Effects of Straw Checkerboard Barriers and Shrublands on Soil Water Physical Properties in the Ulan Buh Desert (Postprint)

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Abstract

To investigate the effects of typical sand control ecological engineering on soil water physical properties and water-holding capacity in the Ulan Buh Desert, straw checkerboard barriers + two native tree species (Haloxylon ammodendron and Hedysarum scoparium) were selected as the research objects, with shifting sand land serving as the control. Using a combination of field sampling and laboratory analysis, soil particle size composition, water content, bulk density, porosity, and water-holding capacity were analyzed for different soil layers within the 0-100 cm depth across various sample plots. The results indicate that establishing sand control ecological engineering primarily based on straw checkerboard barriers + native tree species has a certain ameliorative effect on the soil water physical properties and water-holding capacity of sandy land. (1) The surface soil particle size composition showed an overall trend of fining, soil bulk density decreased, soil porosity increased, soil water retention and water storage capacity increased, and soil water-holding capacity was significantly improved. (2) After the implementation of typical sand control ecological engineering in the Ulan Buh Desert, soil pedogenesis was relatively evident, water-holding capacity was significantly improved, and the desertification control effect was good. The research results can provide basic data for evaluating the effectiveness of regional sand control efforts, and can also provide scientific basis and reference for the selection of regional sand control ecological engineering types.

Full Text

Effects of Straw Checkerboard-Shrub Forest on Soil Moisture Physical Properties in the Ulan Buh Desert

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Abstract

To investigate the effects of typical ecological projects for desertification combating on soil moisture physical properties and water retention capacity in the Ulan Buh Desert, this study selected straw checkerboard barriers combined with two native tree species (*Haloxylon ammodendron* and *Hedysarum scoparium*) as research objects, with shifting sandy land as the control. Using field sampling and laboratory analysis methods, we analyzed soil particle size composition, moisture content, bulk density, porosity, water holding capacity, and water storage capacity across different soil layers within a 0–100 cm depth. The results demonstrated that establishing ecological projects for desertification combating, primarily using straw checkerboard barriers and native tree species, produced significant improvements in sandy soil moisture physical properties and water retention capacity. (1) The surface soil particle composition showed an overall refinement trend, with decreased soil bulk density, increased soil porosity, and significantly enhanced soil water holding capacity and water storage capacity. (2) Following implementation of typical desertification combating ecological projects in the Ulan Buh Desert, soil formation processes became more evident and water retention capacity improved significantly, indicating effective desertified land management. These findings can provide fundamental data for evaluating the effectiveness of regional desertification combating efforts and offer a scientific basis for selecting appropriate ecological project types for future desertification control initiatives.

Keywords: soil physical properties; sand fixation plantation; ecological project of desertification combating; Ulan Buh Desert

Introduction

Desertification represents a major ecological challenge and one of the most pressing environmental issues globally. According to the results of the Sixth National Desertification and Sandification Survey, by 2014, desertified land and sandified land areas in China reached 257.37 million hectares and 168.78 million hectares, respectively. As a contracting party to the United Nations Convention to Combat Desertification, China has earnestly fulfilled its obligations, making desertification prevention and control a critical national task. China's approaches and models for combating desertification have attracted international attention. Vegetation-based measures (including sand closure for vegetation regeneration and establishment of sand-fixation forests) constitute important strategies for preventing land desertification and represent the most effective and sustainable approaches for promoting vegetation recovery in desertified areas. Previous research has demonstrated that vegetation restoration in desertified lands can increase the content of fine soil particles, refine soil texture, and improve soil structure through root development, thereby increasing soil porosity and enhancing soil moisture regulation capacity and infiltration rates. However, vegetation development also consumes soil moisture, which can lead to reduced soil water content and subsequently affect vegetation growth. Given that water is the primary limiting factor for vegetation reconstruction and restoration in arid regions, investigating soil moisture conditions and water retention characteristics following different restoration measures holds important theoretical significance and practical value for ensuring normal growth and long-term stability of forest and grass vegetation.

