Water Retention Characteristics of Clay-Intercalated Sand Dunes at Oasis Margins: Postprint

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Abstract

Clay-interlayered sand dunes refer to sand dunes with a reddish-brown clayified layer distributed in their profile. The burial depth of this clay interlayer is typically around 120-500 cm, with a thickness of 40-100 cm, and the clay and silt particle content reaches over 90%. The canopy density of artificial Haloxylon ammodendron sand-fixing vegetation on clay-interlayered sand dunes is above 0.5, significantly higher than vegetation productivity under the same hydrothermal conditions, which may be related to the clay interlayer improving soil water carrying capacity by altering soil water retention and water regime. Taking clay-interlayered sand dunes at the margin of the Hexi Corridor oasis as the research object, and based on measurements of soil physical properties and soil water characteristic curves in the 0-8.0 m profile, soil pore distribution and water retention characteristics were calculated, and the variation patterns of soil water retention and their influencing factors in the profile were studied. The results show that: (1) The clay interlayer has the highest soil water content, the overlying sandy soil has the lowest water content which increases with depth, and the underlying sandy soil has relatively high water content due to the influence of capillary action from groundwater; (2) Soil mechanical composition determines the water retention characteristics of different soil layers—the higher the clay and silt particle content in soil, the greater the field capacity and saturated water content, and the soil water retention of the clay interlayer is far higher than that of the sandy soil layer; (3) The clay interlayer is an important soil horizon for temporary storage of soil water in sand dunes, capable of providing deep soil water for vegetation, which has important implications for the survival and reproduction of artificial sand-fixing vegetation at oasis margins, while the strength of soil water retention and capillary action determines the clay interlayer's capacity to regulate water in sand dunes. This study provides a theoretical basis for deeply understanding the mechanism underlying the patchy distribution of rain-fed sand-fixing vegetation at oasis margins.

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Full Text

Water Retention of the Clay Interlayer of Dunes at the Edge of an Oasis

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Abstract

A sandwich dune's profile consists of layers with different soil textures, the upper and lower of which are sandy soil layers, and there is a fine soil pan between the surface and the subsoil. The clay interlayer is composed of silty loam containing over 90% silt and clay. Deposits of this layer occur at depths of 120–500 cm and it ranges in thickness from 40 to 100 cm. In arid areas with precipitation of less than 200 mm, artificial sand-fixing vegetation coverage is approximately 10% to 15%; however, the vegetation coverage of the study area with 117 mm mean annual precipitation is approximately 65%, which does not meet the zonal water and heat conditions. Water retention is considered to play an important part in affecting the water conditions and soil water carrying capacity of dunes. With regards to water retention, Bettiet al. have analyzed the effects of soil texture on water retention, revealing that when the sand content is increased, water retention becomes weaker, and the soil layer has a significant effect on the water-holding capacity, and their studies have focused on analysis of the water-holding capacity of homogeneous soil. In order to study the characteristics and mechanisms of the response of the clay interlayer to water retention, we measured the soil water characteristic curve based on the centrifuge test, particle size measured by Mastersizer-2000, and pore distribution based on the measured soil water characteristic curve.

Our results show the following patterns: (1) The soil moisture content of the clay interlayer was the highest, soil water content increased slightly with depth in the surface soil, and the soil moisture of the subsoil was higher than in the surface, which was affected by the capillary action of groundwater. (2) Field capacity, wilting coefficient, saturated water content, total porosity, and aeration porosity were significantly correlated with soil physical properties, such as bulk density, sand content, clay content, and particle size. Sandy soil layers were at 0–4.0 m and 4.6–8.0 m. The soil water characteristic curves of these profiles were steep and the soil was loose (aeration porosity, 14%–27%) with poor soil water retention. The layer at 4.0–4.6 m was an interbedded layer of silty loam, the soil water characteristic curves of which was smooth and the soil water content was high when the soil water suction was high. This type of soil had less aeration porosity, leading to higher soil water-holding capacity than the upper and lower sandy layers. Furthermore, correlation analysis showed that capillary porosity was not significantly correlated with soil physical properties, but was weakly related to soil water content, and increased significantly only at both the interface between the sandy layer and silty loam layer, and the water table. To a certain extent, the distribution of soil porosity affected the soil moisture content and water conveyance between the clay interlayer and the sand layer. In conclusion, soil textures lead to considerable differences in soil water retention of dunes at the edge of an oasis. The clay interlayer can hold more water compared with all profiles, which improves the water conditions of the dune. (3) The soil pan is the region where water collects, and provides water resources for plants. It plays an important role in the improvement of sand-fixing vegetation of dunes at the edge of an oasis. Further, the ability of the clay interlayer to regulate the water conditions of dunes depends on soil water retention and soil capillarity. In conclusion, our findings should provide strong support for future understanding of the mechanism of spatial patterns of artificial sand-fixing vegetation.

