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Enhanced fine soil aggregation and organic matter accumulation facilitated by *Salix Psammophila* sand barriers along desert highways

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Desert ecosystems are inherently nutrient-limited and highly susceptible to disturbances. In such arid environments, sand barriers play a pivotal role in ecological restoration efforts. Despite their importance, the long-term effects of *Salix Psammophila* sand barriers on soil particle size distribution and organic matter content in the Hobq Desert, China, have received limited empirical investigation. To this end, the present study was conducted to investigate sand dunes along the Hobq Desert Sand Penetration Highway, where sand barriers had been established for 1, 3, and 5 years. Specifically, soil particle size distribution was analyzed using multifractal theory to assess spatiotemporal variations associated with varying durations of sand barriers installation. The following observations should be noted: I. Significant differences were identified in soil particle size distribution between dunes with varying sand barrier ages and mobile dunes within the study area. As the duration of sand barriers presence increased, the proportions of clay (3.45%), silt (5.46%), and very fine sand (7.35%) increased correspondingly, whereas the fractions of medium and coarse sand decreased. II. Multifractal spectral analysis of soil particle size distribution enabled the precise quantification of soil texture heterogeneity. Over time following the installation of sand barriers, soil particle size distribution exhibited enhanced heterogeneity, evidenced by an expanded spectrum and increased fine-grained material content. III. Soil organic matter content increased substantially with the duration of sand barriers establishment. Notable spatial variations in organic matter content were detected across different dune slopes, following the trend: bottom slope (0.85 kg/kg) > middle slope (0.77 kg/kg) > top slope (0.62 kg/kg). Moreover, soil particle size distribution exhibited a strong correlation with soil organic matter content, suggesting the essential role of clay, silt, and very fine sand in organic matter stabilization. Collectively, the installation of *Salix Psammophila* sand barriers significantly enhances the accumulation of fine soil fractions (clay, silt, and extremely fine sand), thereby facilitating the sequestration of soil organic matter. This process improves soil physicochemical properties, fosters vegetation establishment, and ensures the long-term stabilization of aeolian landforms along desert highways.

KEYWORDS

soil particle sizes distribution, Hobq desert environment, multifractal theory, *Salix Psammophila* sand barriers, soil organic matter

1 Introduction

The Hobq Desert, recognized as the seventh largest desert in China, has increasingly been impacted by desertification, likely attributed to the early onset of climate change and unsustainable human activities (Du et al., 2014). Consequently, the application of scientific methodologies to address land desertification constitutes a systematic and significant undertaking. Addressing this challenge necessitates systematic scientific interventions, and among these, sand barriers have emerged as a prominent strategy for aeolian sand control (Bouallala et al., 2023). These barriers modify surface topography to regulate sand flow dynamics, altering direction, velocity, and deposition patterns, thereby achieving windbreak and stabilization. *Salix Psammophila*, a dominant xerophytic shrub endemic to the Hobq Desert (Han et al., 2021), exhibits exceptional ecological adaptability to extreme conditions. In comparison with other species, it demonstrates superior resistance to wind erosion and tolerance to burial. Its local availability and low cost further facilitate its extensive use as an effective material for sand barriers in this region (Wang et al., 2020; Morigen et al., 2011; Yan and Yan, 2022).

In contemporary research, a diverse array of indicators can be utilized to evaluate the overall environmental quality of soil (Guryanov, 2004). An analysis was hereby conducted from the perspective of the size characteristics of soil particles (Wang et al., 2023). The particle size, as a stable natural characteristic of soil, plays a pivotal role in various stages of geological processes. It holds considerable significance in assessing the erodibility of soils, mapping changes in aeolian environments (Lin et al., 2022), determining the intensity of wind erosion (Abell et al., 2020), and evaluating the extent of land desertification (Yan et al., 2018). Furthermore, particle size represents an indirect indicator of historical changes in soil within complex environments and can also reflect the current state of soil erosion (Hu and Yang, 2017). The characteristics of soil particle size distribution pertain to the relative proportions of soil particles exhibiting varying degrees of coarseness and fineness present within the soil. This distribution is intricately linked to the characteristics of soil porosity, moisture retention, and multiple other factors. Consequently, it serves as one of the fundamental parameters for comprehending the physical properties associated with soil classification (Su et al., 2018; Hu et al., 2011).

