Characteristics and Influencing Factors of Soil Macropores in the Rhizosphere of Typical Sand-Fixing Plants in Desert-Oasis Transition Zones: Postprint

Authors: Li Jianan, Zhou Chengqian, Hu Guanglu, Yang Penghua, Li Haochen

Date: 2024-12-16T00:00:00+00:00

Abstract

Soil macropores are the main channels for soil water infiltration. Investigating the characteristics of soil macropores and their influencing factors in the root zones of typical sand-fixing plants in desert-oasis transition zones has important implications for regional ecological vegetation restoration and the selection of sand-fixing plants. Through water penetration experiments, the characteristics of soil macropores in the root zones of typical sand-fixing plants in the desert-oasis transition zone of the middle Heihe River were studied, and the influencing factors of soil macropores as well as the effects of macropores on soil saturated hydraulic conductivity were analyzed. The results showed that: (1) The radius range of soil macropores was 0.5–1.6 mm, which is greater than the minimum aeration pore radius of 0.3 mm. Soil water movement was mainly driven by gravitational water. The soil macropores in the root zones of sand-fixing plants in the transition zone showed a decreasing trend with increasing soil depth, and overall exhibited the characteristic of having many small-radius pores and few large-radius pores. (2) Soil bulk density showed a highly significant negative correlation with all soil macropore characteristic indicators except for the total number of macropores; saturated water content showed a significant positive correlation with all macropore characteristic indicators except for the total number of soil macropores; organic matter content showed a highly significant positive correlation with all soil macropore characteristic indicators. (3) Soil saturated hydraulic conductivity ranged from 2.32 to 3.79 $\mathrm{mm \cdot min^{-1}}$, and the macropore volume ratio, macropore area ratio, the fourth power of macropore mean radius, and the total number of macropores accounted for 82%, 68%, 79%, and 43% of the variation in saturated hydraulic conductivity, respectively. (4) Under the same habitat conditions in the study area, compared with bare land, the planting of sand-fixing plants could significantly enhance the infiltration capacity of soil water; the soil water infiltration capacity in the root zones of sand-fixing plants, from strong to weak, was Haloxylon ammodendron, Calligonum mongolicum, and Nitraria sphaerocarpa.

Full Text

Characteristics and Influencing Factors of Soil Macropores in the Root Zone of Typical Sand-Fixing Plants in the Desert-Oasis Transition Zone

LI Jianan[1], ZHOU Chengqian[2], HU Guanglu[2],[3], YANG Penghua[2], LI Haochen[2]

[1]Gansu Provincial Institute of Soil and Water Conservation Science, Lanzhou 730020, Gansu, China
[2]School of Environment and Municipal Engineering, Lanzhou Jiaotong University, Lanzhou 730070, Gansu, China
[3]Key Laboratory of Yellow River Water Environment in Gansu Province, Lanzhou 730070, Gansu, China

Abstract

Soil macropores are the primary channels for soil water infiltration. Investigating the characteristics of soil macropores in the root zones of typical sand-fixing plants in the desert-oasis transition zone and their influencing factors provides valuable insights for regional ecological vegetation restoration and the selection of appropriate sand-fixing species. Through water penetration experiments, we examined the macropore characteristics in the root zone soils of typical sand-fixing plants in the desert-oasis transition zone of the middle Heihe River basin, analyzed the factors influencing soil macropores, and evaluated their effects on soil saturated hydraulic conductivity. The results revealed that: (1) The radius of soil macropores ranged from 0.5 to 1.6 mm, exceeding the minimum aeration pore radius of 0.3 mm. Soil water movement was primarily driven by gravitational water. Macropore density in the root zone of sand-fixing plants in the transition zone decreased with increasing soil depth, exhibiting a pattern of numerous small-radius pores and fewer large-radius pores. (2) Soil bulk density showed a highly significant negative correlation with all macropore characteristics except total macropore number. Saturated water content exhibited a significant positive correlation with macropore characteristics except total macropore number. Organic matter content demonstrated a highly significant positive correlation with all soil macropore characteristic indicators. (3) Soil saturated hydraulic conductivity ranged from 2.32 to 3.79 $\mathrm{mm \cdot min^{-1}}$. Variation in saturated hydraulic conductivity was determined by macropore volume ratio (82%), macropore area ratio (68%), the fourth power of average macropore radius (79%), and total macropore number (43%). (4) Under identical habitat conditions in the study area, planting sand-fixing plants significantly enhanced soil water infiltration capacity compared to bare land. Among the three sand-fixing plants examined, their root zone soil water infiltration capacities ranked from strongest to weakest as follows: *Haloxylon ammodendron*, *Calligonum mongolicum*, and *Nitraria sphaerocarpa*.

