

Characteristics of Soil Moisture Variation under Different Vegetation Restoration Measures in the Eastern Sandy Land of Qinghai Lake (Postprint)

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Abstract

Soil moisture is the primary driver of changes in vegetation patterns and processes in sandy lands, and also the most significant limiting factor for plant growth in arid and semi-arid regions. Soil moisture in desert areas exhibits pronounced spatial heterogeneity. Taking the East Qinghai Lake sandy land in the alpine semi-arid region as the study area, and using dunes planted with artificial sand-fixing plants (*Populus simonii*, *Pinus sylvestris* var. *mongolica*, *Hippophae rhamnoides*, and *Salix cheilophila*) and naturally fixed dunes (with *Artemisia desertorum* as the dominant species) as sample plots, this study investigated the variation characteristics of soil moisture at different geomorphic positions of dunes under the influence of different sand-fixing plants. The results showed that: (1) Seasonal variation of soil moisture is jointly influenced by precipitation, vegetation transpiration, and surface evaporation. Distribution patterns differ among species, but all exhibit the highest soil water content in July. (2) Soil water content at different geomorphic positions varies for the same plant species, being highest on the windward slope for *Populus simonii*, highest on the leeward slope for *Pinus sylvestris* var. *mongolica*, *Hippophae rhamnoides*, and *Salix cheilophila*, and highest at the dune top for *Artemisia desertorum*. However, only *Salix cheilophila* shows significant differences in soil water content among dune geomorphic positions ($P < 0.05$). Soil water content also varies among different plant species at the same geomorphic position, with *Pinus sylvestris* var. *mongolica* on the windward slope having the minimum soil water content of only 1.81%, while *Artemisia desertorum* can reach 3.48%. At the dune top, *Salix cheilophila* has a soil water content of merely 1.82%, while *Artemisia desertorum* can reach 3.58%. On the leeward slope, soil water content shows little variation, with *Salix cheilophila* having the maximum value of 3.41%. (3) The pattern of soil moisture variation differs with soil depth, with the highest soil water content generally occurring at 10-20 cm. The vertical distribution of soil moisture differs among plant species: soil water content

beneath *Populus simonii* and *Pinus sylvestris* var. *mongolica* decreases with increasing soil depth; *Hippophae rhamnoides* and *Artemisia desertorum* show no significant change within 120 cm soil depth; while soil water content beneath *Salix cheilophila* varies with soil depth across different geomorphic positions, specifically showing no significant change on the windward slope, a decreasing trend at the dune top, and an increasing trend on the leeward slope. The distribution of soil moisture under different vegetation restoration measures in alpine semi-arid sandy lands is influenced not only by precipitation, soil distribution, species type, and plant root distribution, but also shows certain correlations with dune micro-geomorphology.

Full Text

Variation of Soil Moisture Content Under Different Vegetation Restoration Measures in the Eastern Sandy Land of Qinghai Lake

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Abstract

Soil moisture represents the primary driving force behind vegetation pattern and process changes in sandy lands, and constitutes the most significant limiting factor for plant growth in arid and semi-arid regions. Desert soils exhibit pronounced spatial heterogeneity in moisture content. This study investigated the eastern sandy land of Qinghai Lake—a cold, semi-arid desert environment—using both artificially stabilized dunes planted with sand-fixing vegetation (*Populus simonii*, *Pinus sylvestris* var. *mongolica*, *Hippophae rhamnoides*, and *Salix cheilophila*) and naturally fixed dunes (dominated by *Artemisia desertorum*) as research plots. Our objectives were to characterize soil moisture variation across different dune geomorphological positions under various sand-fixing plant species.

