Particle Size Characteristics and Spatial Heterogeneity of Cropland Soils in the Syr Darya River Basin, Kazakhstan (Postprint)

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Abstract

Employing both classical statistical and geostatistical methods, this study investigated the particle size characteristics and spatial heterogeneity of farmland soils within Kazakhstan in the Syr Darya River basin at the 0~20 cm depth. The results revealed that: (1) The distribution patterns of various soil particle sizes were relatively similar across all sub-study areas, with the highest average content proportions observed for particles of 0.25~0.05 mm and 0.05~0.01 mm. Except for the 1.0~0.25 mm fraction in sub-area 3, which exhibited strong variability, all other particle size fractions displayed moderate variability; (2) In sub-area 1, nugget coefficients for all particle size fractions except 1.0~0.05 mm were <40%; in sub-area 2, nugget coefficients for all fractions were <50%; and in sub-area 3, nugget coefficients for all fractions except <0.001 mm were <40%, indicating that soil particle composition in each study area has been influenced by random factors to varying degrees; (3) Spatial interpolation using the Kriging method demonstrated that different particle size fractions exhibited distinct spatial distribution patterns across the study area. These findings provide a scientific basis for the rational utilization of farmland soils and the remediation of degraded soils.

Full Text

Grain Size Characteristics and Spatial Heterogeneity of Farmland Soils in the Syr Darya River Basin of Kazakhstan

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Abstract

This study investigates the grain size characteristics and spatial heterogeneity of farmland soils in the Syr Darya River Basin of Kazakhstan using classical statistics and geostatistical methods. The analysis focuses on the 0–20 cm soil layer. Results indicate that: (1) The distribution characteristics of soil particles across different particle sizes are similar in each sub-study area, with particles of 0.25–0.05 mm and 0.05–0.01 mm showing the highest average content. Except for subzone 3, the content of 1.0–0.25 mm particles exhibits strong variability, while other particle sizes show moderate variability. (2) The nugget coefficient for all particle size classes is less than 40% in subzone 1, less than 50% in subzone 2, and less than 40% in subzone 3 (except for particles <0.001 mm), indicating that soil particle composition in each study area has been influenced by random factors to varying degrees. (3) Kriging interpolation reveals distinct spatial distribution patterns for different particle size fractions across the study area. These findings provide a scientific basis for rational farmland soil utilization and the improvement of degraded soils.

Keywords: Syr Darya River Basin; soil grain size; spatial heterogeneity; semi-variogram

Introduction

Soil is a complex and heterogeneous component of terrestrial ecosystems, serving as both a hub connecting environmental elements and a central link between inorganic and organic matter. It forms through a series of physical, chemical, and biological processes acting on parent material. Soil particle size, as one of the most important physical properties, significantly influences water retention, nutrient availability, soil erosion, and wind erosion, and serves as an indicator of soil desertification. As a spatially and temporally continuous variable, soil particle size exhibits strong spatial heterogeneity, with variations in particle size distribution determining this heterogeneity.

With continuous improvement in geostatistical methods, this approach has proven to be the most effective for studying spatial heterogeneity of soil properties. By considering both autocorrelation and randomness, geostatistics enables precise evaluation of spatial variability and has been widely applied to studies of soil moisture, chemical properties, and physicochemical characteristics. In recent years, numerous scholars have conducted extensive research on soil particle size using geostatistical methods. For example, studies have examined the spatial heterogeneity of wind-eroded soil particles in *Nitraria tangutorum* shrublands in the Ulan Buh Desert, finding that spatial autocorrelation of various particle sizes is primarily caused by structural factors. Research in the Hexi Corridor patch vegetation area revealed that coarse and fine sand contents show strong spatial autocorrelation, while medium sand and silt exhibit weak autocorrelation. Other work on the desert-oasis ecotone of the Hexi Corridor demonstrated that different particle sizes possess distinct spatial heterogeneity characteristics.

Since the 1990s, large-scale agricultural development has been undertaken in the Syr Darya River Basin of Kazakhstan, with rapid expansion of farmland area. Long-term human activities may have affected soil particle composition distribution in the region. Previous research on the Syr Darya Basin has focused primarily on soil moisture, heavy metal distribution, and soil element composition, while studies on grain size characteristics and spatial heterogeneity of farmland soils in Kazakhstan' s portion of the basin remain scarce. This paper addresses this gap by combining descriptive statistics and geostatistical methods to investigate soil grain size characteristics and spatial heterogeneity, providing a reference for further studies of other soil properties and offering a scientific basis for rational farmland utilization and agricultural structural adjustment.

1.1 Study Area Overview

The Syr Darya River, the second largest river in Central Asia, covers a drainage area of 2.19$×10^{6}$ km^2 and is a major tributary to the Aral Sea. Formed by the confluence of the Naryn and Karadarya rivers originating in Kyrgyzstan, it flows through Uzbekistan, Kazakhstan, and Kyrgyzstan, serving a population of approximately 1.5$×10^{7}$ people. The study area is located in southern Kazakhstan, primarily within the South Kazakhstan and Kyzylorda regions, occupying the middle and lower reaches of the Syr Darya Basin. The area has low average elevation and experiences hot, dry summers and cold, snow-sparse winters with large seasonal and diurnal temperature variations, characteristic of an arid continental climate.