Soil organic matter (SOM) is a collective term referring to all organic substances present in soil. This includes the remains of animals and plants, microorganisms, and the organic compounds resulting from their decomposition and synthesis. As a vital constituent of soil, SOM profoundly impacts its physical, chemical, and biological properties (Wang et al., 2005). There exists a significant correlation between the characteristics of soil particle sizes and the presence of soil organic matter (Xie et al., 2021). With the emergence of fractal theory, researchers began to use fractal theory to quantitatively analyze the distribution characteristics of soil particle sizes (Arya and Paris, 1981). This theoretical framework was employed to characterize the microstructure of soil, as well as to analyze both the overall and average particle sizes along with their distribution (Tyler and Wheatcraft, 1992; Millán et al., 2003). However, the distribution of soil particle size characteristics is non-uniform; rather, it exhibits notable scale-free and self-similar properties (Li et al., 2014; Pan et al., 2021). A singular fractal theory possesses inherent limitations and is inadequate for effectively characterizing the local variations and distinctive features of soil structure (Meng et al., 204). The advent of multifractal theory has shown that this approach offers a more refined characterization of local soil structure variability. Moreover, the multifractal spectral function effectively captures both the variability degree and the inhomogeneity extent within the fractal structure (Xu et al., 2013; Li et al., 2012). Therefore, the utilization of this innovative method facilitates a more comprehensive investigation into the influence of soil microstructure on soil nutrient dynamics. Consequently, it establishes an innovative framework for future research endeavors.

Salix Psammophila sand barriers located within the Hobq Desert were hereby categorized based on laying ages of 1, 3, and 5 years, respectively. The aim of this study was to assess the impact of these varying ages on soil properties. The Specific objectives of this research included: I. to elucidate and quantify the differences in topsoil properties across different ages; II. to analyze the patterns of change in grain size parameters and grain size frequency distributions across various ages; and III. to identify fractal parameters that reflect trends in soil property changes over time, with potential applications as indicators of soil texture.

2 Materials and methods

2.1 Study area field investigation

The experimental area is located at the southeastern edge of the Hobq Desert (106°55′16″–109°16′02″E, 39°22′33″–40°52′14″N), within the jurisdiction of Hangjin Banner in Ordos City (Figure 1). This region experiences a temperate semi-arid continental monsoon climate, characterized by an average annual precipitation of 186 mm and a mean potential evapotranspiration rate of 2,498.7 mm per year. The recorded extreme maximum temperature reaches 38.1°C, while the extreme minimum temperature drops to −30.5°C. The estimated average annual temperature is approximately 6.3°C. The total annual duration of sunshine amounts to 32,115 h. The average annual wind speed is measured at 3.2 m/s, with predominant wind directions originating from the south and southeast. The soil in this area is classified as wind-sand soil, featuring a loose surface layer with limited development and deficient nutrient content. The study area is predominantly characterized by mobile sand dunes with slopes ranging from 10° to 12°. (Data are based on historicalreanalysis datasets from the European Centre for Medium-Range Weather Forecasts (ECMWF)/National Aeronautics and space Administration (NASA), provided by www.xihe-energy.com). The primary morphological types observed in this region include lattice dunes and composite dunes. Notable dune vegetation comprises *Salix Psammophila*, *Artemisia ordosica*, *Agriophyllum squarrosum*, *Corispermum hyssopifolium*, and *Achnatherum splendens*. In order to safeguard the sand-penetrating highway against the detrimental impacts of quicksand and guarantee smooth traffic flow, semi-concealed square lattice barriers constructed from *Salix Psammophila* have been installed on both sides of the highway. These barriers serve to stabilize wind and sand flow dynamics.

