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Effects of Microtopography on Water Use Characteristics of Alpine Sand-Fixing Plants (Postprint)

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Abstract

Water is the most critical limiting factor for plant survival, and studies on water utilization by plants in sandy areas have become essential for sandy land ecological protection and vegetation restoration. This study examined three typical sand-fixing plants in the eastern Qinghai Lake sandy land—Pinus sylvestris var. mongolica, Populus simonii, and Hippophae rhamnoides—using hydrogen and oxygen stable isotope technology ($ $18O and δD) combined with the IsoSource model to analyze potential water sources (soil water from different layers) and the main water sources of plants under microtopographic influences. The results indicate that: (1) Soil water content exhibits microtopographic variations, with higher soil water content in windward slope lowlands compared to dune tops and the middle of windward slopes, and September shows the highest soil water content. (2) The $ $18O values of xylem water display inter-species differences under various microtopographic conditions, with Pinus sylvestris var. mongolica showing the lowest $ $18O values in windward slope lowlands, while Hippophae rhamnoides and Populus simonii have the lowest $ $18O values in the middle of windward slopes. (3) The main water sources of different plants demonstrate distinct seasonal differences. In June, Pinus sylvestris var. mongolica and Hippophae rhamnoides primarily utilized deep soil water under different microtopographic conditions, whereas Populus simonii mainly used deep soil water at dune tops but showed greater utilization of middle-layer soil water in the middle of windward slopes and lowlands. However, with increasing precipitation, all tree species shifted to primarily utilizing shallow and middle-layer soil water in September. In conclusion, the water utilization patterns of sand-fixing plants in alpine sandy lands are influenced by microtopographic conditions, and different species exhibit varying degrees of response to precipitation.

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Effects of Micro-Topography on Water Use Characteristics of Alpine Sand-Fixing Plants

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Abstract

Water is the most critical limiting factor for plant survival, and studies on water utilization in desert plants have become essential for ecological protection and vegetation restoration in sandy lands. This research focused on three typical sand-fixing species—*Pinus sylvestris*, *Populus simonii*, and *Hippophae rhamnoides*—in the sandy land on the east shore of Qinghai Lake. Using hydrogen and oxygen stable isotope technology (δ^{18}O and δD) and the IsoSource mixing model, we analyzed various potential water sources (soil water at different depths) and the primary water sources for plants under the influence of micro-topography.

The results demonstrate that: (1) Soil water content exhibited significant micro-topographic differences, with higher values in the lowland of the windward slope compared to the dune top and middle windward slope, reaching its maximum in September. (2) The δ^{18}O values of xylem water varied among species under different micro-topographic conditions; *P. sylvestris* showed the lowest δ^{18}O values in the windward slope lowland, while *H. rhamnoides* and *P. simonii* had their lowest values in the middle windward slope. (3) The primary water sources for different plants showed marked seasonal variations. In June, *P. sylvestris* and *H. rhamnoides* primarily utilized deep soil water across all micro-topographic conditions, whereas *P. simonii* mainly used deep soil water at the dune top but relied more on middle-layer soil water in the middle and lowland windward slope. However, with increasing precipitation, all three species shifted to primarily utilizing shallow and middle soil water in September.

In summary, the water use patterns of sand-fixing plants in alpine sandy lands are influenced by micro-topographic conditions, and different species exhibit varying degrees of response to precipitation.

Keywords: alpine sandy land; stable isotopes; micro-topography; plant water source; IsoSource model

1. Introduction

Sandy land is a type of land covered with sand particles and essentially devoid of vegetation, characterized by intense aeolian activity, poor soil fertility, and water distribution patterns that constitute important constraints on vegetation growth [?]. Soil moisture in sandy lands is primarily supplied by precipitation, but in the arid inland regions of northwest China, precipitation is scarce and highly variable, resulting in a chronic state of severe water deficit. As a key limiting factor in the soil-plant-atmosphere continuum, soil moisture not only affects soil properties but also determines plant survival, distribution, and regional microclimate characteristics [?]. Consequently, short-term water resource enrichment triggered by precipitation events can cause some degree of disturbance to the water sources of sand-fixing plants [?].