Based on geographical location and topography, the study area was divided into three subzones (Figure 1). Subzone 1, located in the middle reaches near Shardara, has an annual precipitation of 343.2 mm and average temperature of 15.8°C, with soils classified as Anthrosols and Gleysols according to the World Soil Database (HWSD v1.2). Subzone 2, in the lower reaches near Kyzylorda, receives 138.7 mm of precipitation annually with an average temperature of 11.6°C, where Gleysols dominate. Subzone 3, near Kazaly in the lower reaches, has 127.8 mm annual precipitation and 10.7°C average temperature, with soils primarily consisting of Arenosols and Calcisols. Cotton is the main crop in subzones 1 and 2, while rice is predominant in subzone 3. Land use classification data (Figure 1) were obtained from Globcover2009.

1.2 Methods

1.2.1 Sample Collection and Analysis

From 2019 to 2020, 150 surface soil samples (0-20 cm) were collected across the three subzones, with 50 samples from each area. Samples were sealed in bags and transported to the laboratory, where stones and debris were removed. After air-drying, organic matter removal, and decalcification, samples were passed through a 2 mm sieve. Soil particle size distribution was measured using the pipette method and classified into six grades: 1.0-0.25 mm, 0.25-0.05 mm, 0.05-0.01 mm, 0.01-0.005 mm, 0.005-0.001 mm, and <0.001 mm. All analyses were completed at the Kazakh Research Institute of Soil Science and Agrochemistry.

1.2.2 Data Processing and Analysis

Geostatistical methods are considered the most effective approach for studying spatial heterogeneity of soil properties. The semi-variogram, as the fundamental tool of geostatistics, describes the spatial variation structure of soil properties. Theoretical models and related parameters for different particle size fractions were calculated using semi-variograms:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where $\gamma(h)$ is the semi-variance, h is the separation distance between sample pairs, $N(h)$ is the number of sample pairs at distance h, and $Z(x_i)$ and $Z(x_i+h)$ are measured values at positions x_i and $x_i + h$, respectively.

Descriptive statistical analysis and normality testing were performed using SPSS 26.0. Semi-variogram calculation and model fitting were conducted using GS+9.0 software, with Kriging interpolation employed to generate spatial distribution maps for unsampled areas.

2.1 Descriptive Statistical Characteristics of Soil Particle Size Distribution

Descriptive statistics reflect overall spatial variation characteristics of soil particle size, serving as a prerequisite for further spatial heterogeneity analysis. Minimum, maximum, mean, standard deviation, and coefficient of variation effectively describe soil particle variability. Analysis of 0–20 cm soil samples across the three subzones revealed similar particle size composition (Table 1). Particles of 0.25-0.05 mm and 0.05-0.01 mm showed the highest average contents, collectively accounting for approximately 60% of the total composition. Specifically, 0.25–0.05 mm particles comprised 30.40–39.90%, while 0.05–0.01 mm particles accounted for 21.20-30.40%, indicating that farmland soils are dominated by these two fractions.

The 0.005-0.001 mm and <0.001 mm fractions showed average contents of 11.75-15.81% and 17.28-19.30%, respectively. The 1.0-0.25 mm fraction had the lowest average content at 1.42-2.30%. According to the coefficient of variation classification (weak variation <10%, moderate variation 10-100%, strong variation >100%), all particle size classes showed moderate variability except for 1.0-0.25 mm particles in subzone 3, which exhibited strong variability. Normality tests (Kolmogorov-Smirnov method) confirmed that all data followed normal distributions after transformation where necessary.

2.2 Spatial Heterogeneity and Influencing Factors of Soil Particle Size

The variogram curve consists of nugget (C_0), sill (C_0+C), and range (A) parameters. The nugget coefficient ($C_0/(C_0+C)$) indicates the degree of spatial autocorrelation: values <25% indicate strong spatial autocorrelation (structural factors dominant), 25-75% indicate moderate autocorrelation, and >75% indicate weak autocorrelation (random factors dominant). Random factors include tillage practices, irrigation, and soil improvement, while structural factors comprise topography, climate, and parent material.

In subzone 1, the nugget coefficients for 0.01-0.005 mm and 0.005-0.001 mm particles were 38.26% and 36.09%, respectively, indicating moderate spatial autocorrelation. The <0.001 mm fraction showed a nugget coefficient of 18.36%, indicating strong autocorrelation primarily controlled by structural factors. All other particle sizes had nugget coefficients <25%, showing strong spatial autocorrelation.

In subzone 2, the nugget coefficients for 0.05-0.01 mm and <0.001 mm particles were 42.5% and 37.85%, respectively, indicating moderate spatial autocorrelation. All other particle sizes had nugget coefficients <25%, demonstrating strong spatial autocorrelation.