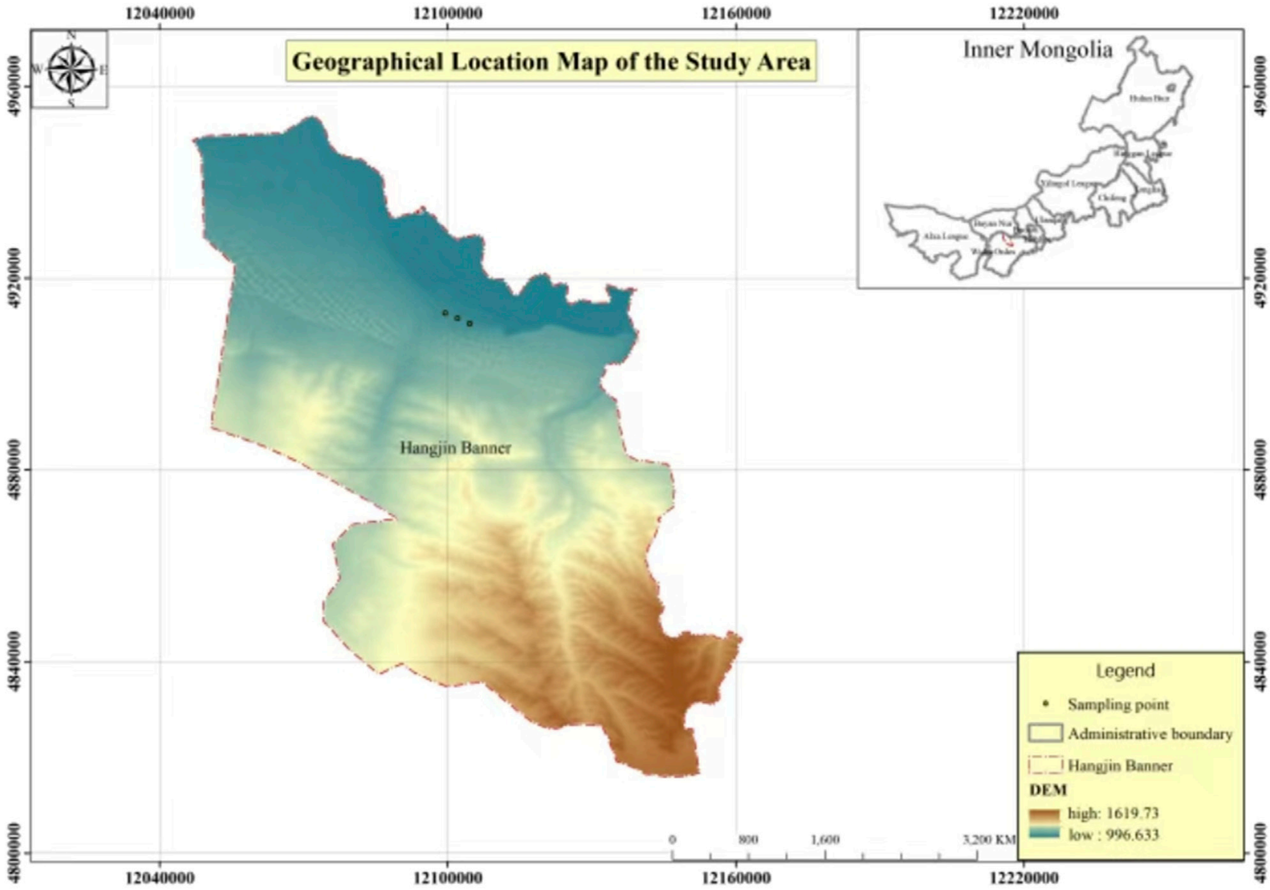

FIGURE 1
Geographical location map of the study area.

2.2 Sampling collection

Considering the impact of slope, experimental dunes featuring *Salix Psammophila* sand barriers of varying ages were hereby selected. These dunes exhibited relatively consistent properties, including dune height and orientation within the study area, and flatter sites were specifically chosen for observation. The *Salix Psammophila* sand barriers consisted entirely of dead branches arranged in a semi-concealed manner, with each barrier measuring 1 m × 1 m. Barriers on dunes aged 1, 3, and 5 years respectively were selected as research factors, while flowing dunes without sand barriers served as controls. Based on previous findings indicating that the windward slope of the dunes was primarily responsible for soil loss—and that different parts of this slope experienced varying degrees of loss along with distinct sorting effects (Zhang, 2022), the present experiments were conducted at different locations along the windward slope. In May 2021, soil samples were collected from the near-surface layer (0–30 cm) at three distinct positions (the bottom, middle, and top) of the sand barriers representing three different ages. A five-point sampling method was employed for this collection. Specifically, soil samples were taken from the four corners and the central point of each block unit. These individual samples were then combined to form a single representative sample, which accurately mirrored the comprehensive soil characteristics of that particular unit. Three barriers constituted a group of replicates for each type based on barrier age, and samples were repeated three times per group. Subsequently, all collected soil samples were packed into ziplock bags and transported back to the laboratory. Ultimately, a total of 108 soil samples were collected for analysis. The samples were air-dried at room temperature prior to pre-treatment, which involved the use of a 2 mm soil sieve to eliminate surface debris.

2.3 Analysis of soil properties

The soil was processed to remove roots, apoptotic material, and impurities. It was then passed using a 2 mm sieve, followed by the addition of hydrogen peroxide (H_2O_2) at a volume fraction of 30% to remove organic matter present in the soil. Subsequently, a hydrochloric acid (HCl) solution with a volume fraction of 10% was introduced and boiled to extract carbonate constituents from the soil. Following that, a diluted ionized water solution was added and allowed to stand undisturbed for a duration of 12 h. Upon these procedures, the clear upper layer of the solution was carefully removed. This dilution process was repeated until a pH level between 6.5 and 7.0 was achieved (Zhang et al., 2017). The particle size distribution of the soil was evaluated using a laser particle size analyzer (Analysette 22 Nano Tec). In this study, soil particles were classified into the following seven size categories based on American grading standards (USDA Soil Classification System): clay (<0.002 mm), silt (0.002–0.005 mm), very fine sand (0.005–0.01 mm), fine sand (0.01–0.25 mm), medium sand (0.25–0.5 mm), coarse sand (0.5–1.0 mm), and very coarse sand (1.0–2.0 mm). Furthermore, to determine the organic matter content in soil particles larger than 2 mm, the soil samples were first sieved through a 2 mm mesh sieve. Subsequently, the standard potassium dichromate external heating method was employed for quantification. Similarly, when assessing the organic matter content of soil particles with a size exceeding 2 mm, after passing them through a 2 mm sieve, the conventional potassium dichromate external heating method was used for its quantification (Wu and Chen, 2016).

2.4 Calculation of particle size parameters

Building upon the Udden-Wentworth scale grain size criterion, Φ the value was derived utilizing the logarithmic transformation method established by Krumbein (1934), as shown in Equation 1

$$\phi = -Log_2 D \tag{1}$$

where, D denotes the fractal dimension.

