

Postprint: Monitoring and Assessment of Land Gravelization Degree Based on Quadratic Mean State

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Abstract

To improve the monitoring and evaluation accuracy of surface gravel coverage—the key indicator for land gravelization degree monitoring—throughout the entire process from sampling, measurement to assessment and analysis, this study designed quadrats of different sizes and investigated the secondary average state sampling method in Alxa League and Bayannur City, western Inner Mongolia Plateau. The ground measurement method and measurement plate method were compared to determine the optimal measurement approach for gravel coverage in small quadrats, while statistical characteristic analysis of means and medians from large and small quadrats was employed to identify the best evaluation method for gravel coverage in large quadrats and sample sites. Additionally, the necessity and preliminary concepts for establishing “pseudo-ecology” were explored. The results demonstrate that: (1) The secondary average state method enhances sample representativeness by reducing quadrat size and increasing sample number; furthermore, the reduction in quadrat size permits a corresponding decrease in measurement plate dimensions, contributing to further improvement in surface gravel coverage measurement accuracy. (2) Progressing from small quadrats to large quadrats and then to sample sites, data dispersion decreases progressively, with right-skewed and leptokurtic distributions becoming more pronounced, thereby increasingly highlighting the overall gravelization characteristics of the study area. Concurrently, high correlations exist between gravel coverage and gravel mass per unit surface area in large quadrats and sample sites, indicating that land gravelization degree monitoring based on secondary average state sampling yields results with high accuracy and stability, which can be utilized to improve both the monitoring process and precision of land gravelization degree assessment while enhancing field work efficiency.

Full Text

Monitoring and Evaluation of Land Gravelization Degree Based on Secondary Average State

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Abstract: To improve the monitoring and evaluation accuracy of surface gravel coverage—the key indicator of land gravelization degree—throughout the entire process from sampling and measurement to assessment, this study selected Alxa League and Bayannur City in the western Inner Mongolian Plateau as the research area. Different sample plot sizes were designed to investigate the secondary average state sampling method. The optimal measurement method for gravel coverage in small sample plots was determined by comparing the ground measurement method with the measuring disk method. The most suitable evaluation approach for gravel coverage in large sample plots and sample sites was identified through statistical characteristic analysis of means and medians. Additionally, the necessity and preliminary concepts for constructing “imitative ecology” were explored. The results indicate that: (1) The secondary average state method enhances sample representativeness by reducing sample plot size while increasing sample quantity. The reduction in sample plot size allows for a corresponding decrease in measuring disk dimensions, which further improves measurement precision of surface gravel coverage. (2) From small sample plots to large sample plots and then to sample sites, data dispersion progressively decreases while right-skewed and peaked distributions become more pronounced, making the overall characteristics of gravelization in the study area increasingly distinct. Moreover, strong correlations exist between gravel coverage and surface gravel mass per unit area at both large sample plot and sample site scales, demonstrating that land gravelization monitoring based on secondary average state sampling achieves high precision and stability. This approach can be used to improve monitoring procedures and accuracy while enhancing fieldwork efficiency.

Keywords: gravelization land; surface gravel coverage; surface gravel mass per unit area; secondary average state; imitative ecology

Introduction

Rock fragments are defined as relatively independent and non-fracturable rock debris [1]. They represent the product of comprehensive weathering and erosion processes, existing in three forms: distributed on the soil surface, partially embedded in soil, and completely buried within soil. Land gravelization (hereinafter referred to as gravelization) is a desertification process characterized by increased quantity or proportion of surface gravel fragments, which is more severe than sandification [2]. Gravelization occurs not only in arid desert regions but also in grassland and forest areas, with modern gravelization often associated with excessive land utilization and human disturbance [3].

The degree of land gravelization serves as a crucial parameter for characterizing soil degradation and ecosystem deterioration [4], and can be measured using various indicators including surface gravel coverage, gravel mass content, surface gravel mass per unit area, surface gravel volume per unit area, surface gravel number per unit area, gravel mass per unit volume in the topsoil layer, and gravel mass per unit mass of soil. Among these, gravel coverage and surface gravel mass per unit area are commonly used metrics, making research on their quantitative monitoring methods theoretically significant and practically valuable.

