

Land Gravelification Characteristics and Monitoring Indicators in the Alxa Plateau: Postprint

Authors: Wen Wenjie^{1,2}, Pei Hao^{1,3}, Bagan 1,4, Yongjun Wu^{1,5}, Liu Zhiming^{1,6}

Date: 2023-08-25T00:00:00+00:00

Abstract

This study investigates the characteristics and correlations of surface gravel coverage (Gc), surface gravel mass per unit area (Gm), and gravel mass content in soil layers at depths of 0~5 cm and 5~10 cm [Gmc(0~5 cm), Gmc(5~10 cm)] in gravelized land areas of the Alxa Plateau, establishing an indicator foundation for monitoring and assessment of gravelized land. Gravel samples were collected from gravelized land areas of the Alxa Plateau to measure Gc, Gm, Gmc(0~5 cm), and Gmc(5~10 cm). Through one-way ANOVA, Duncan's multiple comparison, simple linear regression, and correlation analysis, the characteristics of land gravelization in the Alxa Plateau were investigated. The results show that: (1) The average total Gc (Gm) across all sample plots in the Alxa Plateau was 39.49% (3544.04 g · m⁻²). (2) Gc (Gm) for particle sizes of 4~8 mm and 8~16 mm were significantly higher than those of other particle sizes (P<0.05), and the coefficient of variation for Gc (Gm) at 4~8 mm particle size was the smallest, indicating the highest stability. (3) The spatial distribution pattern across sample plots in the Alxa Plateau showed a gradual increase in Gc and Gm from east to west and from south to north. (4) Gm and Gc for different particle sizes (total) exhibited extremely significant simple linear regression relationships (P<0.01), and Gm can also effectively evaluate the degree of land gravelization. The classification thresholds for gravelization degree of Gm were determined based on the classification thresholds for gravelization degree of Gc. (5) Except for particle sizes of 2~4 mm and >32 mm, the correlations of Gc and Gm with Gmc in the 0~5 cm soil layer were significantly greater than those with Gmc in the 5~10 cm soil layer for other particle sizes; the correlations of total Gc and Gm with Gmc in the 0~5 cm soil layer were also significantly greater than those with Gmc in the 5~10 cm soil layer. (6) The threshold for surface gravel coverage of Gobi, one type of gravelized land, was determined to be 25%. The research results can provide an indicator basis for monitoring and assessment of gravelized land in the Alxa Plateau and other regions.

Full Text

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WEN Wenjie^{1, 2}, PEI Hao^{1, 3}, BA Gen^{1, 4}, WU Yongjun^{1, 5}, LIU Zhiming^{1, 6}

¹Inner Mongolia Desert Ecological Meteorological Center, Hohhot 010051, China

²Inner Mongolia Ecological and Agricultural Meteorological Center, Hohhot 010051, China

³Inner Mongolia Meteorological Bureau, Hohhot 010051, China

⁴Alxa League Meteorological Bureau, Alxa League 750306, China

⁵Dongwuzhumuqin Banner Meteorological Bureau, Xilin Gol 026300, China

⁶Siziwang Banner Meteorological Bureau, Ulanqab 011899, China

Abstract

This study investigates the characteristics of surface gravel coverage (Gc), surface gravel mass per unit area (Gm), gravel mass content in the 0–5 cm and 5–10 cm soil layers [Gmc(0–5 cm) and Gmc(5–10 cm)], and their interrelationships in land graveling areas of the Alxa Plateau, providing a foundational basis for monitoring and assessment indicators. Gravel samples were collected from graveling land areas on the Alxa Plateau to determine Gmc(0–5 cm) and Gmc(5–10 cm). One-way analysis of variance, Duncan multiple comparisons, univariate linear regression, and correlation analysis were employed to explore land graveling characteristics. The results demonstrate that the average total Gc across all sample sites was 39.49% (range: 2.48%–53.78%), while the average total Gm was 3544.04 g·m⁻² (range: 146.56–10488.56 g·m⁻²). Both Gc and Gm showed significant differences among particle sizes (P < 0.05), with the 4–8 mm and 8–16 mm fractions exhibiting the highest values. The coefficients of variation for Gc and Gm were smallest for the 4–8 mm fraction, indicating greatest stability. Spatial distribution patterns revealed gradual increases in Gc and Gm from east to west and from south to north across the Alxa Plateau. Extremely significant univariate linear relationships existed between different particle sizes (total) of Gm and Gc (P < 0.01), indicating that Gm can effectively evaluate land graveling degree. Based on established classification thresholds for Gc, corresponding Gm classification levels were determined. Except for the 2–4 mm and >32 mm fractions, correlations between Gc, Gm, and Gmc in the 0–5 cm layer were significantly stronger than those in the 5–10 cm layer. A surface gravel coverage threshold of 25% was identified for Gobi land as a specific graveling land type. These findings establish an indicator foundation for monitoring and assessing graveling land in the Alxa Plateau and other regions.