The Ulan Buh Desert serves as a major source of dust storms in northern China and constitutes a key construction area for the Beijing-Tianjin sandstorm source control project and a national key ecological function zone. Since the 1990s, afforestation efforts have been implemented in the Ulan Buh Desert, with widespread application and significant success of various sand fixation techniques including aerial seeding, straw checkerboard barrier afforestation, and clay sand barrier afforestation. In recent years, large-scale development and management of desertified land in the northeastern part of the Ulan Buh Desert have intensified, with diversified resource utilization types (photovoltaic power stations, large pastures, agricultural development, etc.) leading to rapid expansion of ecological projects for desertification combating (primarily straw checkerboard barriers combined with windbreak and sand-fixation forests). However, in water-limited environments, ensuring the long-term effectiveness of these ecological projects presents a critical scientific question. Current research on desertification combating ecological projects in the Ulan Buh Desert has primarily focused on windbreak and sand fixation effects, with relatively few studies examining changes in soil moisture content, water retention capacity, and groundwater dynamics following project implementation. Therefore, this study investigated soil moisture physical properties and water retention capacity in typical desertification combating ecological projects (straw checkerboard barriers combined with vegetation measures) in the northeastern Ulan Buh Desert, using adjacent shifting sandy land as a control. The objective was to analyze the impacts of these ecological projects on sandy soil properties and provide theoretical references and data support for future construction and optimized management of regional desertification combating initiatives.

1.1 Study Area Overview

The study area was located in the comprehensive management zone of mobile dunes along a desert-crossing highway (from Dengkou County Industrial Park to the Yellow River flood discharge wetland) in the northeastern Ulan Buh Desert [Figure 1: see original paper]. Following highway construction in 2014, local authorities implemented artificial control measures on mobile dunes along both sides of the road, combining straw checkerboard barriers with psammophytic shrubs and natural vegetation recovery (through grazing prohibition). Both artificial and natural vegetation have recovered substantially, forming relatively stable plant communities with significant sand control effectiveness and minimal sand accumulation on the highway throughout the year. According to meteorological data from the Dengkou County Weather Station, the study area has an average annual precipitation of 140.3 mm, average annual evaporation of 2380.6 mm, mean annual temperature of 7.8 °C, \$ $10°C accumulated temperature of 3289.1°C, annual sunshine hours of 3181h, frost-free period of 146d, and average annual wind speed of 3.7m \cdot s$^{-1}\$. The soil types are primarily aeolian sandy soil, irrigation-silted soil, and saline soil. Natural vegetation mainly consists of drought-resistant and extremely drought-resistant shrubs and annual herbs, including *Nitraria tangutorum*, *Artemisia ordosica*, *Agriophyllum squarrosum*, *Salsola collina*, *Bassia dasyphylla*, *Corispermum mongolicum*, and *Psammochloa villosa*. Artificial vegetation is dominated by *Haloxylon ammodendron*, *Hedysarum scoparium*, and *Calligonum mongolicum*.

1.2.1 Sample Plot Layout

Field investigation and sampling were conducted from May 20–25, 2021. No effective precipitation occurred during the two months preceding the investigation, ensuring that soil moisture content was not influenced by recent rainfall. Three sampling sections with different management intensities were selected along both sides of the highway. Each section included three plot types as sampling sites: shifting sandy land (control), straw checkerboard barrier + *Hedysarum scoparium* shrubland (dominated by *Hedysarum scoparium* with associated species), and straw checkerboard barrier + *Haloxylon ammodendron* shrubland (dominated by *Haloxylon ammodendron* with associated species). Within each site, three 10 m × 10 m plots were established to survey shrub species, quantity, basal diameter, height, and crown width, as well as herbaceous species. Shifting sandy land contained no shrubs, only scattered herbaceous plants, for which 1 m × 1 m plots were established. A total of 27 plots were established across all sites. Basic site conditions are detailed in Table 1 .

1.2.2 Soil Sample Collection

Within each plot, a soil profile was excavated to 100 cm depth. The profile was divided into layers: 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm, totaling five layers per profile. Undisturbed soil samples were collected from each layer using a cutting ring (volume 100 cm^3) to determine soil bulk density, porosity, and water holding capacity. Additionally, approximately 500 g of mixed soil samples were collected from each layer using the quartering method to analyze soil particle size composition and moisture content. Three profiles were excavated per plot, yielding 405 soil samples total.