Keywords: desert-oasis transition zone; sand-fixing plants; water penetration curve; soil macropores

Introduction

A unique landscape type exists in the adjacent areas of deserts and oases in northwest China—the desert-oasis transition zone. This zone connects with oases on one side and borders deserts on the other. Vegetation in the transition zone can resist wind erosion and protect the stability of oasis ecosystems, holding significant ecological importance. The desert-oasis transition zone contains many natural or artificial sand-fixing plants, most of which have simple community structures, low coverage, and characteristics of drought resistance and tolerance to wind erosion and sand burial. Soil moisture content is the primary limiting factor for plant growth, influencing the direction and stability of sand-fixing plant community succession. Research has shown that shrub plants in desert areas can converge atmospheric precipitation to the root zone soil through leaves and branches, primarily infiltrating the soil via preferential flow to supply plant roots. The distribution of these preferential flow channels (macropores) also affects the allocation and utilization of soil moisture by shrub plant roots.

Soil macropores are relatively large physical pores in soil that serve as preferential channels for soil water movement, rapidly transporting water to deep soil layers or discharging it into groundwater. Soil macropores are widely present in various soil types, and their formation is influenced by soil texture, biological activity, wetting-drying cycles, freeze-thaw action, and tillage practices, exhibiting distinct regional characteristics. Many scholars have investigated soil macropore characteristics and water infiltration capacity using methods such as water penetration curves, dye tracing, and CT scanning techniques. Sun et al. combined single-ring infiltration with dye tracing experiments to study soil infiltration characteristics of different land use types in desert-oasis areas, finding that different land use patterns significantly affect soil macropore properties and saturated hydraulic conductivity, with soil texture being a key factor influencing soil water infiltration capacity. Huang et al. used water penetration curves to determine soil macropore characteristics in granite hilly areas under different land use types, finding that although soil macropore volume accounted for less than 4.11% of total soil volume, it could affect approximately 68% of the variation in stable outflow rates. Similar conclusions have been drawn from studies in other regions.

Currently, research on soil macropores primarily focuses on areas with relatively abundant precipitation or irrigation, while studies on soil macropore characteristics in arid desert areas are scarce. Particularly, how do soil macropore characteristics manifest in the desert-oasis transition zone? How do soil properties influence macropores? How do macropores affect water infiltration capacity? These questions have rarely been addressed in the literature. Based on this context, this study selected the root zone soils of three typical sand-fixing plants in the desert-oasis transition zone of the middle Heihe River as research objects. Using water penetration curve methods, we determined the quantity and vertical distribution patterns of macropores in the root zones of sand-fixing plants, identified influencing factors on macropore characteristics by combining key soil physicochemical properties, and analyzed the impact of macropores on soil water infiltration capacity. This research aims to provide a theoretical basis for selecting appropriate sand-fixing plants and restoring regional ecological vegetation in the desert-oasis transition zone.

1.1 Study Area Overview

The study area is located in Pingchuan Town, Linze County, Zhangye City, Gansu Province, approximately 2 km north of the Linze Inland River Basin Research Station of the Chinese Academy of Sciences Cold and Arid Regions Environmental and Engineering Research Institute. Situated within the desert-oasis transition zone, the geographical coordinates are 39°21 53 –39°22 01 N, 100°09 12 –100°09 14 E. The region features a typical continental arid monsoon climate, characterized by drought and low rainfall. Precipitation is concentrated between June and September, with an annual average of approximately 117 mm and an annual evaporation of about 2146 mm. The main sand-fixing plants in the study area include *Haloxylon ammodendron*, *Nitraria sphaerocarpa*, *Calligonum mongolicum*, and *Tamarix ramosissima*. Plant communities have relatively simple structures, distributed in patches or strips with coverage between 10% and 30%. The ecological stability of these sand-fixing plants is relatively poor, and they are prone to degradation under wind-sand activity. The soil in the study area is primarily aeolian sandy soil with poor water and nutrient retention capacity, representing the main limiting factor for sand-fixing plant growth and development.