Ward and Folk (1957) established the cumulative percentage of frequency distribution curves based on the logarithmic values of granularity corresponding to 5%, 10%, 16%, 25%, 50%, 75%, 84%, and 95%, respectively: Φ_5, Φ_{16}, Φ_{25}, Φ_{50}, Φ_{75}, Φ_{84}, and Φ_{95}. Accordingly, the particle size characteristic parameters were calculated as shown in Equations 2–5:

MEAN (d_0) refers to a parameter that indicates the average condition of characteristics of soil particle sizes, determined using the following formula:

$$d_0 = \frac{1}{3}\left(\Phi_{16} + \Phi_{50} + \Phi_{84}\right) \tag{2}$$

2.5 Refinement of soil fractal dimension (D) and multi-fractal parameters calculation

Using characteristics of soil particle sizes volume data for multiple fractal dimensions, multiple fractal parameters calculated before the construction of the partition function, the laser particle size measurement interval in accordance with the form of logarithmic isotropic incremental division of 64 intervals, the interval size of $\varepsilon = 5 \times 2^{-k}$ (K is an integer in the range $1-6$), $u \ (\varepsilon)$ is the probability density of the distribution of characteristics of soil particle sizes in each sub-interval. The group of partition functions was obtained as follows (Hentschel and Procaccia, 1983; Posadas et al., 2001):

$$\mathrm{u_i}(\mathrm{q}, \varepsilon) = \frac{\mathrm{u_i}(\varepsilon)^{\mathrm{q}}}{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{u_i}(\varepsilon)^{\mathrm{q}}} \tag{3}$$

The multifractal singularity function was calculated by the following equation (Yang et al., 2021; Dong and Zheng, 2010):

$$\alpha(q) = \lim_{\varepsilon \to 0} \frac{\sum_{i=1}^{N(\varepsilon)} u_i(q,\varepsilon) lg\, p_i(\varepsilon)}{lg\, \varepsilon} \tag{4}$$

The corresponding multifractal spectral function was calculated as follows:

$$f(\alpha(q)) = \lim_{\varepsilon \to 0} \frac{\sum_{i=1}^{N(\varepsilon)} u_i(q,\varepsilon) lg\, u_i(q,\varepsilon)}{lg(\varepsilon)} \tag{5}$$

where, q is a real number and ui (q, ε) is the qth order probability of the interval of the i-th.

2.6 Statistical analyses

The obtained soil data were calculated and organized using Excel 2021. Graphical processing was conducted using MATLAB R2018a software. A one-way ANOVA was performed on the characteristics of soil particle size parameters and soil organic matter (SOM) content using SPSS version 27.0. Additionally, Pearson correlation analysis was used to examine the relationships among multiple fractal parameters of particle size and indicators of SOM. For graphing purposes, Origin 2021 software was utilized.

3 Results

3.1 Particle size distribution of the sand dunes of different laying years

As shown in Table 1, there existed a significant difference in the composition of soil particle sizes between sand dunes and mobile dunes, particularly when considering the varying years of sand barriers installation within the study area. The soil particle composition on mobile dunes was predominantly characterized by sand and silt particles, with fine sand content ranging from 60.38% to 60.93%. The medium sand content varied between 36.62% and 37.91%, while coarse sand content remains relatively low. Both clay and silt contents were extremely minimal, approaching zero. The grain size distribution of soils from dunes with varying durations of sand barrier installation primarily consisted of fine and medium sands. Specifically, fine sand constituted between 30.87% and 67.26%; very fine sand ranged from 20.69% to 37.83%; medium sand fluctuated between 0.16% and 19.09%; coarse sand spanned from 0.16% to 1.98%; and very coarse sand accounted for approximately 1.10%–1.85%. Notably, an increasing trend in clay and silt content was observed with increasing number of years since the installation of the sandy barriers.

Analysis of grain size composition across various dunes revealed that, in comparison to mobile dunes, the content of clay, silt, and very fine sand in dunes formed over different years of sand barriers deposition increased significantly. Conversely, a notable decrease was observed in the content of medium sand and coarse sand. Furthermore, an examination of different positions on the dune revealed variations in soil particle content across different slopes during the same formation period of the sand barriers. Specifically, for particles such as clay, silt, and very fine sand during this uniform

TABLE 1 Particle sizes Distribution on different slopes under different paving years.

