established in 2010 on mobile sandy land using grid-pattern cuttings of *S. cheilophila* with 1.5 m × 1.5 m grid size. At measurement, *S. cheilophila* showed height of (135$±17)cmandcrownwidthof(79±13)cm, with ∗ H.laeve ∗ communitiesandsparseannualherbspresent.(3) ∗ ∗Latestage ∗ ∗ : Establishedin2000onmobilesandylandusingrow − stripcuttingsof ∗ S.cheilophila ∗ with2mrowspacing.Aftertwocoppicingevents, astable ∗ S.cheilophila ∗ communityformed.Atmeasurement, ∗S.cheilophila ∗ showedheightof(203±15)cmandcrownwidthof(188±14)cm, withnaturallygrowing∗ C.intermedia∗andabundantannualherbs, plusdevelopedlichencrustsonthesurface.(4)∗ ∗Maturestage ∗ ∗ : Establishedin1995usingrow − stripcuttingsof ∗ S.cheilophila∗.Naturalthinningcreatedlarge, clustered"sand−willowislands"withabundant∗ A.ordosica∗andannualherbsininter−islandspaces, highvegetationcoverage, thicklitterlayers, andcontinuous showedheightof(238±24)cmandcrownwidthof(252±$33) cm. Basic plot information is presented in Table 1 .

1.2.2 Index Measurement

Meteorological data were recorded by a HOBO automatic weather station (USA). Soil volumetric water content was monitored using a TRIME-PICO soil moisture observation system (Germany) from May to October in both 2017 and 2018. To verify measurement accuracy of the TDR moisture sensors, we compared TDR data with oven-drying method measurements. In early May, 40 sets of moisture data were measured at slope-top positions across different plots. Results showed extremely significant linear correlation ($P < 0.01$) between oven-drying and TDR methods, with correlation coefficient $R^2 = 0.9115$ (Fig. 1 [Figure 1: see original paper]). Difference testing indicated no significant discrepancy between the two methods, confirming that TRIME-PICO data met precision requirements.

Each plot selected windward slopes for soil moisture monitoring, with three 2-m TDR access tubes installed at the top, middle, and bottom positions (36 monitoring points total). Monitoring depth was 0-180 cm, divided into nine layers: 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm, 100-120 cm, 120-140 cm, 140-160 cm, and 160-180 cm. Measurements were conducted in early and late each month, with 2–3 days of stabilization after rainfall events before monitoring.

1.3 Data Processing

Soil water storage refers to the quantity of water stored per unit area within a certain soil depth, calculated as:

$$S_w = \sum_{i=1}^{n} W_i \times h_i$$

where S_w is soil water storage (mm), W_i is volumetric water content (%) of layer i, h_i is thickness (cm) of layer i, and n is the number of monitoring layers.

Data processing and mapping used Excel and SigmaPlot 14.0 software. Statistical analysis employed SPSS 20.0. Least Significant Difference (LSD) tests (α = 0.05) assessed significant differences in soil water content among plots, slope positions, and soil depths. Two-way ANOVA examined effects of environmental factors on soil moisture.

Results

2.1 Characteristics of Environmental Factor Variation

During the 2017 growing season, 35 rainfall events occurred (Fig. 2 [Figure 2: see original paper]) with cumulative precipitation of 233.8 mm, while 2018 saw 42 events totaling 329.1 mm. Compared to the multi-year average (270.4 mm), 2017 was a relatively dry year and 2018 a relatively wet year. In 2017, maximum single precipitation was 21.7 mm and minimum 0.2 mm, with six events >15 mm (48.1% of precipitation) and 18 events <5 mm (13.9%). In 2018, maximum single precipitation was 35.8 mm and minimum 0.3 mm, with nine events >15 mm (64.3% of precipitation) and 24 events <5 mm (11.9%). Air temperature and humidity showed minor interannual variation: 2017 averaged 19.1 °C with 57.3% humidity, while 2018 averaged 18.0 °C with 57.9% humidity.

2.2.2 Spatial Variation Characteristics of Soil Moisture

Under consistent regional climate conditions, desert soil water content showed significant horizontal spatial variation ($P < 0.05$), decreasing initially then increasing with stand age and vegetation succession (Fig. 3 [Figure 3: see original paper]). From initial to middle stage represented a soil drying process with 20.5% average water content decline. By 18 years post-establishment (late stage), soil moisture gradually recovered, approaching equilibrium by the mature stage.