The results demonstrated that: (1) Seasonal soil moisture dynamics were jointly influenced by precipitation, vegetation transpiration, and surface evaporation, with distinct patterns observed among species, though all showed peak moisture content in July; (2) Soil moisture content varied significantly by dune position for the same species—*Populus simonii* exhibited highest moisture on windward slopes, while *Pinus sylvestris*, *Hippophae rhamnoides*, and *Salix cheilophila*

showed highest values on leeward slopes, and *Artemisia desertorum* peaked at dune crests. Only *Salix cheilophila* showed statistically significant differences in soil moisture across dune positions ($P < 0.05$). Different species also exhibited varying soil moisture at the same position: on windward slopes, *Pinus sylvestris* had the lowest moisture content at 1.81%, while *Artemisia desertorum* reached 3.48%; at dune crests, *Salix cheilophila* showed only 1.82% moisture compared to 3.58% for *Artemisia desertorum*; leeward slope differences were minimal, with *Salix cheilophila* reaching 3.41%; (3) Soil moisture varied with depth, generally peaking at the 10–20 cm layer. Vertical distribution patterns differed among species: moisture decreased with depth under *Populus simonii* and *Pinus sylvestris*, remained relatively stable under *Hippophae rhamnoides* and *Artemisia desertorum* within 0–120 cm, while *Salix cheilophila* showed position-dependent patterns—no clear trend on windward slopes, decreasing at crests, and increasing on leeward slopes. The distribution of soil moisture under different vegetation restoration measures in alpine semi-arid sandy lands was influenced not only by precipitation, soil characteristics, species type, and root distribution, but also correlated with dune microtopography.

Keywords: alpine semi-arid sandy land; sand-fixing plants; soil moisture; seasonal variation; vertical distribution; Qinghai Lake

1. Introduction

Desertification represents one of the most pressing global environmental challenges, profoundly affecting ecosystem stability and threatening human livelihoods and regional sustainable development. Vegetation restoration through artificial measures constitutes the most effective, economical, and sustainable approach for combating desertification and rehabilitating degraded sandy ecosystems. China has over 60 years of experience with biological sand fixation, demonstrating that planted vegetation can effectively control desertification, mitigate wind erosion hazards, and promote vegetation recovery in sandy lands.

In desert environments, water availability is the most critical limiting factor for plant survival and growth, with hydrological processes determining the evolutionary trajectory and ecological functions of soil-vegetation systems. The establishment of artificial vegetation alters the original water balance and spatial distribution patterns of soil moisture in dunes. Soil moisture serves as the primary driver of vegetation pattern and process changes in sandy lands and represents a major constraint on numerous ecological processes, making it crucial for restoration of degraded ecosystems in sandy regions. Soil moisture availability directly influences vegetation growth and controls aeolian activity in desertified areas.

Previous research has documented significant spatial heterogeneity in soil moisture across desert regions. Studies in the Shapotou area revealed that soil moisture content follows the pattern: interdune > leeward slope > windward

slope. Research on the southern margin of the Gurbantungut Desert similarly found that soil moisture content was highest in interdune areas, followed by leeward and windward slopes. However, conclusions vary across studies due to differences in slope, aspect, vegetation type, and soil mechanical composition, highlighting the need to consider local topography, vegetation structure, root distribution patterns, and soil physicochemical properties in concert.

Desertification in alpine regions exemplifies the ecological vulnerability of the Qinghai-Tibet Plateau. While ecological restoration projects have improved sandy land conditions, research on plant-water relationships in alpine sandy ecosystems remains limited. Previous studies in the Qinghai Lake region have examined soil moisture variation across different dune types and analyzed spatial distribution characteristics in *Caragana korshinskii* communities of varying ages. However, these investigations primarily compared soil moisture features among different dunes without exploring the response and feedback mechanisms of different sand-fixing plants across various geomorphological positions. This study addresses this knowledge gap by examining how different sand-fixing species influence soil moisture spatiotemporal dynamics across dune positions, providing a theoretical basis for rational species selection in alpine sandy land restoration.

2. Study Area and Methods

2.1 Study Area Description

The Ketu sandy land on the eastern shore of Qinghai Lake is located at 36°47' - 36°50' N, 100°47' - 100°50' E, situated at the intersection of China's eastern monsoon region, northwest arid zone, and southwest alpine region. The area features a plateau semi-arid, cold climate characterized by dryness, low precipitation, strong winds, intense solar radiation, and large diurnal temperature variations. The mean annual temperature is 0.7°C, with average annual precipitation of approximately 370 mm and mean wind speed of 4.5 m · s⁻¹. Since 1987, extensive straw checkerboard barriers and biological afforestation have been implemented on mobile dunes, establishing a nearly 2000 hm² demonstration area for sand control. The project introduced dozens of plant species from families including Elaeagnaceae, Asteraceae, Fabaceae, Rosaceae, and Salicaceae. Over 30 years, vegetation communities dominated by artificial plantings have transformed large areas of mobile dunes into semi-fixed or fixed dunes.