1.2 Sample Plot Setup and Sample Collection

In July 2022, we established a sample plot (400 m × 200 m) in the study area. Within this plot, we selected three sand-fixing plant species with similar growth ages and healthy development: *Haloxylon ammodendron* (artificial, 5 plants), *Calligonum mongolicum* (artificial, 5 plants), and *Nitraria sphaerocarpa* (natural, 5 shrub mounds). Bare land without vegetation was also selected as a control. Basic information on the sand-fixing plants is presented in Table 1. The selected plants and bare land plots were isolated from competition and mutual influence with other plants of the same or different species, ensuring that no same or other species existed within a 2 m radius. This approach allowed for a more accurate representation of soil macropore characteristics.

In the field, we used the ring knife method (ring knife inner diameter D = 5 cm, height H = 5 cm) to collect root zone soil samples at the edge of the plant canopy. For sand-fixing plant root zone soil sampling, three sampling points were established in approximately 120° directions. For bare land, the center of the selected location served as the sampling point. Soil samples were collected at depths of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm. Simultaneously, approximately 200 g of loose soil was collected at about 20–30 cm from the ring knife sampling point using the same stratification method for determining soil particle size and organic matter content. The collected undisturbed ring knife soil samples and loose soil samples were labeled and transported to the laboratory for analysis.

1.3 Measurements

1.3.1 Soil Water Penetration Experiment First, the field-collected ring knife soil samples were soaked in deionized water for 8–12 h to achieve saturation. The saturated ring knife samples were then placed on dry coarse sand for 8–12 h to reach field water-holding capacity. Finally, the ring knife samples were installed in the apparatus shown in Figure 2. Water was supplied to the upper ring knife via a Mariotte bottle, maintaining a water head of 1.5 cm. The time from water injection to the first drop flowing from the lower ring was recorded as the initial outflow time. The electronic balance reading was recorded every 180 s after water began flowing from the lower ring. Since water density is 1.0 $\mathrm{g \cdot cm^{-3}}$, the balance reading (after deducting the beaker weight) represented the water outflow volume. Recording stopped when the outflow rate stabilized.

1.3.2 Soil Macropore Determination Based on water penetration experiment results, we calculated the number and average radius of soil macropores using the method proposed by Radulovich et al. [18], which primarily employs the Poiseuille equation and steady-state flow equation for fluid in pipes. Specific calculation formulas are detailed in the literature [18]. Since the macropore radius range varies with initial outflow time (the time from water injection in the upper ring to the first drop from the lower ring), we standardized the macropore radius classification criteria for each sand-fixing plant root zone. In calculations, we first averaged the measured water outflow rates and initial outflow times for each plant, then calculated macropore radius and quantity using the Radulovich method.

Macropore radius: Assuming a single macropore has area A ($\mathrm{cm^2}$) and water flow velocity v ($\mathrm{cm \cdot s^{-1}}$), the relationship between unit flow rate Q ($\mathrm{cm^3 \cdot s^{-1}}$)

and macropore number n (individual pores) is:

$$Q = nAv$$

Transforming this yields the macropore number:

$$n = \frac{Q}{Av}$$

where Q is outflow during the corresponding time period ($\mathrm{cm}^3 \cdot \mathrm{s}^{-1}$); r is the average macropore radius calculated for the corresponding time period (cm); is water viscosity coefficient ($\mathrm{Pa} \cdot \mathrm{s}$); P is water head pressure (Pa); τ is the tortuosity coefficient of actual water flow paths ($\tau = 1.2$); L is soil column length, i.e., ring knife sample height (L = 5 cm); t is time since water addition began (s); and t_0 is initial outflow time (s).

Macropore radius intervals were divided based on t values. In this study, intervals were divided every 5 s starting from $t_0 + 5$ s. The macropore radius range was divided into 0.1–0.5 mm, 0.5–0.7 mm, 0.7–0.9 mm, 0.9–1.1 mm, and >1.1 mm.