Years of setting (a)	Different slope positions	Characteristics of soil particle sizes classification (%)						
		Clay <2 μm	Silt 2–50 μm	Very fine sand 50–100 μm	Fine sand 100–250 μm	Medium sand 250–500 μm	Coarse sand 500–1000 μm	Very coarse sand 1000–2000 μm
CK	C	0	0.03 ± 0.01b	0	60.93 ± 2.34b	37.49 ± 3.05b	0.42 ± 1.04b	1.13 ± 0.04c
	M	0	0	0	60.43 ± 1.62a	37.91 ± 3.14a	0.2 ± 3.02c	1.24 ± 0.06b
	B	0.65 ± 0.13b	0	0.10 ± 0.03b	60.38 ± 1.75c	36.62 ± 1.17c	0.52 ± 1.03a	1.73 ± 0.03a
1a	C	0.23 ± 0.04a	0.54 ± 0.04c	0.51 ± 0.05c	62.44 ± 0.34c	32.49 ± 1.73b	1.98 ± 0.63a	1.81 ± 0.43a
	M	0.07 ± 0.01c	0.91 ± 0.02b	0.54 ± 0.02b	67.26 ± 0.62a	29.96 ± 0.52a	0.16 ± 0.09c	1.1 ± 0.24c
	B	0.15 ± 0.06b	1.09 ± 0.03a	0.71 ± 0.01a	63.29 ± 0.75b	32.82 ± 1.06	0.56 ± 0.19b	1.38 ± 0.28b
3a	C	1.71 ± 0.05a	3.24 ± 0.09c	5.62 ± 0.05a	59.15 ± 0.78a	27.14 ± 0.43	1.59 ± 0.24b	1.55 ± 0.46b
	M	1.52 ± 0.08b	3.81 ± 0.11a	5.57 ± 0.04b	57.13 ± 0.09b	29.98 ± 0.45	0.86 ± 0.02c	1.13 ± 0.25c
	B	1.48 ± 0.07c	3.73 ± 0.02b	5.43 ± 0.42c	46.46 ± 1.13c	37.83 ± 0.25	3.32 ± 0.42a	1.75 ± 0.24a
5a	C	3.34 ± 0.04c	5.34 ± 0.03c	7.19 ± 0.01c	58.69 ± 0.30b	22.49 ± 0.47	1.1 ± 0.03a	1.85 ± 0.04a
	M	3.46 ± 0.06b	5.42 ± 0.07b	7.33 ± 0.07b	61.05 ± 0.59a	20.69 ± 0.65	0.92 ± 0.21b	1.13 ± 0.13c
	B	3.55 ± 0.07a	5.62 ± 0.03a	7.53 ± 0.05a	57.48 ± 0.63c	23.89 ± 0.73	0.71 ± 0.04c	1.22 ± 0.12b

Note: Different lowercase letters indicate significant differences in characteristics of soil particle sizes composition under different slope positions in the same year ($p < 0.05$). B, base of slope; C, crest of slope; M, mid of slope.

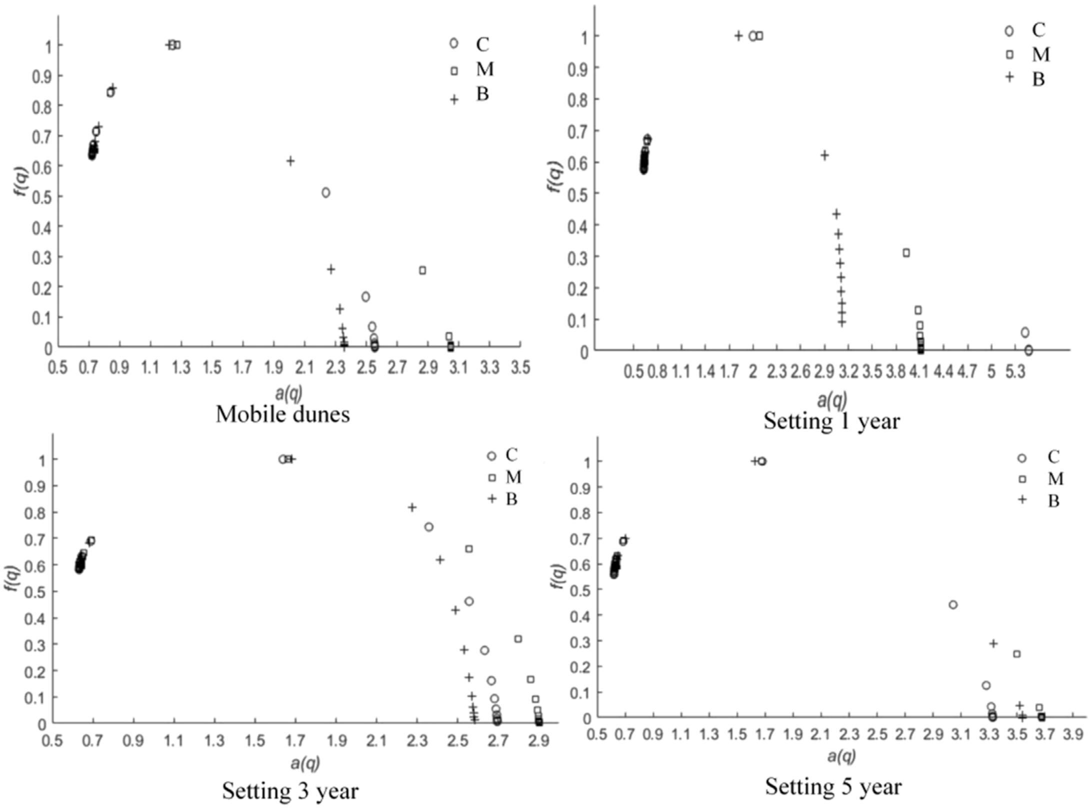

FIGURE 2
Multiple fractal spectral function of characteristics of soil particle sizes distribution. Note: B, base of slope; C, crest of slope; M, mid of slope; ∂ (q), multifractal singularity index; and f (q), multifractal spectrum function.

laying period, a pattern emerged: bottom slope > middle slope > top slope. Conversely, for medium and coarse sands within the same timeframe, the distribution followed a different trend: top slope > middle slope > bottom slope.