Keywords: land graveling; gravel coverage; surface gravel mass per unit area; gravel mass content; Alxa Plateau

Introduction

Gravel is defined as mineral particles with diameters exceeding 2 mm in soil. Three distinct forms exist in the soil surface layer: surface-distributed, partially embedded, and completely buried. Land graveling represents the process of increasing gravel proportion or quantity in the surface soil layer, constituting a manifestation of desertification. Graveling land refers to land with gravel distribution in the surface layer—land that has undergone graveling. Various indicators can measure land graveling degree, including surface gravel coverage (Gc), gravel mass content (Gmc), surface gravel mass per unit area (Gm), surface gravel volume per unit area, and surface gravel number per unit area. Measurement methods include the measuring plate method, background color photography, viewpoint frame method, grid paper projection method, and image analysis for Gc determination, while Gmc can be measured through sieving and weighing. Gm can be directly measured using high-precision electronic balances. While previous research has addressed the former two methods, Gm remains rarely utilized.

Current research on graveling land primarily focuses on Gobi as a special graveling land type, including studies on vertical profile sediment grain size characteristics, fractal spatial variability of Gobi sediments, surface gravel particle size, and aeolian sand transport patterns. However, comprehensive research encompassing all types of graveling land remains scarce. The Alxa Plateau, as a key region in China's "Northern Sand Prevention Belt," continues to face ecological degradation from land desertification. Extensive graveling land areas exist across the plateau beyond deserts, oases, rivers, and lakes—regions characterized by harsh and fragile natural environments, poor transportation access, and sparse populations that have limited scholarly investigation. Consequently, research foundations on land graveling characteristics in the Alxa Plateau remain relatively weak. This study examines Gc, Gm, Gmc(0–5 cm), and Gmc(5–10 cm) characteristics and their relationships in Alxa Plateau graveling land areas, screening monitoring indicators suitable for different graveling conditions and clarifying applicable scenarios for each indicator. This work advances understanding of land graveling characteristics in the Alxa Plateau while establishing an indicator foundation for broader graveling land monitoring and assessment.

1.1 Study Area Overview

The study area is located on the Alxa Plateau in Inner Mongolia, spanning 37°24'–42°47' N and 97°10'–106°53' E, with a total area of approximately 25×10^4 km². The region experiences a continental climate with distinct seasons, large diurnal temperature ranges, arid conditions with minimal precipitation, strong evaporation, and powerful winds. Annual mean temperature ranges from 2.1–9.6°C, while annual precipitation varies between 29–296 mm. Landform types include Gobi, desert, oasis, mountains, hills, rivers, and lakes. Dominant plant communities include *Nitraria tangutorum*, *Reaumuria soongorica*, *Nitraria sphaerocarpa*, *Salsola passerina*, *Potaninia mongolica*,

Haloxylon ammodendron, *Zygophyllum xanthoxylon*, *Ephedra przewalskii*, and *Peganum harmala*.

1.2 Field Sample Collection

Gravel samples were collected from 40 graveling land sites (40 m × 40 m) across the Alxa Plateau during 2021. Site selection followed these principles: prioritizing representativeness based on topography and landforms; considering different dominant vegetation types; establishing plots in typical graveling areas across mountains, hills, plateaus, and basins; and maintaining appropriate distances between sites (minimum separation of 10 km to ensure coverage and manage workload). The specific collection method involved establishing a 50 cm × 50 cm quadrat at each site where gravel coverage represented the average condition. All surface gravel within the quadrat was collected in sealed plastic bags and labeled. Approximately 20 cm from the quadrat, a soil profile was excavated, and soil samples (~500 g) were collected from the 0–5 cm and 5–10 cm layers, sealed in plastic bags, and labeled.

1.3 Laboratory Sample Processing

In the laboratory, soil samples were passed through nested sieves (32 mm, 16 mm, 8 mm, 4 mm, and 2 mm) to separate gravel by particle size. For surface gravel, samples were spread tightly without overlap on a measuring plate to determine area based on length and width readings. The ratio of gravel area to quadrat area (50 cm × 50 cm) yielded G_c for each particle size fraction, with summed fractions giving total G_c . Gravel mass for each fraction was weighed using a 0.01 g precision electronic balance to determine G_m , with summed fractions yielding total G_m . For soil samples from both depths, gravel mass was weighed by particle size, and the ratio of gravel mass to total soil sample mass gave G_{mc} for each fraction, with summed fractions providing total G_{mc} for each layer.

