Fractal characteristics of surface soil particle-size distribution and driving factors in Xinjiang: postprint

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Abstract

Xinjiang is both an ecologically fragile region and an area frequently affected by wind erosion and desertification in China, and the composition of surface soil particles is closely related to regional ecological stability. Taking the surface soil particle size of 180 sampling points within 60 plots in Xinjiang as the research object, the sampling points were classified into semi-arid, arid, and extremely arid plots according to the aridity index. The fractal characteristics of soil particle size under different aridity gradients and the influence of environmental factors on the fractal characteristics of surface soil particle size in Xinjiang were investigated. The results show that: (1) With increasing aridity, the distribution of surface soil particles gradually becomes coarser and exhibits transitional characteristics. In the semi-arid and arid plots, soil particles are dominated by silt, whereas in the extremely arid plots, soil particles are dominated by sand, among which very fine sand and fine sand account for 53.48%. (2) Overall, the sorting of grain-size characteristics is relatively poor. As aridity increases, the degree of dispersion of soil particles decreases, the distribution range becomes more concentrated, and the soil fractal dimension is concentrated between 1.98 and 2.47. (3) The fractal dimension is strongly influenced by clay content, showing a significant positive correlation with clay and silt, and a significant negative correlation with sand. The goodness of fit of fractal dimension for plots under different aridity gradients is: extremely arid > arid > semi-arid. (4) Factor detector analysis indicates that mean annual precipitation (MAP), mean annual temperature (MAT), soil type, and parent material have a relatively high explanatory power for soil fractal dimension. The results of the structural equation model show that, among the continuous variable factors selected in this study, climatic factors have a significant effect on the fractal dimension of surface soils in Xinjiang. Specifically, MAP and wind speed have a positive effect on the fractal dimension, whereas MAT has a negative effect. The findings can provide important scientific support for regional soil use and ecological management,

and are thus conducive to soil and water conservation, vegetation restoration, and ecosystem stability in Xinjiang.

Full Text

Fractal Characteristics and Driving Factors of Surface Soil Particle Size in Xinjiang

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Abstract

Xinjiang, an ecologically fragile region in China that is prone to aeolian desertification, has a surface-soil particle composition that plays a critical role in regional ecosystem stability. This study analyzed the particle composition of surface soils collected from 180 sampling points across 60 plots in Xinjiang, China. Using the aridity index, sampling sites were classified into semi-arid, arid, and hyper-arid plots to examine the fractal characteristics of soil particle-size distributions across drought gradients and to assess how environmental factors influence these fractal properties in surface soils. The results demonstrated that (1) With increasing aridity, the surface-soil particle-size distribution became progressively coarser and showed clear transitional features. Semi-arid and arid plots were dominated by silt, whereas hyper-arid plots were dominated by sand, with very fine and fine sand together accounting for 53.48%. (2) Overall, the soils exhibited poor sorting. Particle dispersion decreased with increasing aridity, resulting in progressively narrower size distributions, and the fractal dimensions ranged from 1.98 to 2.47. (3) The fractal dimension was strongly influenced by clay content, showing positive correlations with clay and silt and a significant negative correlation with sand. Furthermore, the model-fitting performance of the fractal dimension in plots under different aridity gradients followed the order: hyper-arid > arid > semi-arid. (4) The factor detector results indicated that mean annual precipitation (MAP), mean annual temperature (MAT), soil type, and parent material had strong explanatory power for the soil fractal dimension. Structural equation modeling further showed that, among the continuous variables examined, climatic factors had a significant influence on the surface-soil fractal dimension in Xinjiang. Specifically, MAP and wind speed exerted positive effects, whereas MAT had a negative effect. This research provides a scientific basis for regional soil use and ecological management, supporting soil and water conservation, vegetation restoration, and ecosystem stability in Xinjiang.