Keywords: oasis edge; dune; clay interlayer; water retention

Introduction

Wind-sand activities are frequent at oasis edges, and establishing artificial sand-fixing vegetation is an important measure to protect oases from wind-sand hazards. Since the 1970s, large areas of rain-fed *Haloxylon ammodendron* artificial sand-fixing vegetation have been established at the edges of oases in the Hexi Corridor. After many years of natural succession, the originally uniformly planted artificial sand-fixing vegetation has become patchily distributed. Precipitation is a key factor for the growth and development of artificial sand-fixing vegetation in arid regions. Artificial sand-fixing vegetation supported by precipitation typically has a coverage of about 10%–15%, while at the edge of the Linze Oasis with a multi-year average precipitation of 117 mm, the coverage of some dune *Haloxylon ammodendron* forest patches reaches about 65% after 30–40 years of natural succession. This may be related to the clay interlayer in the dune profile.

Soil texture can alter soil moisture conditions within the profile, increasing soil moisture heterogeneity. Studies have shown that the presence of a clay interlayer can significantly reduce the stable infiltration rate and wetting front advance speed, weakening soil water infiltration, with the degree of influence related to the hydraulic properties of the clay interlayer and its combination with other soil layers. Cui et al. found that clay interlayers can significantly improve soil water retention, while Zhou et al. discovered that soil texture composition has a significant impact on soil water retention characteristics. When soil texture changes from clay to sand, water retention weakens. Yan et al. and Wang et al. noted that as soil clay content decreases, soil water retention performance declines, and soil layer structure also significantly affects soil water retention capacity. The upper layer being sandy loam, middle layer being sub-clay, and bottom layer being sand (loam-clay-sand structure) has the best water retention, while uniform sand structure has the poorest.

Sandwich dunes are discontinuously distributed in arid regions, especially at desert-oasis edges. Studying the water retention characteristics of clay interlayers and their influence on soil moisture conditions in dune profiles is important for understanding the growth of rain-fed vegetation with approximately 100 mm precipitation and for guiding artificial vegetation construction. This study selected clay interlayer dunes at oasis edges, measured soil physical properties and water characteristic curves, calculated soil pore distribution and water retention characteristics, and investigated the variation patterns and influencing factors of soil water retention in profiles from 0–8.0 m depth. The aim was to reveal the water retention characteristics of clay interlayer dunes at oasis edges and provide a basis for understanding the development and evolution of artificial *Haloxylon ammodendron* sand-fixing forests.

Materials and Methods

Study Area Overview The study area is located in the Linze Desert in the middle of the Hexi Corridor. This region has a typical continental desert climate at an elevation of 1386 m, with a multi-year average precipitation of 117 mm concentrated in small rainfall events, and annual potential evaporation of about 2360 mm. The groundwater depth is generally 5–10 m, recharged mainly by precipitation and showing seasonal variation. The landform is primarily aeolian, with soil types mainly consisting of gray-brown desert soil and aeolian sandy soil. The soil profile shows distinct layering, with a clay interlayer present. Representative plants include *Haloxylon ammodendron*, *Calligonum mongolicum*, *Nitraria sphaerocarpa*, and *Tamarix chinensis*.