Plant water use patterns affect ecosystem responses to environmental water availability, and ecosystem responses to precipitation exhibit critical thresholds, hierarchical structures, and time lags. For instance, small precipitation events only affect shallow soil water, whereas large precipitation events typically infiltrate to deeper layers, causing different plant species to respond dynamically to precipitation at different magnitudes [?]. Plant water sources vary with precipitation patterns, making it crucial to investigate the response of sand-fixing vegetation to precipitation and its water use characteristics to deepen our understanding of plant-water relationships in sandy regions.

Since the 1990s, stable isotope technology has been applied in ecological research, addressing the limitations of traditional plant water source studies that were overly destructive and unable to meet increasingly complex and refined ecological questions [?]. Research has shown that water absorbed by terrestrial plant roots (except for a few halophytes, xerophytes, and wetland plants) generally does not undergo isotopic fractionation before reaching leaves or young, non-lignified branches [?], providing a theoretical foundation for revealing plant water use mechanisms using stable isotope methods. In arid and semi-arid regions, plant roots exhibit a "two-layer water use pattern," whereby shallow roots utilize more precipitation while deeper roots primarily use deep soil water or groundwater [?]. However, studies have found that root distribution does not necessarily represent plant water uptake characteristics, as topography, precipitation, climate, and growth traits also significantly influence plant water use [?]. Among these factors, topography causes heterogeneous distribution of soil moisture, thereby affecting plant water sources [?]. For example, Zhang et al. [?] studied soil moisture on different micro-topographies at the southeastern edge of the Tengger Desert and found that soil moisture followed the pattern: mobile dunes > semi-fixed dunes > fixed dunes. Zhu et al. [?] investigated the spatiotemporal distribution of moisture in semi-fixed dunes at the southern edge of the Gurbantunggut Desert and concluded that soil moisture content was higher in inter-dune lowlands than on windward slopes. Tian et al. [?] examined the water use characteristics of *Salix cheilophila* in different geomorphic positions of alpine sandy dunes, demonstrating that micro-topography affects plant water sources, though that study focused primarily on a single species.

These studies indicate that micro-topography significantly influences soil moisture content and plant water sources in sandy lands. However, how does micro-topography affect the water sources of mixed species? How do different sand-fixing species respond to different precipitation events? These questions are key to understanding plant-water relationships in alpine sandy regions and constitute an important theoretical foundation for exploring the water adaptability of sand-fixing vegetation.

The Qinghai Lake basin is a typical ecologically fragile area with harsh climate and multiple environmental problems [?]. A sand control experimental station was established on the east shore of Qinghai Lake in 1987. Through a series of sand control and afforestation projects, the expansion of desertified land in this area has been effectively controlled [?]. However, research on vegetation restoration in this region remains limited, focusing mainly on soil improvement [?], vegetation community characteristics [?], and plant-soil moisture relationships [?], while lacking in-depth exploration of vegetation-water feedback mechanisms under micro-topographic influence. Therefore, this study selected three typical sand-fixing tree species—*Pinus sylvestris*, *Populus simonii*, and *Hippophae rhamnoides*—from a comprehensive sand control demonstration area established in 1987 on the east shore of Qinghai Lake. Using hydrogen and oxygen stable isotopes (δ^{18}O and δD), we analyzed the dynamic changes in their water sources and responses to precipitation events to elucidate the water use patterns of mixed plants under micro-topographic influence and their drought adaptation mechanisms, providing a theoretical basis for alpine sandy land management.

1.1 Study Area Overview The study area is located in the Ketu sandy region on the east shore of Qinghai Lake, Qinghai Province (100°75 -100°78 E, 36°77 -36°78 N), covering approximately 3300 m^2 with an average elevation of 753 km^2. Situated at the intersection of three major natural environmental zones [?], the region has a typical plateau semi-arid climate. According to monitoring data from an automatic weather station in the Ketu sandy area from 2017 to 2020, the mean annual temperature is 0.7°C and mean annual precipitation is about 370 mm. Aeolian activity is most intense from late autumn to early spring, with prevailing southwest winds [?]. The area features diverse dune types, with artificial fixed dunes, natural fixed dunes, and semi-fixed dunes distributed near the lakeshore. The sandy surface deposits are dominated by medium sand with a mean particle size of 0.16-0.31 mm (medium sand), while inter-dune deposits have a mean particle size of 0.13 mm (fine sand) [?].