Keywords: fractal dimension; particle size distribution; soil texture; driving factors; Xinjiang

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1. Introduction

Soil particle-size distribution is a key indicator of soil structure, reflecting the source, formation processes, and environmental conditions of soil particles. The composition of soil particles can largely determine fundamental soil properties. Fractal theory quantitatively describes the heterogeneity and self-similarity of soil particle composition through fractal dimension, providing a new perspective for revealing soil texture, wind erosion sensitivity, and degradation mechanisms. The application of fractal theory in soil science began with Tyler and Wheatcraft' s mass-distribution-based soil fractal model in 1992, which provided a feasible method for calculating fractal dimension from mechanical composition data. This breakthrough shifted research from traditional qualitative descriptions to dynamic analysis based on fractal dimension. Since then, scholars have extensively studied the relationship between fractal dimension and soil physicochemical properties, land use patterns, and environmental factors.

Numerous empirical studies have demonstrated clear relationships between fractal dimension and soil particle composition: fine particle content such as clay and silt typically shows significant positive correlations with fractal dimension, while coarse particles like sand exhibit significant negative correlations. For example, during the degradation of the Yellow River wetlands, the surface-soil fractal dimension decreased synchronously with structural degradation from Robinia forests to wasteland, intuitively confirming that fine particle loss is accompanied by soil structural degradation. With the development of spatial analysis techniques, the spatial heterogeneity of fractal dimension and its driving mechanisms have become research hotspots. Scholars have found that fractal dimension and its spatial distribution are influenced by multiple environmental elements including altitude (e.g., fractal dimension increases with elevation in the Helan Mountains), salinity (e.g., fractal dimension decreases with increasing salinity in saline soils), vegetation cover, soil type, parent material, geomorphology, and climate, showing obvious regularity and scale dependence.

Xinjiang is located in an ecologically fragile region of China with frequent wind erosion and desertification disasters, where surface-soil particle composition is directly related to regional soil and water conservation, vegetation restoration, and ecosystem stability. However, to date, there has been no systematic report on soil particle composition and its influencing factors in Xinjiang. Therefore, this study established 60 plots across Xinjiang, classified them into semi-arid, arid, and hyper-arid scales using the aridity index, applied monofractal dimension to describe particle-size distribution characteristics under different drought gradients, and selected environmental factors including climate, topography, soil physicochemical properties, parent material and soil type, land use patterns, and normalized difference vegetation index (NDVI) to investigate how different environmental factors affect soil fractal characteristics, providing a scientific basis for soil utilization, ecological management, and restoration in Xinjiang.

1.1 Study Area Overview

The study area is located in Xinjiang (34°25′~49°10′N, 73°40′~96°23′E), characterized by a typical temperate continental climate with cold winters and hot summers, large annual and diurnal temperature variations, and scarce, unevenly distributed precipitation. The terrain is dominated by mountains and basins, presenting a "three mountains surrounding two basins" pattern. Xinjiang' s soil types show clear regional differentiation: northern Xinjiang plains are dominated by gray desert soil and brown calcic soil; the Tianshan Mountains exhibit vertical zonation of chestnut soil, chernozem, and gray-brown forest soil with elevation; brown desert soil and aeolian sandy soil are widely distributed in the Tarim Basin; and irrigated oasis areas are characterized by irrigated warped soil. This soil distribution pattern is closely associated with climate, topography, and vegetation conditions, providing a typical sample for studying soil systems in arid and semi-arid regions.

1.2 Soil Sample Collection and Processing

Sampling was conducted in July 2023 across 60 plots selected based on topography, geomorphology, and vegetation types (Fig. 1). The plots were classified into semi-arid ($0.2 < AI \leq 0.5$), arid ($0.03 \leq AI \leq 0.2$), and hyper-arid ($AI < 0.03$) categories using the aridity index according to the UNEP (1997) classification scheme. Basic climate information for each plot category is shown in Table 1. Soil texture types were primarily silt and silty loam (Fig. 1).

Within each plot, soil sampling was conducted in areas away from human interference. Three replicate soil samples were collected per plot and designated as three repetitions to ensure representative soil characteristics. A total of 180 samples were collected, including 60 from semi-arid plots, 60 from arid plots, and 60 from hyper-arid plots. For subsequent fractal dimension calculations, because the maximum intervals varied among replicates within the same plot, leading to excessive calculation errors, the average fractal dimension derived from plot means was used to characterize the soil particle fractal features of each plot. Therefore, figures related to fractal dimension used 60 data points, while other figures used 180 data points.