Soil Sampling and Analysis A large soil profile was excavated in the experimental area. Based on vegetation, soil color, and other features, the profile structure was divided into layers. Undisturbed soil samples were collected using cutting rings at depths of 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 4.3, 4.6, 5.0, and 8.0 m from the soil surface. Fresh soil samples were placed in aluminum boxes and ziplock bags and brought back to the laboratory for determination of soil water content and mechanical composition. Soil water content, porosity, and saturated water content were measured using the drying method. Particle composition was measured using a laser particle size analyzer (Mastersizer-2000). The collected undisturbed soil rings were placed in water for 24 hours to saturate, then centrifuged at 14 different rotation speeds (corresponding to soil water suctions of 0.001, 0.005, 0.01, 0.02, 0.04, 0.06, 0.08, 0.1, 0.2, 0.5, 1.0, 1.5, and 2.0 MPa) using an H-1400pf centrifuge. After reaching equilibrium at each suction, the corresponding soil mass water content was measured to obtain the soil water characteristic curve for each profile.

Soil Pore Distribution Soil pore distribution can reflect soil water retention characteristics. The equivalent pore size can be calculated from the soil water characteristic curve using the formula:

$$d = \frac{3}{h}$$

where d is the equivalent pore size (mm) and h is the soil water suction (MPa). In this study, the equivalent pore sizes corresponding to soil water suctions were >10 m, 2-10 m, and <2 m for aeration pores, capillary pores, and inactive pores, respectively.

Soil Water Retention Field capacity and wilting coefficient are commonly used to measure soil water retention characteristics and can be calculated from the soil water characteristic curve. Field capacity is generally considered as the soil water content corresponding to 101.97 cm H O suction, while the wilting coefficient corresponds to 15295.5 cm H O suction.

Results

Soil Physical Characteristics of the Dune Profile The soil texture of the dune profile varied significantly. The sand content was above 80.41% in the 0-4.0 m and 4.6-8.0 m layers, which were sandy soils. The 4.0-4.6 m layer was silty loam. Soil water content was lowest in the surface layer (0-0.2 m) and increased with depth, reaching maximum saturation (0.241 g/cm^3) at the 4.0-4.6 m clay interlayer. The 4.6-8.0 m sand layer showed gradually increasing moisture content (0.005-0.017 g/cm^3) due to capillary action from groundwater, reaching the water table at 8.0 m.

Soil Water Characteristic Curves of the Dune The van Genuchten model, which provides good fitting for sandy soils, was used to fit the soil water characteristic curves of the dune:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^{1-1/n}}$$

where θ is volumetric water content (%), θ_r is residual water content (%), θ_s is saturated water content (%), h is soil water suction (cm H O), α is a coefficient related to soil air-entry suction, and n is an empirical fitting parameter.

The fitting and validation results for different soil layers showed that the van Genuchten model achieved high fitting precision for the clay interlayer dune soil water characteristic curves, with R^2 values of 0.975-0.998 and RMSE of 0.0072-0.0184. The 4.0-4.6 m layer had the highest position for the soil water characteristic curve. At low suction stages (0-1000 cm H O), the 0-4.0 m and 4.6-8.0 m layers showed rapid water release rates, while the 4.0-4.6 m layer showed a significantly slower rate of soil water reduction with increasing suction.

Soil Pore Distribution in the Dune Profile Soil pore quantity increased significantly in the 4.0-4.6 m layer. The total porosity of the 0-4.0 m and 4.6-8.0 m layers was small with no significant difference, while aeration porosity in the 4.0-4.6 m layer was only 2.24%. Aeration porosity in the 0-4.0 m layer gradually decreased with depth, while that in the 4.6-8.0 m layer was 22.39%. Capillary porosity showed little variation with soil depth in the 0-4.0 m and 4.6-8.0 m layers, but increased significantly at the interfaces between the clay interlayer and sand layers and at the water table (8.0 m), reaching maximum values of 12.73% and 7.35% at the upper and lower interfaces, respectively.

Soil Water Retention Performance of the Dune Profile Calculated from the soil water characteristic curve fitting equations, field capacity, wilting coefficient, and available water content varied by depth. Field capacity and saturated water content were highest in the 4.0-4.6 m layer, demonstrating better water retention than the sand layers above and below. The wilting coefficient was also highest in the 4.0-4.6 m layer at 0.21 cm^3/cm^3, while available water content was smallest in this layer, indicating that although the clay interlayer can hold more water, its water availability to plants is less than that of sand layers.