Since 1987, eight sand-fixing plant species have been planted in this area, with typical species including *Pinus sylvestris*, *Populus simonii*, *Hippophae rhamnoides*, *Salix cheilophila*, *Caragana korshinskii*, *Artemisia desertorum*, *Hedysarum scoparium*, *Sabina vulgaris*, *Tamarix chinensis*, *Picea crassifolia*, and *Potentilla fruticosa*. The vegetation restoration benefits have been significant [?]. In 1987, wheat straw sand barriers (1.5 m × 1.5 m) were laid on a dune, and *H. rhamnoides* and *P. sylvestris* seedlings were planted. In autumn of the same year, *P. simonii* was planted on the dune using deep planting methods [?]. In 2019, three 10 m × 10 m fixed plots were established at the lowland, middle, and top of the windward slope of this dune. In August 2019, plant height, crown width, and other indicators were measured within the fixed plots to calculate coverage and density.

1.2 Sample Plot Characteristics The study area' s vegetation community characteristics are shown in . The table presents mean values ± standard deviation (n = 3). Different uppercase letters in the same column indicate significant differences among tree species under the same micro-topography ($P < 0.05$), while different lowercase letters indicate significant differences for the same tree species among different micro-topographies ($P < 0.05$).

1.3 Sample Collection During the plant growing season (June–September), 28 precipitation events occurred ([Figure 1: see original paper]), among which small precipitation events (0–5 mm) had high frequency, while events of 5–10 mm and >10 mm had relatively low frequency. In arid and semi-arid regions, small precipitation events (<5 mm) only affect shallow soil moisture, whereas large precipitation events can infiltrate to deeper layers and significantly impact deep soil moisture [?]. To investigate plant responses to precipitation under different micro-topographic conditions, plant and soil samples were collected on the 4th day after a small precipitation event (4.1 mm) on June 28 and on the 4th day after a large precipitation event (25.5 mm) on September 5.

Within each plot, three healthy, vigorous, and morphologically similar individuals of each species were selected as experimental plants. Non-green, lignified small branch segments (3–5 cm long, 0.3–0.5 cm in diameter) were cut from east, west, south, and north directions of each plant. After removing the bark and phloem, samples were placed in glass bottles, sealed with Parafilm, stored in ice boxes, transported to the laboratory, and frozen until extraction.

Soil samples were collected using a soil auger at the center of each plot. Samples were taken at depths of 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, and 100–150 cm. For each layer, one portion was quickly placed in a sampling bottle, sealed with Parafilm, stored in an ice box, and frozen in the laboratory; the remaining portion was placed in an aluminum box for fresh weight measurement, then oven-dried at 105°C for dry weight measurement to calculate soil mass water content (SWC).

Precipitation samples were collected using a homemade precipitation stable isotope sampler after each rainfall event. Samples were transferred to 30 mL bottles, sealed with Parafilm, and refrigerated until measurement. Precipitation data were obtained from a self-recording rain gauge placed in the study area. Since the height of artificially controlled dunes in this area is generally 14.83°

and groundwater is deeply buried [?], groundwater was not considered as a water source for the three plant species.

1.4 Sample Measurement Sample measurements were completed at the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. Plant and soil water was extracted using a low-temperature vacuum condensation extraction system (Li-2100, Beijing LICA United Technology Co., Ltd.), filtered, and stored in 2 mL bottles at 4°C. Stable isotopes of extracted plant water, soil water, and precipitation were measured using a liquid water isotope analyzer (DLT-100). The isotopic composition is expressed in δ notation (‰) relative to Vienna Standard Mean Ocean Water (VSMOW):

δ(‰) = (R_{sample}/R_{standard} - 1) × 1000‰

where R represents the ratio of heavy to light isotope abundance (e.g., $^{18}O/^{16}O$ or D/H) in the sample and standard.