1.2.3 Soil Sample Measurement

Soil particle size composition was measured using the sieving method (according to Chinese sand particle size classification standards: >1 mm as extremely coarse sand, 1–0.5 mm as coarse sand, 0.5–0.25 mm as medium sand, 0.25–0.1 mm as fine sand, 0.1–0.05 mm as very fine sand, and <0.05 mm as silt and clay). Soil moisture content was determined using the oven-drying method, bulk density using the cutting ring method, and porosity and water holding capacity using the cutting ring immersion method. Based on soil porosity data, soil water storage capacity, including capillary water storage, non-capillary water storage, and saturated water storage, was calculated using the following formulas:

$$W_c = 10 \cdot P_c \cdot H$$

$$W_n = 10 \cdot P_n \cdot H$$

where W_c, W_n, and W represent capillary water storage, non-capillary water storage, and saturated water storage ($\mathrm{t \cdot hm^{-2}}$), respectively; P_c and P_n represent capillary porosity (%) and non-capillary porosity (%), respectively; and H represents soil layer thickness (cm). Data were processed using Excel 2010, one-way ANOVA was performed using SAS 9.0, and figures were prepared and correlations among soil moisture physical properties were analyzed using Origin 19.0.

2.1 Soil Particle Size Composition

As shown in Figure 2 [Figure 2: see original paper], soil particle size composition across different layers in shifting sandy land, *Hedysarum scoparium* shrubland, and *Haloxylon ammodendron* shrubland was dominated by fine sand (50.87%–60.94%), followed by medium sand (29.71%–43.42%). Very fine sand content ranged from 4.21% to 8.71%, while silt and clay content was very low at only 0.21%–2.14% and 0.44%–1.01%, respectively. Significant differences existed in the percentage content of different particle sizes within the same soil layer across plot types (P < 0.05). Shifting sandy land had higher coarse and medium sand content compared to shrublands, with particularly pronounced differences in the 0–40 cm layer. Conversely, shifting sandy land had lower very fine sand, silt, and clay content than both shrubland types. Soil particle composition in shifting sandy land was relatively uniform with good sorting, showing minimal variation between soil layers. In contrast, shrublands exhibited greater variation, with lower coarse sand content in surface layers compared to deeper layers, while very fine sand, silt, and clay showed the opposite pattern. These characteristics indicate that establishing straw checkerboard barriers with native tree species significantly improved sandy soil properties, particularly for surface soil layers.

2.2 Soil Moisture Content

Soil moisture content in all three plot types remained at very low levels, ranging from 0.23% to 1.64% and increasing with soil depth (Figure 3 [Figure 3: see original paper]). Significant differences existed among soil layers (P < 0.05). Shifting sandy land had the lowest surface soil moisture content (0–10 cm) compared to shrublands, but its moisture content in deeper layers (10–80 cm) exceeded that of both *Hedysarum scoparium* and *Haloxylon ammodendron* shrublands, particularly in the 10–80 cm layer where differences were most pronounced. Overall, significant differences in soil moisture content existed among the three plot types (P < 0.05).

2.3 Soil Bulk Density

Soil bulk density varied among plot types but differences were not statistically significant (P > 0.05), ranging from 1.47 to 1.58 $g \cdot cm^{-3}$. Shifting sandy land had lower bulk density than shrublands in the 0–10 cm layer, but nearly equal values in the 10–20 cm layer. In the 20–100 cm depth range, shifting sandy land exhibited higher bulk density than shrublands. Bulk density in shifting sandy land increased with soil depth, whereas shrublands showed an overall decreasing trend with depth.

2.4 Soil Porosity

As shown in Table 2 , capillary porosity (30.51%), non-capillary porosity (9.15%), and total porosity (39.66%) of shifting sandy land were all lower than those of *Hedysarum scoparium* shrubland (37.61%, 9.69%, and 39.04%, respectively) and *Haloxylon ammodendron* shrubland (29.35%, 8.83%, and 28.80%, respectively). Significant differences in soil porosity existed among the three plot types (P < 0.05). *Hedysarum scoparium* shrubland showed variation among soil layers but differences were not significant (P > 0.05), whereas *Haloxylon ammodendron* shrubland exhibited significant differences among layers (P < 0.05). Soil porosity in shifting sandy land was relatively uniform across layers without significant differences ($P > 0.05$). Both shrubland types showed fluctuating patterns without clear trends across soil layers.

2.5 Soil Water Holding Capacity and Water Storage

Shifting sandy land had lower mean saturated water holding capacity (24.16%), capillary water holding capacity (19.35%), and field water holding capacity (15.29%) compared to *Hedysarum scoparium* shrubland (26.48%, 20.69%, and 19.10%) and *Haloxylon ammodendron* shrubland (25.91%, 19.03%, and 19.10%) (Table 3). While saturated and capillary water holding capacities showed no significant differences among plot types ($P > 0.05$), field water holding capacity differed significantly ($P < 0.05$). Shifting sandy land also had lower saturated water storage (225.93 $t \cdot hm^{-2}$), capillary water storage (172.82 $t \cdot hm^{-2}$), and non-capillary water storage (52.81 $t \cdot hm^{-2}$) compared to *Hedysarum scoparium* shrubland (237.98, 183.08, and 54.88 $t \cdot hm^{-2}$) and *Haloxylon ammodendron* shrubland (234.22, 176.08, and 58.14 $t \cdot hm^{-2}$) (Table 4). Water storage capacity in shifting sandy land differed significantly from shrublands ($P < 0.05$) and showed no significant variation among soil layers ($P > 0.05$), whereas shrublands exhibited significant differences among layers, particularly in *Haloxylon ammodendron* shrubland ($P < 0.05$).