Discussion

Water Retention Characteristics of Clay Interlayer Dune Profiles The soil water characteristic curve describes the relationship between soil matric potential and water content and is key to studying soil water movement. The position of the curve reflects the strength of soil water retention capacity. Our results show the 4.0-4.6 m layer had the highest curve position, indicating better water retention than sand layers. However, at low suction stages, the 0-4.0 m layer had a higher curve position than the 4.6-8.0 m layer, primarily due to differences in soil pore distribution. Soil pore distribution directly affects soil water movement patterns. At low suctions, water drainage occurs mainly in aeration pores. The 0-4.0 m layer had more aeration pores than the 4.6-8.0 m layer, resulting in weaker water retention and a lower curve position.

Soil water retention refers to the soil' s ability to hold and store water. Field capacity, wilting coefficient, and saturated water content are important indicators characterizing soil water retention capacity. Our results show that the silty loam clay interlayer had higher saturated water content and field capacity than the upper and lower sand layers, indicating better water retention performance. However, available water content, which measures water availability to plants (the difference between field capacity and wilting coefficient), was smallest in the 4.0–4.6 m layer. This suggests that although the clay interlayer can hold more water, its water availability is less than that of sand layers, differing from studies on clay interlayers in the Loess Plateau, possibly due to differences in the development degree of clay coatings.

Factors Influencing Soil Water Retention in Clay Interlayer Dune Profiles Many factors can alter soil water retention performance, including soil silt and clay content, organic matter content, and pore distribution status. Soil physical properties and organic matter content are the main factors affecting water retention. Increased sand content and macropores lead to weaker water retention but greater water availability. Our results show that silt and clay content, bulk density, and aeration porosity significantly affect field capacity and saturated water content. When soil silt and clay content increases and aeration porosity proportion decreases, water retention capacity strengthens. The 0–4.0 m layer had higher sand content than the 4.6–8.0 m layer, but its field capacity and saturated water content were smaller, indicating that soil texture and permeability differences affect water retention.

Capillary porosity was not significantly related to soil physical properties but was weakly correlated with soil water content, increasing significantly only at the interfaces between sand and silty loam layers and at the water table. The distribution of capillary pores affects water conveyance between layers. Although capillary porosity in the 0–4.0 m layer was basically equal to that in the 4.6–8.0 m layer, it increased significantly at the sand-silty loam interfaces, suggesting that changes in soil texture and permeability can increase capillary pores and ultimately affect water retention performance.

Soil Moisture Conditions in Clay Interlayer Dune Profiles In clay interlayer dunes, the surface layer (0–0.2 m) had the lowest water content, which increased with depth. The 4.0–4.6 m silty loam clay interlayer had the highest water content. The 4.6–8.0 m layer had high water content due to capillary action from groundwater. Most soil water movement occurs in capillary pores, and the interfaces between the clay interlayer and sand layers are affected by capillary action. The distribution characteristics of soil pores can influence soil water content and water conveyance.

Analysis of soil water characteristic curves and profile moisture distribution shows that the 4.0–4.6 m layer had the highest soil water potential. When water potential in the lower sand layer decreases below that of the clay interlayer, the clay interlayer can transport water upward, thereby improving soil moisture conditions in the dune. However, further research is needed on how capillary rise height, thickness, and position of the clay interlayer affect dune moisture.

Conclusion

The clay interlayer in dune profiles has significantly higher water retention than the upper and lower sand layers. Soil particle composition and pore distribution are the main factors affecting water retention in clay interlayer dunes. Higher sand content, fewer aeration pores, and more pronounced capillary action result in stronger water retention. Soil moisture distribution varies considerably across the clay interlayer dune profile, with the clay interlayer having the highest water content, significantly higher than the upper and lower sand layers. The clay interlayer serves as a transition layer for water movement from the lower sand layer to the upper sand layer. Although this layer has high water content, its water availability is poor, making it difficult for vegetation to utilize. The clay interlayer plays a dual role in storing deep soil water and transmitting water to the overlying sand layer, which is important for improving dune soil moisture conditions. Its ability to regulate dune soil moisture depends on the strength of soil water retention and capillary action. The distribution of clay interlayers in dunes can alter soil moisture conditions and thus change vegetation growth patterns, which may explain the patchy distribution of rain-fed vegetation at oasis edges with approximately 100 mm precipitation.

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