2.2 Experimental Plot Selection

Within the Ketu sand control demonstration area, we selected semi-fixed dunes planted with *Populus simonii*, *Pinus sylvestris* var. *mongolica*, *Hippophae rhamnoides*, and *Salix cheilophila* (including windward slopes, dune crests, and leeward slopes), along with a natural fixed dune as a control site. In each plot, we established 10 m × 10 m permanent quadrats (3 replicates per plot, totaling 15

quadrats). Within each quadrat, we measured height and crown width of trees and shrubs, then calculated vegetation cover and richness.

Populus simonii and *Hippophae rhamnoides* were planted on the same dune (designated XYY-SJ), with *Pinus sylvestris* added in 2009; the dominant species were *P. simonii* and *H. rhamnoides*. The dune planted with *Pinus sylvestris* (designated ZZS) was established in 2000, with *Sabina vulgaris* added in 2009; *P. sylvestris* was the dominant species. The *Salix cheilophila* dune (designated WL) was established in 2000 with mixed *Caragana korshinskii* and *Hedysarum scoparium*; *S. cheilophila* was dominant. Natural vegetation gradually recovered on all three artificially stabilized dunes, including *Agropyron cristatum*, *Leymus secalinus*, and *Oxytropis imbricata*. The natural fixed dune (designated ZR) was dominated by *Artemisia desertorum*, with additional planting of *H. rhamnoides*, *Potentilla fruticosa*, and *P. sylvestris* in 2016 due to micro-erosion at the crest. This dune had rich natural vegetation including *Oxytropis aciphylla*, *L. secalinus*, *O. imbricata*, *O. falcata*, *Achnatherum splendens*, *Poa annua*, and *A. cristatum*.

2.3 Soil Moisture Measurement

Soil moisture was determined using the oven-drying method. In mid-month from May to September, we collected samples from permanent quadrats using a soil auger (5 cm diameter). For the XYY-SJ plot, we sampled under both *Populus simonii* and *Hippophae rhamnoides* (6 sampling points per quadrat, 18 total). Sampling depths for *P. simonii* were 0-5, 5-10, 10-20, 20-40, 40-60, 60-80, 80-100, 100-150, and 150-200 cm. Other sampling points were measured to 150 cm depth, following the same depth intervals as *P. simonii* but only to 150 cm.

Samples were weighed wet using an electronic balance (0.01 g precision), then oven-dried at 105°C to constant weight and weighed again after cooling. Soil gravimetric water content (M) was calculated as:

$$M(\%) = \frac{(g_{\text{wet}} - g_{\text{dry}})}{(g_{\text{dry}} - g_{\text{container}})} \times 100$$

where g_{wet} is wet soil weight, g_{dry} is dry soil weight, and $g_{\text{container}}$ is container weight.

2.4 Data Analysis

Differences in soil moisture content among different plants at the same dune position, and differences for the same plant across dune positions, were analyzed using one-way ANOVA in SPSS 17.0 (SPSS Inc., Chicago, IL, USA). When significant differences were detected ($P < 0.05$), pairwise comparisons were performed using the least significant difference (LSD) method.

3. Results

3.1 Seasonal Distribution of Soil Moisture

Soil moisture content exhibited seasonal fluctuations, with the highest values occurring in July (Figure 2). In May, at the beginning of the growing season, plants consumed minimal soil water, maintaining moisture levels around 2.5%. However, *Pinus sylvestris*, as an evergreen species with year-round water demand, showed the lowest soil moisture content during this period. June brought increased precipitation, yet soil moisture remained relatively low due to high water consumption during rapid plant growth, reaching minimum values for most communities. Trees required substantial water during early growth stages, with *Populus simonii* maintaining moisture between 2.19–2.68% and *Pinus sylvestris* showing the lowest values at 1.26% on windward slopes.