In subzone 3, the nugget coefficients for 0.25-0.05 mm and 0.05-0.01 mm particles were 71.20% and 77.85%, respectively, indicating weak spatial autocorrelation dominated by random factors. The 1.0-0.25 mm fraction showed a nugget coefficient of 36.21%, indicating moderate autocorrelation, while all remaining particle sizes had coefficients <25%, showing strong autocorrelation.

Overall, random factors (primarily long-term anthropogenic activities) have caused varying degrees of impact on spatial autocorrelation of soil particle content across the subzones, representing the main driver of spatial heterogeneity.

2.3 Spatial Interpolation Analysis

Kriging interpolation was applied to map the spatial distribution of different particle size fractions. In subzone 1, 1.0–0.25 mm particles showed high values in central areas, decreasing radially outward, while low values occurred in northwest and southeast regions. The 0.25–0.05 mm fraction exhibited high values in central and eastern areas with a south-to-north increasing trend. High values of 0.05–0.01 mm particles were concentrated in the south, decreasing outward. The 0.01–0.005 mm fraction showed an east-to-west decreasing trend, while <0.001 mm particles displayed high values in the southeast and scattered low values.

In subzone 2, 1.0–0.25 mm particles decreased from southwest to northeast, with high values in the southwest. The 0.25–0.05 mm fraction showed high values in northwest and central areas, decreasing outward. High values of 0.05–0.01 mm particles were located in the southeast, decreasing northwestward. The 0.01–0.005 mm fraction had high values in a small northern area, decreasing toward the center, while 0.005–0.001 mm particles showed high values in a small northwestern area with low values dominating elsewhere.

In subzone 3, 1.0–0.25 mm particles decreased from southwest to northeast, with high values in the southwest. The 0.25–0.05 mm fraction exhibited high values in the southeast, decreasing northwestward. The 0.05–0.01 mm fraction showed high values in a small northern area, while 0.01–0.005 mm particles had high values in a small northwestern area with low values occupying most of the region.

3 Discussion

The study reveals that subzones 1 and 2, dominated by cotton cultivation, and subzone 3, primarily under rice cultivation, show similar soil particle composition at the watershed scale, with sand and silt fractions (1.0–0.05 mm) being predominant. The coefficient of variation indicates moderate variability in soil particle distribution across the study area. Nugget coefficient analysis demonstrates moderate spatial autocorrelation, confirming that soil particle composition has been influenced by random factors to varying degrees.

Comparison with Funakawa's research from the 1990s reveals significant changes. In subzones 1 and 2, sand and silt contents have decreased while clay content increased. In subzone 3, sand content increased substantially while clay decreased. Since the 1990s, rapid expansion of cotton and rice cultivation occurred across Central Asia, with South Kazakhstan representing the country's primary cotton-growing region. Plant roots secrete organic acids that alter soil physicochemical properties, enhance cohesion, and stabilize soil structure, potentially leading to particle fining. Conversely, increased cultivation duration can disrupt soil self-regulation functions, causing progressive sandification. Research indicates that with increased cultivation years, surface soil sand content rises while silt and clay contents decline, suggesting that long-term farming may be driving soil sandification in the region.

Soil particle composition significantly influences salt ion distribution. Sand particles, being coarse with large pores, facilitate salt leaching but have low water and nutrient retention capacity. Clay particles, being fine with numerous small pores, exhibit strong adsorption capacity but poor aeration and permeability, promoting salt accumulation at the surface under strong evaporation. Studies show that salt ion distribution is primarily affected by clay content in normal soils, but by sand content in saline soils. With 67.8% of the Kyzylorda irrigation area and South Kazakhstan region classified as moderately to highly saline, this research on soil particle size provides a theoretical foundation for soil salinization control and fertility management.

4 Conclusion

This study of farmland soils in Kazakhstan’ s Syr Darya River Basin demonstrates that:

1) Surface soil particle composition shows similar distribution characteristics across subzones at the watershed scale, dominated by 0.25–0.05 mm particles (approximately 40% of total composition) and 0.05–0.01 mm particles (approximately 30%). Except for 1.0–0.25 mm particles in subzone 3 showing strong variability, all other particle sizes exhibit moderate variability.
2) Variogram analysis indicates that different particle size fractions follow various theoretical models with differing degrees of spatial autocorrelation. Except for 1.0–0.05 mm particles in subzone 1 showing weak spatial autocorrelation due to random factors, most particle sizes demonstrate moderate to strong spatial autocorrelation across subzones. Agricultural practices such as tillage have altered soil particle composition and represent an important factor influencing spatial heterogeneity.
3) Spatial interpolation reveals distinct distribution patterns for different particle size fractions across subzones, showing irregular banded and patchy distributions with scattered high and low value areas lacking clear patterns.

These results provide valuable insights for rational farmland soil management and agricultural structural adjustment in the Syr Darya River Basin.

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