Surface soil (0–10 cm) was collected using a 100 cm^3 stainless steel ring cutter to determine soil bulk density (BD) and water content (SWC). For the 0–10 cm layer, soil samples were air-dried at room temperature, impurities were removed, and the samples were passed through a 2 mm sieve for determination of particle size, organic carbon, pH, and electrical conductivity. Soil BD was measured using the ring cutter method; SWC was determined by gravimetric method; particle size was measured using a laser particle size analyzer (Bettersize BT-

2001) with wet dispersion; soil organic carbon was determined by the potassium dichromate heating method and converted to soil organic matter (SOM) content using a conversion factor of 1.724; pH and electrical conductivity (EC) were measured in a 1:5 soil-water ratio.

1.3 Other Data Sources

NDVI data were obtained from https://ladsweb.modaps.eosdis.nasa.gov/ at 250 m resolution for July 2023. Mean annual temperature (MAT) and mean annual precipitation (MAP) were obtained from WorldClim Global Climate Data (https://www.worldclim.org/) at 1 km × 1 km resolution for 1970–2000. Wind speed (maximum sustained wind gust) data were obtained from the NOAA National Centers for Environmental Information (https://www.ncei.noaa.gov/) at 0.1° × 0.1° resolution for 2023 and interpolated using inverse distance weighting. All data were extracted to sampling points using the "Extract values to points" tool in ArcGIS.

Geographic information including longitude, latitude, elevation (ASL), slope, aspect, parent material, soil type, and land use pattern was recorded during soil sampling.

1.4 Soil Particle-Size Parameter Calculation

For particle-size parameter calculation, the Udden-Wentworth scale was used to convert particle diameter from mm to Φ values through the Krumbein logarithmic transformation:

$$\Phi = -\log_2 d$$

where d is the soil particle diameter (mm). Cumulative percentage curves were plotted using the graphical method to obtain representative Φ values at specific cumulative percentages.

Median particle size (d_{50}): The Φ value corresponding to 50% cumulative frequency, reflecting the central tendency of the distribution. Calculated as:

$$d_{50} = \Phi_{50}$$

Mean particle size (d_m): Reflects the concentration trend of the distribution. Calculated as:

$$d_m = \frac{\Phi_{16} + \Phi_{50} + \Phi_{84}}{3}$$

where Φ_{16}, Φ_{50}, and Φ_{84} are Φ values at 16%, 50%, and 84% cumulative frequencies, respectively.

Standard deviation (σ): Reflects the dispersion degree of soil particle-size distribution. Calculated as:

$$\sigma = \frac{\Phi_{84} - \Phi_{16}}{4} + \frac{\Phi_{95} - \Phi_5}{6.6}$$

Skewness (S_k): Reflects the symmetry of the distribution. Calculated as:

$$S_k = \frac{\Phi_{16} + \Phi_{84} - 2\Phi_{50}}{2(\Phi_{84} - \Phi_{16})} + \frac{\Phi_5 + \Phi_{95} - 2\Phi_{50}}{2(\Phi_{95} - \Phi_5)}$$

Kurtosis (K_g): Reflects the concentration degree of particle size. Calculated as:

$$K_g = \frac{\Phi_{95} - \Phi_5}{2.44(\Phi_{75} - \Phi_{25})}$$

Classification standards for these parameters are shown in Table 2.

Soil particles were classified according to the USDA system into sand (50–2000 μm), silt (2–50 μm), and clay (<2 μm). The volume fractal model was used to calculate the monofractal dimension (D) following Wang Guoliang’ s method:

$$D = 3 - \frac{\log\left(\frac{V(r<R_i)}{V_T}\right)}{\log\left(\frac{R_i}{R_{\max}}\right)}$$

where D is the fractal dimension, r is the particle size (mm), R_i is the upper limit of the i-th particle-size class (mm), $V(r < R_i)$ is the cumulative volume fraction of particles smaller than R_i, and V_T is the total volume fraction of all particle-size classes.