3.2 Multiple fractal characteristics of dune soil particles at different years of sand barriers placement

The relationship between α~f (α) for different slopes of mobile dunes, as well as sand barriers laid for 1 year, 3 years, and 5 years, is illustrated in Figure 2. As shown in Figure 2, the multifractal spectral functions for both the mobile dune and the dunes with different installation durations of sand barriers displayed asymmetric arch-shaped curves. Additionally, there was a local superposition of soil particle content, indicating that as the time since the sand barriers were installed increased, external disturbing forces had caused non-uniform alterations in the distribution characteristics of soil particle sizes. The shape features Δf were consistently exceeding zero. Thus, the graphs displayed a leftward bias, and all demonstrated a left-hooked appearance. This suggested that a large probability subset predominated within these distributions. For the mobile dune and sand barriers laid for 5 years, Δα was wider at the slope base yet narrower at its apex. In contrast, for those laid for only 1 year, it was wider at the bottom of the dune slope yet narrowed towards its top. Meanwhile, for barriers installed over a period of 3 years, Δα exhibits a broader range at mid-slope while being narrower at both ends. Δα represents an indicator of non-uniformity within soil particle-size distribution. Specifically, a wider Δα signifies more pronounced changes in dune particle size and indicates overall enhanced heterogeneity within particle size distribution.

3.3 Characteristics of SOM distribution in different sand barriers laying years

The distribution of organic matter at the top, middle, and bottom of the slopes of sand dunes and mobile dunes with varying years of sand barriers are illustrated in Figure 3. Obviously, the average soil organic matter (SOM) content for mobile dunes, as well as for sand barriers established for 1 year, 3 years, and 5 years, were 0.29 g/kg, 0.55 g/kg, 0.75 g/kg, and 0.78 g/kg, respectively. Notably, with an increase in the duration of barrier establishment, there was a significant upward trend in SOM content. The differences in SOM content between mobile dunes and sand barriers established for different durations (1 year, 3 years, and 5 years) were statistically significant ($P < 0.05$). However, no significant difference was observed between the SOM contents of sand barriers laid down for 3 years *versus* those laid down for 5 years. Furthermore, analysis revealed that within different slope positions on dunes with varying durations of barrier establishment, the SOM content tended to accumulate at the bottom slope position, specifically: bottom slope > middle slope > top slope.

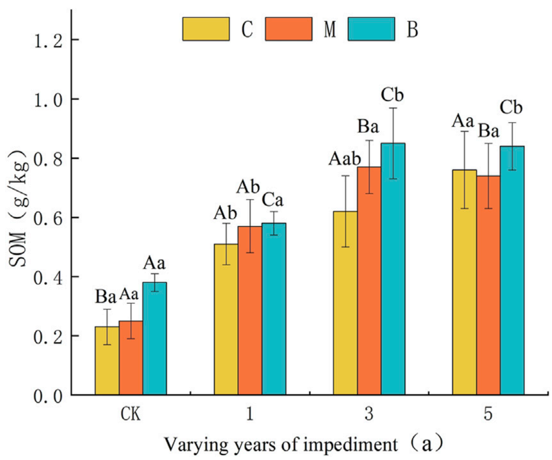

FIGURE 3
Distribution of SOM contents on different slopes of sand dunes with different years of barricading. Note: Different lowercase letters indicate significant differences in characteristics of soil particle sizes composition under different slope positions in the same year ($P < 0.05$). B, base of slope; C, crest of slope; and M, mid of slope.

3.4 Correlation between characteristics of soil particle sizes composition and SOM content

As shown in Figure 4, the correlation between soil grain size composition and the SOM content varied significantly across different years after the establishment of sand sand willow barriers. The correlation coefficient between SOM and clay was determined to be 0.74, while the coefficients for fine sand and very fine sand were 0.86 and 0.84, respectively. These values indicated a strong positive correlation in all cases. Conversely, the correlation coefficient between SOM and coarse sand was −0.87, whereas that between SOM and medium sand was −0.75, both reflecting a significant negative correlation. These findings suggested that the enhanced accumulation of fine-grained materials within sand dunes was correlated with elevated levels of SOM content. Moreover, the clay and silt fractions in sand dunes could be concluded as key grain sizes impacting organic matter accumulation.