Windward slope position significantly altered soil moisture distribution (Table 3). For initial, middle, and late stages across both years, water content generally ranked: top > bottom > middle, while the mature stage showed: bottom > top > middle. Across all succession stages, the middle windward slope position had the lowest moisture content, averaging 9.8% and 7.9% lower than top and bottom positions, respectively.

Vertical variation in desert soil moisture was pronounced, showing a decreasing-then-increasing trend with depth (Fig. 4 [Figure 4: see original paper]). The 0-20 cm layer had significantly higher mean water content than deeper layers across both years, increasing with succession: mature stage (10.0%) > late stage (8.9%) > middle stage (8.7%) > initial stage (8.6%). All plots showed clear inflection points where moisture reached minima (dry sand layers), with depth varying by precipitation and succession stage. In the dry year (2017), inflection points occurred at 120-140 cm in initial stage (52.8% below surface), rising to 60-80 cm in wet year (2018) (25.1% below surface). Middle stage showed similar patterns: 120-140 cm in 2017 (69.9% below surface) and 80-100 cm in 2018 (28.8% below surface). Late stage inflection points were at 40-60 cm in both years (58.0% and 25.8% below surface, respectively). Mature stage inflection points were at 80-100 cm in both years (71.5% and 26.8% below surface, respectively). Thus, deep soil moisture decline relative to surface layers was significantly greater in dry years, indicating excessive depletion.

2.2.3 Influencing Factors of Soil Moisture Content

Two-way ANOVA revealed (Table 4) that both seasonal variation and vegetation succession significantly affected desert soil moisture ($P < 0.01$), with significant interactive effects ($P < 0.05$). Vegetation succession exerted stronger influence than seasonal variation. For vertical dynamics, both slope position and soil depth showed extremely significant effects ($P < 0.01$) with significant interaction ($P < 0.05$), though soil depth influenced moisture more than slope position. These findings demonstrate that soil moisture is highly sensitive to environmental changes, with both temporal dynamics and spatial patterns significantly altering desert soil moisture regimes.

2.3 Variation Characteristics of Soil Water Storage

As shown in Fig. 5 [Figure 5: see original paper], interannual precipitation variation directly affected soil water storage, with the dry year (2017) showing significantly lower storage (89.8 mm) than the wet year (2018) (150.8 mm). Across succession stages, storage ranked: initial stage (129.8 mm) > mature stage (126.3 mm) > late stage (120.7 mm) > middle stage (104.4 mm). During the dry year, soil water storage increased by 13.1 mm, 4.1 mm, and 11.7 mm from early to late growing season in initial, middle, and late stages, respectively, but decreased by 2.5 mm in the mature stage. During the wet year, all four plots showed increased storage, averaging 52.2 mm. This indicates that in low-precipitation years, the mature stage with maximum vegetation coverage and biomass consumed more soil water than precipitation could replenish, potentially causing water deficits.