1.5 Data Processing Since plant samples may experience spectral contamination during extraction, potentially causing errors, plant water δ values were corrected using the method provided by the manufacturer: deionized water from the same source was mixed with 99.9% chromatography-grade ethanol and methanol to prepare solutions of different concentrations. These solutions were measured using the liquid water isotope analyzer to establish correction curves:

Ethanol spectral contamination correction curve:
$\Delta\delta^{18}O$ = 0.1455 ln(C_{ethanol}) + 0.3292 (R^2 = 0.9946)

Methanol spectral contamination correction curve:
$\Delta\delta^{18}O$ = -9.14 ln(C_{methanol}) + 9.1269 (R^2 = 0.8926)

Deviations in $\delta^{18}O$ values (NB and BB) can be obtained directly through spectral diagnostic software.

Based on the growth characteristics of each tree species and soil moisture distribution in alpine sandy lands [?], soil water was divided into three layers: (1) shallow soil water (0–20 cm), which is significantly affected by precipitation infiltration and evaporation, showing large variation in moisture and stable isotope values; (2) middle soil water (20–60 cm), where the effects of precipitation infiltration and evaporation are relatively smaller, and moisture and isotope values show depth-dependent characteristics; and (3) deep soil water (60–150 cm), which is unaffected by precipitation and evaporation, with relatively stable moisture and isotopic composition.

Statistical analyses were performed using SPSS 26.0, with significance tested at $P < 0.05$. Origin 2022 was used for figure preparation. The IsoSource model was used to analyze the proportional contributions of potential water sources to plant xylem water.

2. Results

2.1 Precipitation Distribution and Variation in δ^{18}O and δD Values The stable isotopes of precipitation in the study area showed significant seasonal variation. Precipitation was low from June to July and higher from August to September, mainly consisting of small events concentrated in July. Large precipitation events were less frequent but contributed substantially to total rainfall, with the maximum single event reaching 25.5 mm on September 1. Regression analysis of precipitation δ values yielded the local meteoric water line: $\delta D = 7.705\delta^{18}O + 21.625$ ($R^2 = 0.948$). Compared with the global meteoric water line ($\delta D = 8\delta^{18}O + 10$), the smaller slope indicates that precipitation primarily consists of secondary or multiple evaporated terrestrial water from the arid northwest region, with strong kinetic fractionation of hydrogen and oxygen stable isotopes [?]. The δ^{18}O and δD values showed consistent overall trends, ranging from -30.29‰ to -1.40‰ and -5.80‰ to 9.02‰, respectively, demonstrating significant seasonal variation ([Figure 2: see original paper]).

2.2 Distribution of Soil Water Content and δ^{18}O Values Across Micro-Topographies Soil water content showed distinct micro-topographic differences. In September, soil moisture was higher across all micro-topographies compared to June. The average soil water content in the windward slope lowland was 7.38%, followed by the dune top (6.96%), with the middle windward slope being lowest (5.56%). Soil water δ^{18}O values also showed clear micro-topographic differences and varied with depth ([Figure 4: see original paper], [Figure 5: see original paper]). In June, δ^{18}O values ranged from -9.02‰ to -4.86‰ in the dune top, -9.39‰ to -7.56‰ in the middle windward slope, and -7.41‰ to -5.72‰ in the windward slope lowland. In September, the ranges were -6.11‰ to -3.55‰, -9.11‰ to -5.36‰, and -5.80‰ to -4.86‰, respectively.

In the shallow soil layer, δ^{18}O values showed polarization under micro-topographic influence in June, decreasing with depth. In September, δ^{18}O values gradually increased with depth. In the dune top, middle-layer soil water δ^{18}O values decreased with depth and stabilized in the deep layer. In the middle windward slope, middle-layer soil water δ^{18}O values gradually decreased with depth in both June and September, stabilizing in the deep layer. In the windward slope lowland, middle and deep soil water showed little difference between June and September.