Gravel coverage is defined as the percentage of vertical projection area of gravel fragments relative to the total sampled surface area [5]. Since quantitative monitoring of gravel coverage involves both sampling and measurement, its accuracy depends on both sampling precision and measurement precision. Current measurement methods include the background color photography method [6], measuring disk method [7], viewpoint frame method [8], grid paper method [9], and image method [10]. Gao et al. [11] compared the viewpoint frame method and image method for measuring gravel coverage across different particle size ranges (2–6 mm, 6–20 mm, and 20–60 mm), finding that both methods achieved certain precision levels. The image method showed relatively weak observation capability and lower precision for small-sized gravel, while its observation precision for 20–60 mm gravel coverage was superior to the viewpoint frame method. Compared with traditional image methods, the background color photography method overcomes issues such as inability to distinguish sand particles from gravel in original photographs and interference from vegetation cover in gravel extraction, while increased contrast yields more accurate measurement results [12]. Wen et al. [13] employed the measuring disk method to investigate land gravelization characteristics on the Alxa Plateau, revealing extremely significant linear regression relationships between gravel coverage and surface gravel mass per unit area across different particle sizes, with both metrics showing increasing trends from east to west and from south to north. Compared with the background color photography method, the measuring disk method is easier to operate, has lower environmental requirements, and is more suitable for field applications. However, potential overlapping and gaps between gravel fragments when spread in the measuring disk may reduce measurement precision [14].

In addition to measurement errors inherent in these methods, sample plot size also affects monitoring precision of gravel coverage. Previous studies typically employed the following sampling approach: within each selected sample site, three 50 cm \times 50 cm plots were established at locations representing average gravel coverage states [13]. However, when using larger sample plots as reference, the human brain struggles to estimate the area scale of measured objects based on the reference system, and larger plots tend to produce greater measurement errors.

Therefore, building upon previous research and field sampling experience, this study proposes a novel gravel sampling method—the secondary average state method. This approach involves first establishing a 50 cm \times 50 cm large sample plot at the average coverage state location, then further selecting the average state within this plot to establish at least three 10 cm \times 10 cm small sample plots. Based on this secondary average state method, large and small sample plots were established, and both ground measurement method and measuring disk method were used to measure gravel coverage in small plots. The measuring disk size was also reduced from 30 cm \times 15 cm to 10 cm \times 5 cm (or 10 cm \times 10 cm for larger gravel particles). This allowed determination of the optimal measurement method for small plot gravel coverage. Subsequently, through statistical characteristic analysis of means and medians from large and small sample plots, the optimal evaluation approach for large sample plot and sample site gravel coverage was determined, thereby validating the feasibility and stability of the secondary average state sampling method. This research aims to comprehensively improve monitoring and evaluation precision of surface gravel coverage from sampling through measurement to assessment, ultimately establishing a more accurate and complete method for monitoring and evaluating land gravelization degree.

1.1 Study Area Overview

Alxa League and Bayannur City in the western Inner Mongolian Plateau were selected as the study area (Fig. 1 [Figure 1: see original paper]). Alxa League is located between 37.5°–42.6°N and 93.1°–106.6°E, covering an area of approximately 270,000 km². The region features a typical temperate continental climate characterized by aridity, low precipitation, strong winds, and abundant sand, with cold winters, hot summers, and large diurnal temperature ranges. It represents one of China's major sources of sandstorms. The terrain slopes gently northward with an average elevation of 900–1400 m, where deserts and gobi are widely distributed. Bayannur City is located between 40.2°–42.8°N and 105.2°–109.9°E, covering approximately 65,000 km². It has a typical mid-temperate continental monsoon climate with high central terrain and low northern/southern elevations. The east-west oriented Yinshan Mountains divide the region into distinct northern and southern landforms: the northern part consists of the Inner Mongolian Plateau at 1000–1400 m elevation, the central part comprises the Yinshan Mountains at 1500–2200 m elevation, and the southern part is the

Hetao Plain at 1030–1050 m elevation. The mountainous area can be further classified into four geomorphic types: medium-low mountains, low hills, intermontane basins, and valleys. Due to water erosion and wind erosion, gravel is predominantly distributed across low hills and intermontane basins.