After calculating macropore number n (individual pores) and average radius r (cm) in the ring knife, we computed macropore area ratio and volume ratio:

Macropore area ratio:

$$S = \frac{\sum_{i=1}^{k} n_i \pi r_i^2}{\pi \times 25} \times 100\%$$

Macropore volume ratio:

$$V = \frac{\sum_{i=1}^{k} n_i \pi r_i^2 \times 5}{\pi \times 25 \times 5} \times 100\%$$

where S is macropore area ratio (%); V is macropore volume ratio (%); k is the number of macropore radius divisions (5 total); n is total number of macropores in the i-th class (individual pores); r is average radius of the i-th macropore range (cm); t is outflow time (recorded from when the first drop fell from the lower ring) within 0–5 s, 5–10 s, 10–15 s, etc.; τ is actual water flow path tortuosity coefficient ($\tau = 1.2$); L is ring knife height (L = 5 cm); and 25 is ring knife inner radius squared (cm^2).

1.3.3 Soil Physical and Chemical Property Indicators Soil water content was determined by oven-drying at 105 °C. Soil bulk density, total porosity, and saturated water content were measured using the ring knife method. Saturated hydraulic conductivity was calculated from outflow measured at 150–180 s during water penetration experiments. Soil organic matter was determined by the potassium dichromate external heating method. Soil mechanical composition was measured using a Mastersizer 3000 laser particle size analyzer. Each indicator was measured three times, with averages used as final values.

Soil indicator calculation formulas:

Soil bulk density:

$$\rho_b = \frac{W_2 - W_1}{100}$$

where W_1 is ring knife weight (g); W_2 is oven-dried ring knife soil weight (g); and 100 is ring knife volume (cm^3).

Total porosity:

$$P_t = \left(1 - \frac{\rho_b}{\rho_s}\right) \times 100\%$$

where ρ_b is soil bulk density ($\mathrm{g \cdot cm^{-3}}$) and ρ_s is soil particle density ($\mathrm{g \cdot cm^{-3}}$).

Saturated water content:

$$\theta_s = \frac{W_3 - W_2}{100} \times 100\%$$

where W_3 is ring knife soil saturated water-holding weight (g) and W_2 is oven-dried ring knife soil weight (g).

Saturated hydraulic conductivity:

$$K_s = \frac{V \times 60}{\pi r^2 \times t}$$

where K_s is saturated hydraulic conductivity ($\mathrm{mm \cdot min^{-1}}$); V is outflow during 150–180 s (mL); r is ring knife inner radius (25 mm); and t is time difference between 150–180 s (1 min).

Soil organic matter content:

$$W_O = \frac{(V_0 - V) \times c \times 3.0 \times 1.1 \times 1000 \times 1.724}{m \times k}$$

where W_O is soil organic matter content ($g \cdot kg^{-1}$); V_0 is $FeSO_4 \cdot 7H_2O$ volume consumed in blank titration with 0.2 $mol \cdot L^{-1}$ $K_2Cr_2O_7$ (mL); V is $FeSO_4 \cdot 7H_2O$ volume consumed in soil sample titration (mL); c is 1/4 carbon atom molar concentration of 0.80 $mol \cdot L^{-1}$ $K_2Cr_2O_7$ (0.80 $mol \cdot L^{-1}$); k is air-dried soil to oven-dried soil conversion coefficient; m is air-dried soil mass (g); 1.724 is organic carbon to soil organic matter conversion coefficient; 3.0 is 1/4 carbon atom molar mass ($g \cdot mol^{-1}$); and 1.1 is oxidation correction coefficient.

1.4 Data Analysis

Microsoft Excel 2010 was used for data compilation and processing. IBM SPSS Statistics 26 was employed for significance testing and comparative analysis. Origin 2022 was utilized for graphing and linear fitting.

2.1 Soil Water Penetration Curves in the Root Zone of Sand-Fixing Plants

Water penetration experiments were conducted on collected ring knife soil samples. Based on outflow time and rate (averaged across measurements for each plant), water penetration curves were plotted (Figure 3). The results show that soil water outflow rates for different sand-fixing plants generally exhibited a rapid initial increase, followed by a slower increase until stabilization. Within the 0–50 cm soil layer, maximum macropore radii appeared in the 0–10 cm layer: 1.6 mm for *Haloxylon ammodendron*, 1.5 mm for *Calligonum mongolicum*, and 1.4 mm for *Nitraria sphaerocarpa*. Minimum macropore radii were 0.5 mm, appearing in various quantities across all soil layers. Outflow rates increased rapidly during the initial 0–25 s, with the rate of increase slowing during 25–50 s and essentially stabilizing by 80–100 s. This indicates that early-stage water penetration was primarily influenced by larger macropores, while smaller macropores gradually participated as penetration progressed.