2.3 Stable Isotope Characteristics of Plant Xylem Water The δ^{18}O values of xylem water for the three plant species fell to the right of the local meteoric water line, indicating that their primary water sources were affected by soil water enriched in heavy isotopes due to evaporation. The δ^{18}O values varied among species and micro-topographies: for *P. sylvestris*, *H. rhamnoides*, and *P. simonii*, the ranges were -5.67‰ to -4.97‰, -5.78‰ to -4.86‰, and -5.80‰ to -4.86‰, respectively. The δ^{18}O values of *P. sylvestris* were highest at the dune top and lowest in the windward slope lowland. *H. rhamnoides* and

P. simonii showed the highest values at the dune top and lowest in the middle windward slope. Differences among species at the same geomorphic position varied, being smallest in the middle windward slope and relatively larger in the windward slope lowland ([Figure 6: see original paper]).

2.4 Proportions of Plant Water Sources The proportional contributions of potential water sources differed among micro-topographies ([Figure 7: see original paper]). In June, *P. sylvestris* at the dune top primarily used middle (43.2%) and deep (47.8%) soil water, while those in the middle and lowland windward slope mainly used deep soil water (48.3% and 49.6%, respectively). In September, *P. sylvestris* at the dune top increased its use of shallow soil water while slightly decreasing middle and deep water use. In the middle and lowland windward slope, *P. sylvestris* primarily used shallow soil water (45.6% and 45.9%, respectively), with greatly reduced use of middle and deep soil water.

In June, *H. rhamnoides* at the dune top mainly used middle (37.3%) and deep (55.8%) soil water; in the middle windward slope, it primarily used deep soil water (58.5%); and in the windward slope lowland, it used all layers relatively evenly (33.5%, 31.2%, and 35.4% for shallow, middle, and deep, respectively). In September, *H. rhamnoides* at all three micro-topographic positions increased its use of shallow soil water.

In June, *P. simonii* at the dune top mainly used deep soil water (50.4%), while those in the middle and lowland windward slope primarily used shallow and middle soil water. In September, *P. simonii* at the dune top mainly used middle soil water (74.4%), in the middle windward slope it primarily used shallow soil water (44.5%), and in the windward slope lowland it mainly used middle soil water (59.8%).

In summary, all species primarily used middle and deep soil water in June. With increased precipitation in September, all species showed varying degrees of increased utilization of shallow soil water.

3. Discussion

3.1 Response of Soil Moisture and Its Isotopic Composition to Precipitation Soil moisture is a primary limiting factor for vegetation restoration, determining plant survival in arid environments, while precipitation is the main source of soil water replenishment [?]. In June, low precipitation and strong evaporation resulted in relatively low soil water content across all micro-topographies. In September, shallow soil water was significantly replenished by precipitation, increasing soil moisture content, though this effect gradually weakened with depth [?].

In arid and semi-arid regions, soil water stable isotopic composition shows pulse-like changes in response to precipitation [?]. After precipitation events, shallow soil water is more sensitive to small precipitation events, while large precipitation events significantly impact soil water δ^{18}O values through infiltration. For example, after a 24.8 mm precipitation event, soil water δ^{18}O values were greatly affected, demonstrating that precipitation amount significantly influences infiltration volume and depth [?]. In June, low precipitation and strong evaporation caused enrichment of stable isotopes in soil water. In September, with increased precipitation, soil water δ^{18}O values gradually decreased and showed a trend of decreasing with depth ([Figure 5: see original paper]), consistent with findings from Zhou et al. [?] on water sources of *Tamarix ramosissima*, *Nitraria sphaerocarpa*, and *Reaumuria soongorica* at the southeastern edge of the Junggar Basin.

3.2 Effects of Micro-Topography on Soil Moisture and Its Isotopic Composition Soil water and its δ^{18}O values showed significant differences among micro-topographies. The windward slope lowland had the highest soil water content (7.38%), followed by the dune top (6.96%), with the middle windward slope being lowest (5.56%). Previous studies have demonstrated that different micro-topographies on dunes create habitat heterogeneity [?], affecting spatiotemporal distribution of soil moisture and nutrients [?]. Micro-topography influences soil moisture mainly through slope-induced spatial variation; steeper slopes have lower soil water content, while gentler slopes have more adequate moisture [?]. This study confirms these findings. Huang et al. [?] showed that increased slope gradient reduces water infiltration, as greater slopes convert more potential energy to kinetic energy, increasing runoff formation and reducing infiltration. The middle windward slope has a steeper gradient, 不利于 precipitation infiltration, causing precipitation to flow as runoff into the windward slope lowland, which has relatively flat terrain conducive to water collection and deep infiltration [?]. Therefore, the middle windward slope has the poorest soil moisture conditions, the dune top is intermediate, and the windward slope lowland has the best conditions.