1.5 Data Processing

Original data were organized in Microsoft Excel 2019. Descriptive statistics and stepwise regression analysis were performed using SPSS 26.0. One-way ANOVA with Duncan’ s method was used for significance testing. The factor detector in GeoDetector was employed to determine the explanatory power of different environmental factors on fractal dimension. Pearson correlation analysis and structural equation modeling (SEM) were used to examine relationships between continuous environmental variables and soil particle fractal dimension. SEM was performed using the “plspm” package in R 4.2.3. Figures were created in Origin 2021 and Adobe Illustrator 2025.

2. Results

2.1 Soil Particle-Size Distribution Characteristics

As the drought gradient progressed from semi-arid to arid to hyper-arid, soil particles showed a clear coarsening trend (Table 3). Semi-arid and arid plots were dominated by silt (85.17% and 72.63%, respectively), with low clay and sand contents, indicating fine-textured soils. In contrast, hyper-arid plots were dominated by sand (53.48%), with very fine and fine sand accounting for 54.45%, significantly higher than in semi-arid and arid plots ($P < 0.05$), reflecting coarse-textured soils.

Particle-size distribution curves across all drought gradients showed bimodal patterns (Fig. 2), with inflection points around 15 μm and 125 μm. The first peak cumulative distribution was 95.49% for semi-arid and 85.64% for arid plots, both significantly higher than the 62.44% for hyper-arid plots ($P < 0.05$). The second peak cumulative distribution was 39.03% for hyper-arid plots, significantly higher than the 4.81% and 14.34% for semi-arid and arid plots, respectively ($P < 0.05$). This indicates that semi-arid and arid plots had more dispersed particle distributions, while hyper-arid plots showed more concentrated distributions.

Fractal dimension effectively reflected soil structural complexity (Fig. 3). The median fractal dimension for semi-arid and arid plots was approximately 2.44, significantly higher than the 2.20 for hyper-arid plots ($P < 0.05$), indicating that semi-arid and arid plots had finer, more complex soil structures.

2.2 Soil Particle-Size Parameter Characteristics

Mean particle size (d_m) and median particle size (d_{50}) showed significant increasing trends from semi-arid to arid to hyper-arid plots ($P < 0.05$) (Fig. 3). Standard deviation values ranged between 1.56–3.00, indicating poor sorting for all plots. Hyper-arid plots had significantly lower standard deviation than semi-arid and arid plots ($P < 0.05$), suggesting more concentrated particle-size distributions in hyper-arid conditions.

Skewness values decreased from semi-arid to hyper-arid plots ($P < 0.05$), with semi-arid plots showing near-symmetrical distributions and arid and hyper-arid plots showing negative skewness, indicating coarser particles in the latter two categories. Kurtosis values were at medium levels in semi-arid and arid plots but significantly higher in hyper-arid plots ($P < 0.05$), reaching a narrow-peaked distribution.

2.3 Relationship Between Soil Particle Size and Fractal Dimension

Surface-soil clay content in Xinjiang showed extremely significant positive correlations with fractal dimension ($P < 0.01$), while sand content showed extremely significant negative correlations ($P < 0.01$) (Fig. 4). This indicates that increased clay content promotes structural complexity, whereas increased sand content simplifies soil structure. In semi-arid plots, clay (Fig. 4) and sand (Fig.

4) showed significant correlations with fractal dimension ($P < 0.05$), but silt did not ($P > 0.05$). In arid plots, silt (Fig. 4) and clay showed extremely significant positive correlations ($P < 0.01$), while sand showed significant negative correlations ($P < 0.05$). In hyper-arid plots, clay (Fig. 4) and sand (Fig. 4) showed significant correlations ($P < 0.05$), but silt did not ($P > 0.05$).

The coefficient of determination (R^2) indicated that fractal dimension fit best with clay content overall (clay > sand > silt). Across drought gradients, the fitting performance followed the order: hyper-arid > arid > semi-arid. Stepwise regression analysis further revealed the relationships:

- Semi-arid plots: $D = 0.041X_1 + 2.256$ ($R^2 = 0.96$)
- Arid plots: $D = 0.033X_1 + 0.001X_2 + 2.219$ ($R^2 = 0.74$)
- Hyper-arid plots: $D = 0.054X_1 + 2.256$ ($R^2 = 0.88$)

where X_1 is clay content and X_2 is silt content. These results confirm that clay content had the greatest influence on fractal dimension across all drought gradients.