4 Discussion

4.1 Mechanisms of the effect of *Salix Psammophila* sand barriers on characteristics of soil particle sizes composition

The study area is situated on the southeastern edge of the Kubuqi Desert, flanking both sides of a sand-penetrating highway in an ecologically fragile and sensitive region characterized by delicate soil structure and overall poor soil nutrients (Gao et al., 2006). As indicated by the present findings, following 3–5 years of establishing sand barriers, the contents of fine sand, clay, and silt particles within these barriers increased significantly compared to those in mobile dunes. Conversely, the contents of medium sand and coarse sand decreased slightly. This change could be primarily attributed to the implementation of *Salix Psammophila* sand barriers, which altered subsurface characteristics and increased ground surface roughness. As a result, wind-sand flow dynamics as well as surface erosion and accumulation processes were correspondingly affected. The result was an effective reduction in wind speed and intensity of sand transport while simultaneously mitigating nutrient depletion in near-surface layers. Overall, these interventions significantly decreased near-surface wind speeds while reducing the intensity of sand transport. They also slowed down the movement frequency of sand particles within the barriers, stabilized quicksand surfaces, and preserved fine-grained materials contained within the constructed sand barriers (Wen and Zhao, 2004).

Microtopography represents a significant factor influencing the spatial heterogeneity of soil characteristics (Vivekananthan et al., 2018). As a complement to the broader concept of topography, the characterization of microtopography varies across different studies. One aspect focuses on the unique topographical features of gullies and ravines that have developed due to long-term rainfall and surface runoff erosion. This perspective is frequently applied in research regarding loess hilly regions and soil erosion in China (Zhao, 2014; Puyang et al., 2020; Wang et al., 2012). Another aspect pertains to small-scale topographic variations, where microtopography in hilly areas can be classified into seven categories, including slope tops, upper side slopes, valley head depressions, lower side slopes, foothill slopes, floodplain terraces, and valley beds. The third aspect addresses distinct microtopographical features resulting from changes in surface microelevation and undulation, i.e., variations that occur with minimal alterations in relative elevation at small scales on slopes. These changes significantly influence the redistribution of water, heat, light, and nutrients. This perspective is commonly utilized in studies examining vegetation elemental stoichiometry, community composition, diversity distribution, and ecological functionality (Qi et al., 2016; Chen et al., 2020; Zhang et al., 2016). While each approach emphasizes distinct elements of microtopography, they all have in common their concentration on phenomena occurring at the microscopic scale.

The present study falls into the third category, focusing on the analysis of soil nutrients across three dune slopes: the top of the windward slope, the middle slope, and the bottom slope within the study area. During the years when sand barriers were installed, the contents of clay, silt, and very fine sand followed a consistent trend: bottom slope > middle slope > top slope. Conversely, for medium sand and coarse sand, an opposing pattern emerged, with top slope > middle slope > bottom slope. This finding aligned with Xu Tingting's conclusions (Xu et al., 2014), which indicated that upon installation of sand barriers, there was an increase in clay and silt particle content in the soil. Furthermore with the prolonged installation of sand barriers, the grain size distribution across different slopes gradually approached stability.

4.2 Effect of *Salix Psammophila* sand barriers on multiple fractal characteristics of soil grain size

Multifractal parameters effectively capture the interception effects of sand barriers on fine-grained materials and variations in soil

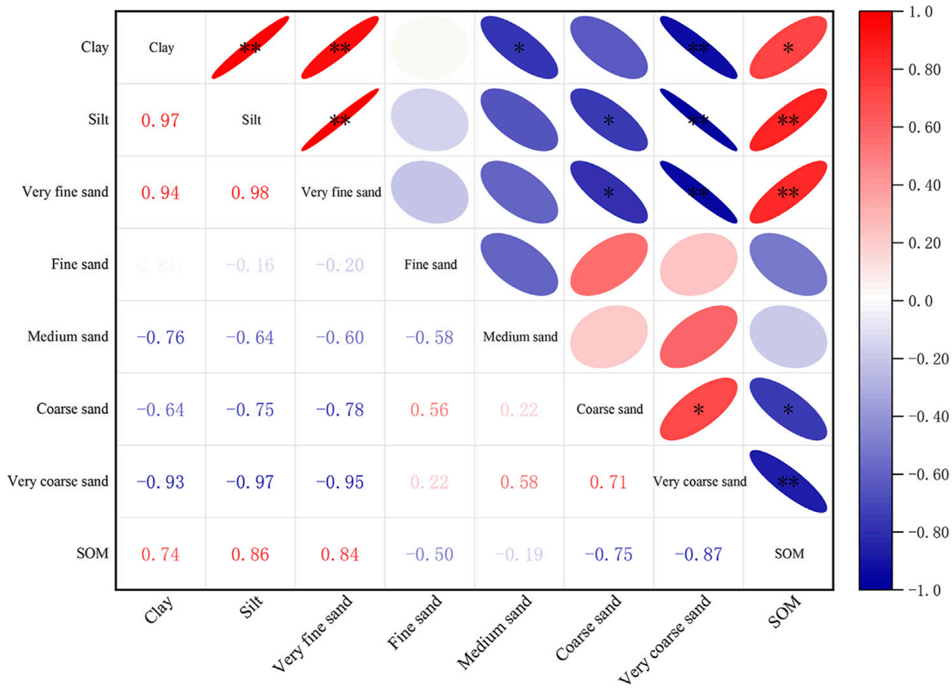

FIGURE 4
Correlation between soil grain size composition and SOM content of *Salix Psammophila* sand barriers at different years of laying.