Stable outflow rates showed significant differences due to plant species and soil depth. As shown in Figure 3, stable outflow rates for different sand-fixing plants generally decreased with increasing soil depth, ranging from 0.077 to 0.125 $mL \cdot s^{-1}$. Initial outflow times after water addition until the first drop fell ranged from 7 to 30 s in the 0–10 cm layer, with outflow times increasing with depth in other layers (10–15 s). This demonstrates that sand-fixing plant root zone soils exhibited characteristics of numerous small-radius pores and fewer large-radius pores.

2.2.1 Distribution Characteristics of Soil Macropores by Pore Size

The characteristics and quantities of soil macropores of different radii in the root zones of sand-fixing plants are shown in Table 2. Total macropore numbers in the root zones of the three sand-fixing plants ranged from 2.99$×10^{4}$ to 4.82$×10^{4}$ individuals, specifically: *Haloxylon ammodendron* 3.77$×10$^{\{4\},*Calligonummongolicum*3.56\times10}${4}–4.39×10$^{\{4\},*Nitrariasphaerocarpa*2.99\times10}${4}–4.49×10$^{\{4\},andbarela}$ Using the minimum aeration pore radius of 0.3 mm as a reference, we classified macropores >1.1 mm as “extra-large macropores.” These extra-large macropores accounted for only 7.97% of total macropores, while those in the 0.5–1.1 mm range comprised 92.03%, indicating a predominance of small-radius pores.

Analysis of extra-large macropores showed they primarily occurred in upper soil layers, likely due to greater external influences (wind erosion) on surface soils. Deeper soils were protected by overlying layers and exhibited compaction and smaller pores under gravity. Overall, under the same habitat conditions, all sand-fixing plant root zone soil macropore characteristic indicators decreased with soil depth, ranking from highest to lowest as: *Haloxylon ammodendron*, *Calligonum mongolicum*, *Nitraria sphaerocarpa*, with bare land showing the lowest values.

2.2.2 Soil Macropore Characteristic Indicators

Soil macropore characteristic indicators in the root zones of different sand-fixing plants are presented in Table 3. Average macropore radii ranged from 0.58 to 0.75 mm, specifically: *Haloxylon ammodendron* 0.62–0.75 mm, *Calligonum mongolicum* 0.60–0.73 mm, *Nitraria sphaerocarpa* 0.59–0.72 mm, and bare land 0.58–0.71 mm. Macropore area ratios ranged from 3.19% to 8.56%: *Haloxylon ammodendron* 4.57%–8.56%, *Calligonum mongolicum* 3.67%–8.07%, *Nitraria sphaerocarpa* 3.19%–6.07%, and bare land 3.19%–5.68%. Macropore volume ratios ranged from 0.39% to 0.84%: *Haloxylon ammodendron* 0.57%–0.84%, *Calligonum mongolicum* 0.50%–0.73%, *Nitraria sphaerocarpa* 0.39%–0.59%, and bare land 0.39%–0.50%. Saturated hydraulic conductivity ranged from 2.32 to 3.79 $\mathrm{mm \cdot min^{-1}}$: *Haloxylon ammodendron* 2.86–3.79 $\mathrm{mm \cdot min^{-1}}$, *Calligonum mongolicum* 2.80–3.61 $\mathrm{mm \cdot min^{-1}}$, *Nitraria sphaerocarpa* 2.55–3.43 $\mathrm{mm \cdot min^{-1}}$, and bare land 2.32–3.10 $\mathrm{mm \cdot min^{-1}}$.

Statistical analysis revealed significant differences in soil macropore characteristic indicators among different soil layers for the same plant species ($P < 0.05$). Among different plant species within the same soil layer, all macropore characteristic indicators except average radius showed significant differences ($P < 0.05$).