2.4 Influence of Environmental Factors on Soil Particle Fractal Characteristics

2.4.1 Differences in Soil Particle Composition Under Different Environmental Factors Soil particle composition is the result of multiple driving factors. This section examined various environmental variables, including parent material, soil type, and land use patterns as categorical variables, and MAP, MAT, wind speed, elevation, slope, aspect, BD, SWC, SOM, EC, and NDVI as continuous variables.

Parent materials were primarily slope/residual, alluvial, aeolian, and loess-like materials (Table 4). Aeolian parent material was dominated by sand, with significantly coarser particles than other parent materials ($P < 0.05$). Soil types were dominated by aeolian sandy soil, chernozem, chestnut soil, and brown desert soil, with land use primarily grassland. Aeolian sandy soil and unused land showed significantly lower fractal dimensions than other soil types and land uses, indicating coarser particles.

2.4.2 Influence of Different Environmental Factors on Soil Particle Composition Factor detector results (Fig. 5) showed that MAP, MAT, soil type, and parent material had high explanatory power for fractal dimension (q values), while other environmental factors had lower explanatory power ($q < 0.05$). Table 7 shows that fractal dimension was extremely significantly positively correlated with MAP ($P < 0.01$) and wind speed ($P < 0.01$), significantly positively correlated with NDVI ($P < 0.05$), significantly negatively correlated with MAT ($P < 0.05$), and not significantly correlated with elevation, slope, aspect, BD, SWC, SOM, or EC ($P > 0.05$).

Pearson correlation analysis (Table 8) identified continuous variables strongly correlated with fractal dimension. SEM was constructed by grouping these into soil physical properties (BD, SWC), soil salinity (EC), climate factors (MAP, MAT, wind speed), and NDVI. The SEM results (Fig. 6) showed that climate factors had the strongest influence on fractal dimension ($P < 0.001$), with MAP and wind speed having positive effects and MAT having negative effects. Other factors were not significant ($P > 0.05$). The model explained 38% of the variance in fractal dimension, with a goodness-of-fit index (GOF) of 0.51, indicating acceptable model fit.

3. Discussion

3.1 Characteristics of Surface Soil Particle-Size Distribution and Fractal Dimension Across Drought Gradients

Soil particle-size distribution is an important indicator of soil physical properties, reflecting soil formation processes and environmental conditions that largely determine fundamental soil characteristics. Our results show that surface-soil particle-size distribution curves across all drought gradients exhibited bimodal characteristics (Fig. 2). Semi-arid and arid plots had higher first-peak cumulative percentages, with soil textures dominated by fine particles (<50 μm) and rapid accumulation in the fine range (<100 μm), indicating relatively dense structures with high water-holding capacity and fertility potential. In contrast, hyper-arid plots showed a prominent second peak with significantly increased sand content (>50 μm), where easily eroded very fine and fine sand accounted for over half of the particles (53.48%) (Table 3), reflecting coarse texture, loose structure, and weak erosion resistance. Arid plots showed transitional characteristics.

As drought intensity increased, silt content decreased significantly while sand content increased significantly, showing a clear coarsening trend from fine to coarse particles, consistent with findings from Australian drylands. Granulometric parameters quantified these changes: mean particle size increased significantly with drought (Fig. 3), confirming the coarsening trend. Meanwhile, hyper-arid plots showed significantly decreased standard deviation (Fig. 3) and increased kurtosis (Fig. 3), indicating reduced dispersion, more concentrated distributions, and narrower overall ranges—possibly related to parent material differences or wind erosion events such as dust storms causing changes in fine particle input.

Fractal dimension quantifies the complexity of soil particle-size distribution, offering advantages over single parameters by integrating distribution characteristics. In this study, semi-arid and arid plots had significantly higher fractal dimensions than hyper-arid plots (Fig. 3), indicating finer, more uniform particles and more complex structures. This aligns with research in Xilingol typical grasslands showing lower fractal dimensions in arid versus semi-arid regions. Well-structured soils reportedly have fractal dimensions around 2.8, while all plot types in this study fell below this threshold, reflecting limitations on soil structural development imposed by environmental factors.