Under the same micro-topography, soil water δ^{18}O values varied significantly with depth [?]. Compared to deep soil, shallow soil is more affected by evaporation, showing isotopic enrichment [?]. Soil water δ^{18}O values gradually decreased with depth, with evaporation effects weakening accordingly [?]. The dune top showed the largest δ^{18}O values, followed by the middle windward slope, with the windward slope lowland showing the smallest values. This indicates that even within the same precipitation area, differences in micro-topographic conditions cause spatial redistribution of precipitation and solar radiation, altering regional microclimate conditions and spatial distribution of soil moisture [?], resulting in differences in soil water content and isotopic composition.

3.3 Ecological Implications of Water Use Patterns in Alpine Sand-Fixing Plants Plant water use characteristics play an important role in the ecohydrological cycle of sandy lands. Affected by season and potential water sources, plants regulate their water use strategies to avoid drought stress and better adapt to environmental changes [?]. In alpine sandy lands, water is a key factor for plant survival and regeneration [?]. In June, surface soil moisture was relatively deficient and could not support plant growth, so *P. sylvestris*, *H. rhamnoides*, and *P. simonii* primarily relied on deep soil water, supplemented by middle soil water, to adapt to the dry environment. With increased natural precipitation in September, the three species adjusted their strategies by increasing their use of shallow soil water to sustain life, showing a positive response to precipitation pulses [?]. As surface soil moisture increased, plants consumed less energy using shallow soil water compared to deep soil water [?], which is related to root water uptake characteristics [?]. During dry periods with low precipitation, taproots absorb deep soil water to adapt to drought stress, mainly because shallow roots may become inactive under dry conditions [?], while during wet periods with abundant precipitation, rainwater-supplemented shallow soil water increases, and plants absorb it through lateral roots [?].

This study shows that plant water sources differed among micro-topographies. At the dune top, *P. sylvestris* and *H. rhamnoides* primarily used middle and deep soil water when precipitation was low, increasing shallow water use as precipitation increased. *P. simonii* used deep soil water when precipitation was low, but shifted to middle soil water (74.4%) when precipitation increased. In the middle windward slope, all species primarily used deep soil water, though *P. simonii* used relatively more shallow and middle soil water. In the windward slope lowland with better soil moisture, all species used water from all layers, increasing shallow water use when precipitation was abundant. In summary, micro-topography and precipitation significantly influence plant water use.

This study analyzed water sources of three typical alpine sand-fixing plants under different micro-topographies and precipitation conditions but did not deeply explore the close relationships between plant roots, eco-physiological factors, and water sources. Particularly, how plant roots and other factors regulate water use by alpine sand-fixing plants and the rational allocation of water use among species—i.e., how species coexist based on water use—are key issues in plant community water use strategies and represent important directions for future research.

4. Conclusions

1) Micro-topography is an important factor affecting soil water content. Steeper topography results in lower soil water content. Specifically, the windward slope lowland has the highest soil water content, followed by the dune top, with the middle windward slope being lowest.

2) Alpine sandy land plants show positive responses to precipitation. In June with low precipitation, all species strongly depended on deep soil water. In September with higher precipitation, all species increased their use of shallow soil water.

3) Mixed plant species have different water sources under different micro-topographies. At the dune top, *P. sylvestris* used all soil layers, while *H. rhamnoides* and *P. simonii* primarily used middle and deep soil water.

In the middle windward slope, all species mainly used deep soil water, though *P. simonii* used relatively more shallow and middle layers. In the windward slope lowland, *P. sylvestris* primarily used deep soil water, while *H. rhamnoides* and *P. simonii* mainly used shallow and middle soil water.

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