1.4 Data Processing and Analysis

Statistical analyses were performed using SPSS 25 software. One-way ANOVA compared significant differences in G_c , G_m , $G_{mc}(0-5\text{ cm})$, and $G_{mc}(5-10\text{ cm})$ among particle sizes, with Duncan's method for multiple comparisons. The coefficient of variation ($C_v = \sigma / \bar{x}$, where σ is standard deviation and \bar{x} is arithmetic mean) quantified data variability, with larger C_v indicating greater fluctuation. Origin 2018 software performed univariate linear regression of total G_c and G_m against longitude and latitude and generated corresponding maps. Linear regression was also conducted between different particle sizes (total) of G_m and G_c , and between total $G_{mc}(0-5\text{ cm})$ and total G_c and G_m . Spearman correlation analysis in SPSS 25 examined relationships among different particle sizes (total) of G_c , G_m , $G_{mc}(0-5\text{ cm})$, and $G_{mc}(5-10\text{ cm})$.

2.1.1 Gravel Particle Size Composition

Table 1 presents statistical characteristics of total Gc, Gm, Gmc(0–5 cm), and Gmc(5–10 cm) across all sites. The average total Gc was $39.49\% \pm 14.84\%$ (range: 2.48%–53.78%), while average total Gm was $3544.04 \pm 1737.18 \text{ g} \cdot \text{m}^{-2}$ (range: 146.56–10488.56 $\text{g} \cdot \text{m}^{-2}$). Average total Gmc(0–5 cm) was $16.69\% \pm 8.08\%$ (range: 0.82%–67.81%), and average total Gmc(5–10 cm) was $14.04\% \pm 10.58\%$ (range: 2.34%–83.57%). Both Gc and Gm showed significant differences among particle sizes ($P < 0.05$), with 4–8 mm and 8–16 mm fractions exhibiting the highest and second-highest values, respectively. Similarly, Gmc(0–5 cm) and Gmc(5–10 cm) differed significantly among particle sizes ($P < 0.05$), with the 4–8 mm fraction showing the highest values. The same pattern occurred across soil depths. The particle size distribution curve for surface gravel showed steep slopes in the >4–8 mm and >8–16 mm ranges, indicating that 4–8 mm and 8–16 mm fractions dominate surface soil gravel composition.

Table 2 presents coefficients of variation for different particle sizes. For Gc and Gm, the 4–8 mm fraction showed the smallest coefficients (48.44% and 54.29%, respectively), indicating greatest stability, while the >32 mm fraction showed the largest variation. For Gmc(0–5 cm), the 4–8 mm fraction had the smallest coefficient (60.99%) and the >32 mm fraction the largest (101.15%). For Gmc(5–10 cm), the 4–8 mm fraction again showed the smallest coefficient (73.40%) and the >32 mm fraction the largest (110.38%). Overall, coefficients of variation for Gmc(0–5 cm) were smaller than those for Gmc(5–10 cm), indicating more stable gravel content in the surface layer.

2.1.2 Spatial Distribution Characteristics

Figure 7 illustrates that total Gc and Gm across the Alxa Plateau increase gradually from east to west and from south to north, indicating intensifying land graveling in these directions. The spatial distribution of different graveling grades follows the same pattern, with severity increasing from east to west and south to north. This distribution correlates with climatic factors including wind speed, precipitation, and temperature. Generally, more arid and windier climates correspond to larger graveling land areas and greater graveling severity. Based on topography, graveling land can be classified as graveling mountains, hills, plateaus, or basins. Field observations and sieving revealed that graveling mountains typically contain large, angular, unpolished gravel derived from bedrock weathering and fine material loss through water and wind erosion. Graveling hills contain relatively smaller gravel with some edge rounding, while graveling plateaus and basins feature smaller, smoother, more rounded gravel formed through fine material loss and transport processes.

2.2 Correlation between Gm and Gc and Land Graveling Classification

Extremely significant univariate linear relationships existed between different particle sizes (total) of Gm and Gc ($P < 0.01$) [Figure 8: see original paper]. Following the land graveling classification standards for surface gravel coverage by Miao Bailing et al. [3], Gm thresholds corresponding to different graveling degrees were established. Among the 40 sample sites, severely gravelized sites (Class IV) were most numerous (22 sites, 55%), reflecting the region's severe land graveling conditions.