particle composition, thereby elucidating the local variability and nonuniformity in the characteristics of soil particle size distribution (Meng et al., 2024). In this study area, a comparison of mobile dunes with sand barriers installed for different durations revealed that the singularity spectral function exhibited a phenomenon of superposition in local distributions. This observation further substantiated that as the duration of barrier installation increased, the distribution characteristics of soil particle sizes became increasingly non-uniform. The study by Posadas et al. (2001) conducted an analysis on multifractal spectra derived from 30 particle-size distributions encompassing a broad spectrum of soil textural classes. The findings demonstrated multifractal parameters as promising indicators for describing particle size distribution. Furthermore, various sand control measures exhibited distinct pore structures, which consequently altered the spatial patterns associated with soil particle size distribution characteristics (Howell et al., 2018). The results indicated a significant probability subset demonstrating a predominance of fine sand intervals.

4.3 Grain size distribution and SOM in *Salix Psammophila* sand barriers

Characteristics of soil particle size distribution and SOM content are critical parameters for evaluating composite soil indices. The relationship between these two factors directly affects the stability of soil structure as well as the advantages and disadvantages of various soil properties. There exists a varying degree of correlation between the characteristics of soil particle size distribution and organic matter content. In this study, the results demonstrated that as the number of years since the establishment of sand barriers increased, a significant correlation developed between the characteristics of soil particle sizes and organic matter content (Dong et al., 2017). The rise in fine particle content within wind-sand areas indicated an improvement in soil texture, revealing a positive correlation between fine particulate matter and organic matter accumulation. As organic matter content increased, it enhanced the bonding strength within the microstructure of the soil, thereby improving its resistance to external forces and increasing its overall resilience against wind erosion. Furthermore, fine-grained materials could adsorb organic matter, contributing positively to SOM accumulation. The underground portion of sand barriers was particularly affected by prolonged exposure to a sand-buried environment, leading to microbial decomposition processes influenced by microorganisms present in the surrounding soils (Wang et al., 2021). Additionally, fluctuations in moisture levels within lower layers of sandy land contributed to a cyclical process involving moisture absorption and desorption. This cyclic moisture movement led to repeated expansion and contraction cycles for the barrier structures, causing ruptures in internal cell walls along with structural damage. As a consequence, the barriers became more vulnerable to microbial decomposition (Liang et al., 2022a; Liang et al., 2022b). Such phenomena might significantly account for notable increases in organic matter content observed in surrounding soils during later stages following barrier establishment.

5 Conclusion

The deployment of *Salix Psammophila* sand barriers on both sides of the desert highway holds much significance for altering the sedimentary environment and facilitating the restoration of soil texture. In this study, a quantitative analysis of soil particle distribution, multifractal parameters, and soil organic matter content was conducted between dunes with varying years of sand barrier presence and mobile dunes. Furthermore, the relationship between soil organic matter content and soil particle size distribution was assessed. It was observed that, with the prolonged existence of the sand barriers, the proportions of clay, silt, and very fine sand increased, whereas those of medium sand and coarse sand decreased. Moreover, with the passage of time since the installation of sand barriers, the variations in grain size distribution gradually converged towards a stable state. The establishment of sand barriers markedly modified the sedimentary environment of desert soils, facilitating the refinement of soil particles while decreasing their sorting efficiency. Multifractal spectral analysis of soil particle size distribution effectively quantified the heterogeneity of soil texture. Comparative analyses of Δα width and Δf shape indicated that 1 year post-establishment of the sand barriers resulted in substantial alterations to dune soil particle size characteristics, characterized by a broader distribution amplitude and an increased degree of heterogeneity. Concurrently, a marked rise in fine-grained material present within the soil was observed. In addition, the SOM content exhibited a significant increase with prolonged time duration since the establishment of sand barriers. Notably, significant variations in SOM content were observed across different slope positions of the sand dunes. A strong correlation was found between soil particle size distribution and SOM content, with fine sand and very fine sand being the primary contributors to organic matter accumulation. Collectively, it is strongly recommended that multifractal parameters of soil be utilized as supplementary indicators for characterizing the properties of desert soils. This study bridges the information gap regarding the recovery of soil texture on both sides of desert highways, providing valuable guidance for the restoration of desert soil ecosystems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

CZ: Writing – original draft, Writing – review and editing. YG: Funding acquisition, Writing – review and editing. YH: Data curation, Writing – review and editing. XY: Data curation, Software, Writing – review and editing.

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Conflict of interest

Author XY was employed by Liaoning Zhongda Construction Group Limited.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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