3.2 Relationship Between Soil Particle Size and Fractal Dimension Across Drought Gradients

Soil particles form a complex system whose fractal characteristics result from multiple factors. Stepwise regression showed that clay content had the greatest influence on fractal dimension across drought gradients (Fig. 4), with overall positive correlations with clay (Fig. 4) and silt (Fig. 4) and negative correlations with sand (Fig. 4). Previous studies confirm that higher clay volume fractions yield higher fractal dimensions. Our regression analysis aligns with findings that fine particle content is the main factor influencing soil fractal dimension.

The fitting performance of particle composition to fractal dimension followed the order: hyper-arid > arid > semi-arid, closely related to soil distribution characteristics and environmental conditions. Hyper-arid plots (Fig. 4) had coarse texture with high sand proportions and low clay and silt contents, resulting in more concentrated particle distributions and better fractal dimension fit. In contrast, semi-arid (Fig. 4) and arid (Fig. 4) plots had more complex distributions with higher clay and silt contents, potentially introducing more interference. Additionally, wind erosion in hyper-arid plots removes fine particles, simplifying distribution characteristics and strengthening the relationship between fractal dimension and clay content, thereby improving fit.

3.3 Influence of Environmental Factors on Soil Particle Fractal Dimension

Factor detection showed that MAP, MAT, soil type, and parent material had the highest explanatory power for fractal dimension (Fig. 5). Aeolian parent material and aeolian sandy soil showed significant coarsening characteristics, with fractal dimensions of 2.01–2.09 (Table 5), indicating poor sorting and fine particle deficiency in aeolian deposits. Other parent materials formed high-organic-matter soils such as chernozem and black felty soil with fractal dimensions of 2.47–2.49 (Table 5), likely due to organic cementation promoting aggregate formation. Unused land (sand, gobi) had significantly lower fractal dimensions than grassland and forest land (Table 6), demonstrating vegetation amelioration: higher vegetation cover corresponds to more complete soil structure development and higher clay and silt contents, resulting in higher fractal dimensions.

Drought gradients caused systematic differences in key soil properties (Table 7). SEM results showed that among continuous variables, climate factors significantly influenced Xinjiang surface-soil fractal dimension, with MAP and wind speed having positive effects and MAT having negative effects. Previous studies indicate that reduced precipitation leads to lower fractal dimension and soil coarsening, while humid environments correspond to higher fractal dimension. Wind significantly affects particle redistribution, with fine particles increasing substantially after dust storms. Temperature increases may weaken soil water retention and erosion resistance. Certini et al. (2023) identified climate as a primary factor controlling soil formation and change. Although the model fit well, the explained variance ($R^2 = 0.38$) was moderate, reflecting that soil fractal characteristics result from complex interactions among multiple environmental factors, warranting future research on multi-factor comprehensive effects and scale dependence.

4. Conclusions

(1) With increasing aridity, soil particles became progressively coarser, showing clear transitional features. Semi-arid and arid plots were dominated by silt, while hyper-arid plots were dominated by sand, with very fine and fine sand accounting for 53.48%.

(2) Overall sorting was poor. Particle dispersion decreased with increasing aridity, resulting in more concentrated distributions, with monofractal dimensions ranging from 1.98 to 2.47.

(3) Fractal dimension was strongly influenced by clay, showing significant positive correlations with clay and silt and significant negative correlations with sand. Model fitting performance followed the order: hyper-arid > arid > semi-arid.

(4) Factor detection showed that MAP, MAT, soil type, and parent material had high explanatory power for fractal dimension. Among continuous variables, climate factors significantly influenced Xinjiang surface-soil fractal dimension, with MAP and wind speed having positive effects and MAT having negative effects.

These findings provide important scientific basis for regional soil utilization and ecological management, benefiting soil and water conservation, vegetation restoration, and ecosystem stability in Xinjiang.

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