2.2.3 Correlation Between Soil Macropore Characteristics and Soil Properties

Correlation analysis between soil macropore characteristic indicators and soil physicochemical properties in sand-fixing plant root zones (Table 4) showed that bulk density was highly significantly negatively correlated with average macropore radius, area ratio, and volume ratio ($P < 0.01$), but not significantly correlated with total macropore number. This indicates that denser soil structure corresponds to fewer macropores and smaller proportions, and vice versa. Total porosity was highly significantly positively correlated with average macropore radius and area ratio ($P < 0.01$). Saturated water content was highly significantly positively correlated with average macropore radius and area ratio ($P < 0.01$), and significantly positively correlated with volume ratio ($P < 0.05$). Organic matter content was highly significantly positively correlated with all soil macropore characteristic indicators ($P < 0.01$), demonstrating that organic matter promotes macropore formation. Different soil particle size fractions showed no significant correlation with macropore characteristics. Overall, after sand-fixing plant establishment, root zone soil organic matter content increased, leading to more macropores, larger average radii, and enhanced water infiltration capacity, which promotes sand-fixing plant survival, growth, and maintenance of regional ecological stability.

2.3 Influence of Soil Macropore Characteristics on Saturated Hydraulic Conductivity

Linear fitting between soil macropore characteristic indicators and saturated hydraulic conductivity in sand-fixing plant root zones (Figure 4) revealed that macropore volume ratio, area ratio, the fourth power of average radius, and total macropore number were all significantly positively correlated with saturated hydraulic conductivity ($P < 0.05$). The linear fitting equations followed the form $y = ax + b$, with R^2 values of 0.82, 0.68, 0.79, and 0.43, respectively. This indicates that macropore volume ratio determined 82% of saturated hydraulic conductivity variation, area ratio determined 68%, the fourth power of average radius determined 79%, and total macropore number determined 43%. These results demonstrate that soil macropores significantly affect soil water movement: more numerous macropores with larger area and volume ratios correspond to greater saturated hydraulic conductivity and stronger water infiltration capacity.

Discussion

Outflow rates for different sand-fixing plant root zone soils in the study area all showed rapid initial increase, followed by decreasing growth rate, then stabilization. This pattern aligns with findings from Shi et al. and Tian et al. in other regions but differs from Wang et al.'s research on successive *Eucalyptus* plantations, which showed uniform initial increase then stabilization—likely due to different soil properties. In this study, stable outflow rates also decreased with soil depth. Although all three sand-fixing plants had higher stable outflow rates than bare land, significant differences existed among the three species, possibly related to differences in plant type, root distribution characteristics, and soil organic matter content. The maximum average macropore radius appeared in the 0–10 cm layer, consistent with Jin's findings. The average macropore radius range of 0.58–0.75 mm exceeds the 0.3 mm minimum radius for free gravitational water movement, indicating that soil water movement in the study area is primarily gravity-driven. With increasing soil depth, all macropore characteristic indicators for the three sand-fixing plants and bare land generally decreased, consistent with results from Zhang and Ao, suggesting that water infiltration capacity weakens layer by layer with depth in the study area.

Soil macropore characteristic indicators are important for characterizing macropore quantity and distribution, reflecting soil water infiltration capacity. In the study area, macropore numbers in sand-fixing plant root zones decreased with soil depth, with macropores primarily in the 0.5–1.1 mm range. Extra-large macropores >1.1 mm accounted for only 7.97% of the total, while 0.5–1.1 mm macropores comprised 92.03%, showing a pattern of numerous small pores and few large pores. Soil properties, planting density, and root quantity all influence macropore distribution characteristics and thus affect soil water infiltration capacity. Saturated hydraulic conductivity, bulk density, and porosity reflect soil compaction degree—higher compaction corresponds to lower porosity and poorer water permeability. In this study, saturated hydraulic conductivity ranged from 2.32 to 3.79 $\mathrm{mm \cdot min^{-1}}$, and the overall ranking from highest to lowest was *Haloxylon ammodendron*, *Calligonum mongolicum*, *Nitraria sphaerocarpa*, with all three exceeding bare land values. This matches Gong et al.'s findings in the same region, demonstrating that sand-fixing plant establishment significantly enhances soil water infiltration capacity and that different species produce different root zone pore characteristics and saturated hydraulic conductivity values.