3.1.1 Soil Particle Size Composition

Soil physicochemical properties serve as important indicators for desertification monitoring and assessment, with soil particle size composition (changes in fine versus coarse particles) considered one of the most sensitive parameters. Following implementation of desertification combating measures along the desert-crossing highway, significant differences emerged in soil particle size composition among plot types, particularly in surface layers. The content of very fine sand, silt, and clay in the surface layer of shifting sandy land was 4.84%, 2.14%, and 0.21%, respectively, while in sand-fixation forests (*Hedysarum scoparium* and *Haloxylon ammodendron*), these values increased to 8.71%, 1.59%, and 4.43%, respectively, with a corresponding decrease in medium sand content from 43.42% to 29.71%–33.10%. This indicates a clear refinement trend. Although the overall content of very fine sand, silt, and clay remained relatively low, it increased significantly compared to shifting sandy land (Figure 2 [Figure 2: see original paper]). These findings align with previous studies. For instance, Li et al. found that during vegetation restoration along the southern edge of the Taklimakan Desert, fine particle content in sandy soil increased. Tian et al. reported that artificial vegetation restoration in the Shazhuyu area significantly refined soil texture, particularly within the surface 60 cm. Tang et al. studied the effects of typical desertification combating projects in the middle reaches of the Yarlung Zangbo River valley and found that surface soil texture showed significant refinement, with silt and very fine sand content increasing by 2.31–5.56 times compared to shifting sandy land. Research indicates that during vegetation establishment on shifting sandy land, plant growth introduces litter that decomposes into organic matter, while root exudates promote biological processes that facilitate soil particle decomposition. Additionally, once vegetation reaches a certain height, it can intercept dust particles (30%–60% of atmospheric dust is intercepted by plant canopies), increasing fine particle content at the surface and promoting pedogenesis. However, soil formation in sandy land is a long-term process, and human intervention primarily accelerates surface soil environmental changes and recovery processes. Therefore, this study found the most pronounced increases in fine particles in surface layers.

3.1.2 Soil Moisture Content

Soil moisture is the driving force behind vegetation patterns and processes in sandy ecosystems, controlling primary processes such as plant growth and vegetation succession. Conversely, vegetation restoration and reconstruction in sandy land significantly affects soil moisture, enhancing spatial heterogeneity in both horizontal and vertical patterns. In this study, soil moisture content in all plot types was low and increased with soil depth (Figure 3 [Figure 3: see original paper]), consistent with findings from other researchers. For example, soil moisture in the riparian ecotone of the Yarlung Zangbo River showed an increasing trend with depth, with strong spatial correlation in the 0–20 cm layer that weakened with increasing depth. The restoration and reconstruction of artificial vegetation in sandy land significantly affects soil moisture conditions. Li et al. conducted long-term monitoring of soil moisture in sand-fixation vegetation areas at different stages in the Shapotou region and found that soil moisture content began to decrease significantly after 9–10 years of vegetation development. Similar results were observed in this study: after nearly 10 years of vegetation restoration, surface soil moisture (0–20 cm) in sand-fixation forests (0.35% for *Hedysarum scoparium* and 0.64% for *Haloxylon ammodendron*) was higher than in shifting sandy land (0.23%), but overall moisture content remained lower than in shifting sandy land, particularly in the 10–80 cm layer. Shifting sandy land moisture content ranged from 1.45% to 1.64%, while *Hedysarum scoparium* and *Haloxylon ammodendron* shrublands ranged from 0.78% to 1.25% and 1.14% to 1.42%, respectively. This reduction primarily occurs because establishing sand-fixation vegetation consumes soil moisture for plant growth, with water consumption increasing significantly as stand age increases. Additionally, sand-fixation vegetation alters water redistribution, reduces rainfall infiltration, and decreases water recharge to deeper soil layers. As vegetation coverage increases, the water supply capacity per unit dune area decreases significantly. The results show that after 10 years of growth, both shrubland types have lower soil moisture than shifting sandy land, confirming that vegetation growth consumes soil moisture. However, current vegetation status and soil moisture levels indicate that water can temporarily meet vegetation requirements, with evident windbreak and sand fixation effects. Nevertheless, appropriate management practices such as thinning, pruning, or cutting are recommended to reduce excessive water consumption as individual plants grow larger and populations increase, thereby preventing stand degradation.