July, the month with highest precipitation (130.80 mm), corresponded with peak soil moisture content across all communities. Shrubs (*Salix cheilophila*, *Hippophae rhamnoides*, and *Artemisia desertorum*) showed higher soil moisture than trees (*Populus simonii* and *Pinus sylvestris*). During the peak growth period of August, despite being the second-highest precipitation month (107.60 mm), soil moisture reached annual minima (with *Pinus sylvestris* showing the absolute lowest values) due to maximum transpiration demand. In the late growing season of September, transpiration demand decreased while precipitation (51.2 mm) remained adequate, causing soil moisture to rise to secondary peak values. Seasonal differences in soil moisture among dune positions were not significant ($P > 0.05$), though shrub understory moisture approached July levels.

3.2 Soil Moisture Variation Across Dune Positions

Soil moisture content varied by dune position for individual species, though differences were only statistically significant for *Salix cheilophila* ($P < 0.05$). *Populus simonii* showed relatively high moisture on windward slopes (2.03–2.92%). *Pinus sylvestris* exhibited highest moisture on leeward slopes and lowest on windward slopes. *Salix cheilophila* reached maximum moisture on leeward slopes, with July values of 2.86%. *Hippophae rhamnoides* also peaked on leeward slopes, while windward and crest positions showed comparable values. *Artemisia desertorum* had highest moisture at dune crests, though values remained relatively low throughout the growing season (1.82% at crests vs. 3.42% on leeward slopes).

Different species also showed varying moisture content at the same dune position (Table 3). On windward slopes, *Pinus sylvestris* had the lowest moisture (1.81%) while *Artemisia desertorum* reached 3.48%. At dune crests, *Salix cheilophila* showed the lowest moisture (1.82%) compared to 3.58% for *A. desertorum*. Leeward slope differences were minimal, with *Salix cheilophila* showing the highest value at 3.41%.

3.3 Vertical Variation of Soil Moisture with Depth

Soil moisture patterns with depth varied among species (Figure 3). *Populus simonii* showed decreasing moisture with depth, though the rate of decline differed by position—most pronounced on windward slopes, less so at crests and leeward slopes. *Pinus sylvestris* exhibited consistent decreases with depth across all positions, with the most dramatic reduction on leeward slopes where moisture fell below 1% below 100 cm. *Salix cheilophila* displayed position-dependent patterns: no clear trend on windward slopes, decreasing at crests, and increasing on leeward slopes. *Hippophae rhamnoides* showed relatively stable moisture with depth, with slight fluctuations. *Artemisia desertorum* maintained relatively high moisture throughout the profile, showing a general increasing trend with depth.

Overall, soil moisture peaked at 10–20 cm depth across most species and positions. In July (the month with highest precipitation), different species showed varying responses to rainfall at different depths and positions (Figure 4). On windward slopes, *Populus simonii* and *Salix cheilophila* showed increasing moisture with depth, while *Pinus sylvestris*, *Hippophae rhamnoides*, and *Artemisia desertorum* showed fluctuating decreases. At dune crests, all species except *Hippophae rhamnoides* (which decreased consistently) showed initial increases followed by decreases, with maximum moisture occurring at 60–80 cm for *Populus simonii*. On leeward slopes, all species except *Pinus sylvestris* (which decreased) showed fluctuating increases, particularly pronounced for *Hippophae rhamnoides*.

4. Discussion

Soil moisture represents the primary limiting factor for vegetation restoration in the Qinghai Lake basin, where sand control measures rely primarily on biological approaches or combinations of mechanical and biological methods. In arid and semi-arid regions, groundwater is generally deep and atmospheric precipitation constitutes the main source of soil moisture. In our study area, July precipitation was highest, corresponding with peak soil moisture content. The interdune water table is typically around 0.5 m, while most dunes exceed 3 m in height, making groundwater recharge minimal and precipitation the dominant moisture source.

Soil moisture seasonality is also influenced by initial moisture conditions, vegetation transpiration, and soil evaporation. In May, surface thawing rapidly replenishes soil moisture while plants are still germinating with low water demand. From June through August, moisture is consumed primarily through upper soil evaporation and vegetation transpiration. The upper soil profile is most affected by external environmental factors, with these influences diminishing with depth. In the vertical profile, moisture consumption is greatest where root density is highest.