2.3 Correlation Analysis between Gc, Gm and Gmc(0–5 cm), Gmc(5–10 cm)

Spearman correlation analysis revealed that, except for the >32 mm fraction, Gc and Gmc(0–5 cm) showed extremely significant positive correlations for the same particle sizes ($P < 0.01$). Similarly, Gm and Gmc(0–5 cm) exhibited extremely significant positive correlations ($P < 0.01$). Univariate linear regression between total Gmc(0–5 cm) and total Gc and Gm yielded equations with $P < 0.01$, indicating that higher Gmc(0–5 cm) corresponds to higher Gc and Gm [Figure 9: see original paper]. Thus, Gmc(0–5 cm) can serve as an auxiliary monitoring indicator for land graveling degree.

Correlation analysis between Gc and Gmc(5–10 cm) showed that, except for the >32 mm fraction, most particle sizes exhibited extremely significant positive correlations ($P < 0.01$). The 2–4 mm fraction showed only significant correlation ($P < 0.05$). Similarly, Gm and Gmc(5–10 cm) showed extremely significant positive correlations for most fractions ($P < 0.01$), with the 2–4 mm fraction showing significant correlation ($P < 0.05$). These results indicate that Gmc(5–10 cm) can also indicate land graveling degree, though correlations were weaker than for the 0–5 cm layer. The stronger correlations in the surface layer reflect that more severe graveling corresponds to greater surface gravel coverage, where gravel layers protect underlying soil, reduce erosion of fine materials, alter spectral reflectance, moderate temperature fluctuations, and decrease water evaporation. As fine material loss decreases and graveling processes stabilize, the land reaches a relatively stable state of maximum graveling severity.

Discussion

While scholars have scientifically defined Gobi concepts, detailed classification of Gobi gravel coverage remains limited. Analysis of coverage distribution intervals across sample sites revealed that different Gobi positions exhibit varying gravel coverage. Integrating findings from Feng Yiming et al. [19], Qian Guangqiang et al. [31], Miao Bailing et al. [3], and Shen Yuancun et al. [32], this study considers Gobi a special graveling land type that forms when specific climatic, dynamic, geomorphic, surface material, vegetation, soil, and moisture conditions are met and gravel coverage reaches the Class III threshold (25%). This study

established univariate linear regression equations for each particle size and total fractions. With large sample sizes ($n = 40$) and $P < 0.01$, these equations demonstrate representativeness for the Alxa Plateau.

In field measurements, G_m is easier, faster, and more precise to measure than G_c . When G_c measurement conditions are unavailable, G_m can be measured using an electronic balance and substituted into the regression equations to obtain corresponding G_c values, enabling objective evaluation of actual gravel coverage. Expanding this approach to other Inner Mongolia regions requires verification of whether significant linear relationships exist. In practical application, G_c is suitable for monitoring graveling land with only a single surface gravel layer but becomes saturated and less effective when multiple gravel layers exist. G_m applies to both single-layer and multi-layer gravel scenarios. Future research should explore new monitoring indicators such as gravel mass per unit volume at different soil depths to improve monitoring accuracy and comprehensiveness.

Except for the >32 mm fraction, correlations between G_c , G_m , and $G_{mc}(0-5$ cm) were significantly stronger than with $G_{mc}(5-10$ cm). This reflects intense surface weathering that erodes and rounds large gravel, substantially reducing coarse fraction content. The absence of significant correlations for >32 mm gravel ($P > 0.05$) results from these weathering processes that deplete large gravel fractions.

Conclusions

This study examined characteristics and relationships of G_c , G_m , $G_{mc}(0-5$ cm), and $G_{mc}(5-10$ cm) in Alxa Plateau graveling land areas, yielding the following conclusions:

- 1) The average total G_c across all sample sites was 39.49%, with average total G_m of $3544.04 \text{ g} \cdot \text{m}^{-2}$. Severely gravelized sites (Class IV) were most numerous (22 sites, 55%). Spatial distribution patterns showed gradual increases in G_c and G_m from east to west and south to north, highlighting the need for enhanced desertification control efforts in the Alxa Plateau.
- 2) Intense weathering erodes and rounds large surface gravel, significantly reducing coarse fraction content and resulting in no significant correlations between G_c , G_m , and G_{mc} for >32 mm gravel ($P > 0.05$). The 4–8 mm fraction dominated across all particle sizes, with 8–16 mm as the second most abundant. The 4–8 mm fraction exhibited the smallest coefficient of variation, indicating greatest stability.
- 3) This study proposes G_m as a monitoring indicator for land graveling degree for the first time. Extremely significant univariate linear relationships existed between different particle sizes (total) of G_m and G_c ($P < 0.01$). In practice, G_m is easier, faster, and more precise to measure than G_c . Additionally, $G_{mc}(0-5$ cm) showed extremely significant positive correlations with G_c and G_m ($P < 0.01$), enabling its use as an auxiliary monitoring

indicator for land graveling degree.

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