Table 4 shows that higher bulk density and lower total porosity correspond to fewer macropores and poorer water infiltration capacity. Research indicates that soil texture significantly affects infiltration capacity, with higher sand content promoting stronger infiltration. In this study, although soil texture differences among the three sand-fixing plants and bare land were minimal, saturated hydraulic conductivity differences were substantial, indicating that in areas with similar soil texture, saturated hydraulic conductivity is also influenced by soil organic matter, particle arrangement, and root distribution. Li and Fan found that higher soil organic matter content enhances water infiltration capacity. Wang et al. studied macropore formation in agricultural soils in Beijing's Changping District, finding that increased organic matter content raises macroporosity and water infiltration capacity. Tian et al. and Zhang et al. also demonstrated that soil organic matter can increase saturated hydraulic conductivity. In this study, soil organic matter content was significantly positively correlated with saturated hydraulic conductivity, indicating that increased organic matter promotes macropore formation and stronger water infiltration capacity. Overall, under similar soil texture conditions in the study area, sand-fixing plant establishment increased root zone soil organic matter, enhanced soil aggregation, facilitated formation of larger aggregates, increased soil porosity, and thereby improved water infiltration capacity.

Zhao et al. showed that afforestation improves soil pore structure and nutrient content, with longer-established plantations developing more extensive root systems, greater total pore numbers, more complex pore structures, and higher organic matter content. Other researchers have noted that vegetation coverage relates to planting density—higher density increases coverage, which enriches root systems, creates more macropores, and enhances hydraulic conductivity. Shi et al. found that macropores formed by plant roots significantly increase soil water conductivity, representing the essence of root-enhanced infiltration. Therefore, subsequent research on soil macropores in sand-fixing plant root zones in desert-oasis transition zones should incorporate factors such as root systems and vegetation coverage to clarify their impacts on macropore formation and water infiltration capacity, helping to elucidate macropore formation characteristics and their relationship with soil water-holding capacity.

Under identical habitat conditions in the study area, saturated hydraulic conductivity in the root zones of the three sand-fixing plants was positively correlated with macropore volume ratio, area ratio, the fourth power of average radius, and total macropore number. According to the Poiseuille equation and steady-state flow equation, saturated hydraulic conductivity is proportional to the fourth power of pipe radius. Consistent with this, the fourth power of average macropore radius in sand-fixing plant root zones determined 79% of saturated hydraulic conductivity variation, while total macropore number determined only 43%. These results align with findings from Wang et al. and Sun et al. Soils with more macropores enable deeper soil layers to receive more water during rainy seasons, promoting plant growth while effectively reducing rainfall runoff erosion and soil loss risk.

Conclusions

This study examined typical sand-fixing plants (*Haloxylon ammodendron*, *Calligonum mongolicum*, and *Nitraria sphaerocarpa*) in the desert-oasis transition zone of northern Linze County, Gansu Province. Through field ring knife sampling, laboratory water penetration experiments, and data analysis, we compared and analyzed soil macropore characteristics, saturated hydraulic conductivity, and influencing factors under identical habitat conditions, reaching the following main conclusions:

1. **Macropore radius in sand-fixing plant root zones ranged from 0.5**

to 1.6 mm. Extra-large macropores >1.1 mm accounted for only 7.97% of the total, while 0.5–1.1 mm macropores comprised 92.03%, showing a pattern of numerous small-radius pores and few large-radius pores. All soil macropore characteristic indicators in both bare land and the three sand-fixing plant root zones decreased with increasing soil depth.

2. **Soil macropore characteristics were related to soil properties.** Bulk density was highly significantly negatively correlated with all macropore indicators except total number. Saturated water content was significantly positively correlated with all macropore indicators except total number. Organic matter content was highly significantly positively correlated with all soil macropore characteristic indicators.

3. **Saturated hydraulic conductivity in sand-fixing plant root zones ranged from 2.32 to 3.79 mm · min^{-1}**, significantly higher than bare land (2.32–3.10 mm · min^{-1}), indicating that sand-fixing plants substantially improve root zone water conductivity. Variation in saturated hydraulic conductivity was determined by macropore volume ratio (82%), area ratio (68%), the fourth power of average radius (79%), and total macropore number (43%). Macropore volume ratio and the fourth power of average radius were key factors enhancing soil water infiltration capacity.

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