Our results show that soil moisture peaked at 10–20 cm depth across different vegetation measures, consistent with the zone of maximum precipitation infiltration. The surface layer (0–10 cm) contains high proportions of fine and very fine sand with weak crust development, resulting in low water-holding capacity and rapid infiltration to deeper layers. Consequently, during the peak growing season (July–August), soil moisture trends diverged from precipitation patterns. The seasonal distribution pattern was consistent across dune positions, though individual plant water consumption created species-specific differences. *Pinus sylvestris* showed the lowest soil moisture due to its evergreen habit and high water demand throughout the year, combined with high canopy cover that increased water consumption.

Soil moisture distribution under different restoration measures correlated with vegetation type, planting patterns, density, and individual plant size. The vertical distribution was influenced by both precipitation infiltration and root water uptake. Previous studies indicate that in this region, precipitation significantly affects the upper 100 cm, with diminishing influence below this depth. Our findings align with this: 10–20 cm soil moisture was highest across most species and positions, while deeper layers showed more stable moisture levels.

In alpine sandy lands, both soil moisture and nutrients are scarce. Seasonal precipitation creates high moisture in the surface 40 cm, where roots concentrate to access water and nutrients. The complex ecological relationship between plants and soil moisture involves both water consumption by plants and moisture conservation through canopy shading of surface evaporation and root stabilization of soil structure. While plants require substantial soil moisture for growth, they also protect against natural evapotranspiration and wind erosion.

Comparing plant growth characteristics (Table 2) with underlying soil moisture reveals no simple linear relationship, as soil moisture is influenced by multiple factors including topography, soil properties, vegetation, groundwater depth, precipitation, and meteorological conditions. The vegetation-soil system exhibits high spatiotemporal heterogeneity through ecohydrological cycling and feedback mechanisms.

In our study area, soil moisture under artificially stabilized dunes ranged from 1.81% to 3.41%, with dominant species cover ranging from 14.60% to 54.06%. The natural fixed dune maintained *Artemisia desertorum* cover around 54.06% with stable soil moisture near 3.41%, suggesting dynamic equilibrium between vegetation and soil moisture at this cover level. This indicates that vegetation can effectively utilize local precipitation while inhibiting deep percolation, storing water in deeper sand layers. Given that different sand-fixing species have varying water requirements and use efficiencies, both seasonal and depth-related moisture patterns show species-specific differences. Future research on water sources for sand-fixing plants and their dynamic relationship with soil moisture will be crucial.

Both natural vegetation (*Artemisia desertorum*) and artificial plantings (*Popu-*

lus simonii, Pinus sylvestris, Salix cheilophila, Hippophae rhamnoides) increased and stabilized soil moisture across soil layers, demonstrating clear regulation functions. Natural vegetation showed superior soil moisture improvement benefits compared to artificial plantings, with longer-established vegetation exhibiting stronger water regulation capacity. Artificial vegetation increased surface cover, inhibited soil moisture evaporation, and enhanced surface soil moisture, which can increase the threshold wind velocity for sand movement and reduce wind erosion—beneficial for early plant establishment. Therefore, comprehensive consideration of species type, planting density, depth, and species combination patterns is essential for maximizing the ecological functions of sand-fixing vegetation.

5. Conclusions

1. Seasonal soil moisture variation is influenced by precipitation, vegetation transpiration, and surface evaporation. Different species show distinct distribution patterns, but all exhibit peak soil moisture content in July.
2. Soil moisture content varies by dune position for the same species. Populus simonii shows highest moisture on windward slopes, while Pinus sylvestris, Hippophae rhamnoides, and Salix cheilophila peak on leeward slopes, and Artemisia desertorum reaches maximum moisture at dune crests. Only Salix cheilophila shows statistically significant differences across positions ($P < 0.05$). Different species at the same position also vary in moisture content, with Artemisia desertorum generally showing higher values across all positions.
3. Soil moisture varies with depth, peaking generally at 10–20 cm. Vertical distribution patterns differ among species: moisture decreases with depth under Populus simonii and Pinus sylvestris, remains relatively stable under Hippophae rhamnoides and Artemisia desertorum within 0–120 cm, while Salix cheilophila shows position-dependent patterns.
4. Soil moisture distribution under different vegetation restoration measures in alpine semi-arid sandy lands is affected by precipitation, soil characteristics, species type, root distribution, and dune microtopography.

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