Discussion

Desert soil moisture is closely related to precipitation, evaporation, soil properties, vegetation type, and structural composition, exhibiting long-term dynamic changes with distinct spatiotemporal patterns [16]. This study revealed that soil moisture generally decreased then increased during vegetation succession, following: initial stage > mature stage > late stage > middle stage. This pattern aligns with Ma et al. [17], who found that during desertification reversal in arid regions, soil moisture peaked in initial mobile dunes, gradually decreased, then increased again after 25 years of enclosure recovery. Key mechanisms include: (1) At establishment, mobile sandy land had low vegetation coverage and water consumption, with loose soil texture facilitating precipitation infiltration [18], resulting in relatively high initial-stage moisture. (2) As sand-fixing vegetation developed, increased coverage and biomass caused sharp rises in water consumption, gradually drying deep soil moisture through root extraction [19]. Canopy interception reduced effective precipitation input; at individual plant level, *A. ordosica* and *C. intermedia* canopy interception losses accounted for 15% and 27% of precipitation, respectively [20]. Increased water expenditure and decreased income primarily caused the lowest moisture in middle succession stage. (3) From late to mature stages, the dominant *S. cheilophila* naturally thinned, deep-rooted *C. intermedia* gradually declined, shallow-rooted *A. ordosica* increased, herbs proliferated, and biological crusts developed from algae to lichens and mosses. This reduced canopy interception, increasing effective precipitation. Additionally, *C. intermedia* shrublands had high evapotranspiration and severe root-zone water depletion, while *A. ordosica* maintained low evapotranspiration throughout the growing season [21], allowing deep soil moisture recovery after *C. intermedia* decline while preventing overuse by shallow-rooted *A. ordosica*. (4) Vegetation shifted from single artificial species to mixed shrub-herb communities, with plant transpiration rates and water use efficiency in monocultures exceeding those in mixtures—mixed *C. intermedia* showed ~20% lower transpiration and *A. ordosica* ~40% lower compared to monocultures [22], reducing soil water extraction. (5) Biological crusts altered surface evaporation; Liu and Zhang [23-24] found moss crusts inhibited evaporation after small rainfall events (<7.5 mm) but enhanced it after larger events (>10 mm). With 75.3% of rainfall events being small in this region, mature-stage moss crusts effectively reduced evaporative loss. (6) Biological crusts adsorbed atmospheric condensation water, becoming an important shallow soil moisture source that increased with crust development [25]. Collectively, reduced water expenditure and increased income caused gradual moisture recovery from late to mature stages.

However, other studies report different patterns. Zhang et al. [26] found continuously decreasing moisture from pioneer to established stages. Li et al. [27] reported decreasing-increasing-decreasing patterns with succession. Xi et al. [28] found surface moisture increased with stand age while deep moisture decreased. These discrepancies likely stem from spatial heterogeneity in soil properties [29].

Many studies find that meteorological and vegetation factors provide limited explanation for regional soil moisture spatial variation, whereas local soil factors such as mechanical composition, field capacity, and saturated water content show significant correlations with primary spatial structures [30-31]. In this study, soil bulk density decreased with succession while porosity and saturated water content increased (Table 1). These changes in hydraulic and physical parameters improved water-holding capacity and retention, representing another key reason for moisture recovery in later fixation stages. Thus, vegetation succession and soil property differences cause spatial variation in hydraulic conductivity, altering ecohydrological processes and feedback mechanisms in the soil-vegetation system and creating differentiated moisture patterns during succession.

This study employed space-for-time substitution to classify succession stages, consistent with most research [17,26]. This method requires consistent site conditions and climate elements to minimize uncertainty from background differences. In this study, the four-stage plots were located in the same region without obvious variation in microtopography, soil, precipitation, or temperature, making space-for-time substitution reasonable and applicable. Overall, artificial planting-promoted vegetation restoration in desert regions initially causes soil moisture decline or even deficit through plant water consumption, with extensive root-zone water use preventing effective deep soil recharge and creating new moisture patterns in horizontal and vertical space. As water is fundamental for life, plants adapt to these changing moisture patterns by gradually altering community composition and ecological niches. Clearly, desert soil moisture conditions and carrying capacity determine vegetation distribution patterns and succession processes, with water balance formed through the interplay of consumption and supply representing the natural law that desert vegetation construction must follow.

Conclusion

Artificial planting-promoted vegetation succession, combined with interannual and seasonal precipitation differences and variations in topography and soil depth, creates pronounced spatiotemporal dynamics in desert soil moisture. During vegetation succession, soil moisture generally decreases then increases, following: initial stage > mature stage > late stage > middle stage. Large interannual precipitation differences occurred, with 2017 as a dry year and 2018 as a wet year, producing corresponding moisture variation (2018 moisture was 1.84 times that of 2017). Within growing seasons, soil moisture showed three distinct phases: slow decline in early season, rapid increase after precipitation recharge during vigorous growth, and stable accumulation at season end. Among windward slope positions, the middle slope had lowest moisture, while top and bottom positions varied by succession stage. Soil moisture decreased then increased with depth, showing clear inflection points. Soil water storage fluctuated with precipitation and succession; except for minor deficits in the mature stage during dry years, the study area generally maintained positive balance between water supply and consumption, meeting water requirements for existing vegetation growth.

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