3.1.3 Soil Bulk Density and Porosity

Soil bulk density is a critical physical indicator reflecting soil compaction. Following establishment of sand-fixation vegetation on shifting sandy land, soil bulk density generally decreased. While bulk density in shifting sandy land increased with depth, sand-fixation forests showed an overall decreasing trend (Figure 3 [Figure 3: see original paper]), consistent with studies from other regions. For example, in the desert-oasis transition zone of the Hexi Corridor, soil bulk density in sand-fixation plant root zones decreased with increasing depth. In the Ordos arsenic sandstone area, establishing *Hippophae rhamnoides* plantations significantly reduced soil bulk density, with this effect increasing with stand age. This may be attributed to higher fine particle content in surface soil of forested areas, combined with greater influence of external factors (wind-blown sand, rainfall, temperature) causing increased soil particle cohesion through wet-dry cycles, resulting in higher surface bulk density compared to shifting sandy land. However, this influence diminishes with depth. Additionally, sand-fixation plant root distribution and growth loosen soil layers, reducing bulk density. Soil pores serve as migration pathways and storage reservoirs for air, water, and nutrients, influencing soil permeability and water storage capacity. Numerous studies have shown that vegetation and soil are mutually influential systems. Establishing artificial vegetation on various soil types (loess, aeolian sandy soil, arsenic sandstone) leads to root development that affects soil structure and increases porosity. Special biological communities in the rhizosphere can also increase soil porosity. Consequently, soil porosity increases significantly after vegetation establishment, enhancing water regulation capacity and infiltration, which benefits soil water storage. This study's results align with previous findings, showing significant differences in soil porosity between sand-fixation forests and shifting sandy land, with capillary porosity, non-capillary porosity, and total porosity all being greater in forested plots (Table 2).

3.2 Effects of Straw Checkerboard-Shrub Forest on Soil Water Holding Performance

Soil water holding performance is a key factor limiting long-term stable vegetation growth and represents an important indicator of water conservation function. Soil water storage capacity reflects vegetation's ability to regulate and conserve water. Saturated water holding capacity represents the maximum water content soil can retain, capillary water holding capacity is the maximum water content held by capillary action, and field water holding capacity (the maximum water content held by capillary suspension) is considered the highest stable soil moisture level and the maximum effective water content. Numerous studies have shown that plant growth and development significantly affect soil texture. As vegetation develops on sandy land, root growth and associated chemical processes alter soil structure (mechanical composition, porosity), promoting formation of soil aggregates, increasing porosity, and directly or indirectly enhancing soil water holding capacity. Consequently, forested lands exhibit higher water holding and storage capacities than bare sandy land. This study obtained similar results, with mean values of saturated water holding capacity, field water holding capacity, capillary water holding capacity, saturated water storage, capillary water storage, and non-capillary water storage in the 0–100 cm layer of sand-fixation forests exceeding those of shifting sandy land (Table 3 and Table 4). The overall water holding capacity of the study area was relatively low, with no clear patterns among soil layers but rather fluctuating states, differing from other studies. This discrepancy may be primarily related to soil texture, forest type, stand age, and differences in root distribution and development of sand-fixation plants.

4 Conclusion

Haloxylon ammodendron and *Hedysarum scoparium* are the two main tree species commonly selected for desertification combating projects in the Ulan Buh Desert. Establishing windbreak and sand-fixation forests (both *Haloxylon ammodendron* and *Hedysarum scoparium* stands) on shifting sandy land significantly affected soil physical properties, creating substantial differences in soil moisture physical properties compared to shifting sandy land. Surface soil particles in forested plots showed refinement trends, with evident soil formation processes. The content of very fine sand and silt/clay in surface layers of forested plots was 8.71% and 4.43%, respectively, significantly higher than the 4.84% and 0.21% in shifting sandy land. Soil bulk density decreased by 3.7%–7.2%, total porosity increased by 3.8%–5.5%, saturated water holding capacity increased by 4.8%–9.6%, and saturated water storage capacity increased by 3.7%–9.6%, indicating significantly improved soil water holding performance and effective desertified land management.

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