Within the study area, gravel coverage is nearly zero in deserts, oases, saline-alkali lands, and lake bottoms with thick sand or soil layers. During this study, multiple sample sites in these areas were surveyed to confirm gravel presence and record conditions. In regions with varying degrees of land gravelization, sample sites for surface gravel coverage measurement were selected in relatively flat and open locations with different landforms, vegetation types, and gravelization degrees (for mountainous and hilly areas, the top, middle, and bottom sections were selected).

1.2.1 Sampling Method

Sample plot size and quantity directly affect the representativeness and accuracy of field surveys. Generally, appropriately sized and numerous plots facilitate more efficient and comprehensive data collection. Traditional sampling methods [13] determine gravel monitoring plot size based on the ratio between herbaceous vegetation monitoring plot size and plant canopy width: since larger individual or clustered plants typically measure $1\text{ m} \times 1\text{ m}$, while maximum gravel particle size generally does not exceed 10–20 cm, the ratio of 1:5–1:10 determines the $50\text{ cm} \times 50\text{ cm}$ plot size for gravel coverage monitoring [13].

However, considering that gravel particle sizes in the study area are generally smaller than 10 cm, this study further determined the small sample plot size as $10\text{ cm} \times 10\text{ cm}$ based on the $50\text{ cm} \times 50\text{ cm}$ large plot size. Building upon extensive field survey experience, this study proposes and employs the secondary average state method for sample collection. The specific procedure is as follows: first, within each sample site, the overall surface gravel distribution is assessed through reconnaissance to understand coverage differences, excluding areas with extremely low or high gravel coverage. The location representing average gravel coverage state is selected to establish a $50\text{ cm} \times 50\text{ cm}$ large sample plot. Then, within each large plot, the location representing average gravel coverage state is selected to establish at least three $10\text{ cm} \times 10\text{ cm}$ small sample plots (Fig. 2 [Figure 2: see original paper]).

Thus, compared with traditional sampling methods, the secondary average state method reduces sample plot size to appropriate dimensions while increasing sample quantity to more than three times the number of large plots, thereby enhancing sample representativeness and effectively reducing measurement errors.

1.2.2 Measurement Method

Gravel coverage in each small sample plot was measured sequentially using the ground measurement method and measuring disk method, generating ground

measurement gravel coverage sample data and measuring disk method gravel coverage sample data, respectively. Surface gravel mass within each small plot was then measured using an electronic balance with 0.1 g precision to generate surface gravel mass per unit area sample data. Gravel samples were collected on August 15–20, 2023, yielding 22 large sample plots and 66 samples (small plots) of gravel coverage and surface gravel mass per unit area data. Specific monitoring procedures were as follows:

- 1) **Ground measurement method:** Gravel fragments within the small plot were concentrated on one side (or corner) of the plot, arranged tightly without overlapping to form a rectangular gravel-covered area. By reading scale data (length and width) on adjacent borders of the small plot, the gravel coverage area value was obtained. Since the small plot area is 100 cm², the area value directly represents gravel coverage percentage.
- 2) **Measuring disk method:** All surface gravel fragments from each small plot were collected and placed in a measuring disk, spread as tightly as possible without mutual coverage. Gravel coverage by the measuring disk method was calculated based on length and width readings of the disk. To distinguish gravel approximately 2 mm in size from sand particles, a 2 mm gravel sieve was used in the field to separate gravel from fine particles such as sand, preventing sand contamination from affecting measurement results. An excessively large measuring disk may create excessive gaps between gravel fragments, while an excessively small disk is more likely to cause overlapping and increase measurement frequency, both potentially reducing measurement precision. Therefore, considering gravel particle sizes in the study area, this study used a 10 cm × 5 cm measuring disk, with length and width both reduced to one-third of the original large disk (30 cm × 15 cm). For larger gravel particles, a 10 cm × 10 cm measuring disk was used. The measuring disk, small sample plots, gravel sieve, and other tools used in this study are shown in Fig. 3 [Figure 3: see original paper].
- 3) After measuring with the disk, all surface gravel fragments from each small plot were collected in bags and weighed using an electronic balance to obtain surface gravel mass per unit area.

1.2.3 Evaluation Method

Both arithmetic mean and median are commonly used statistical measures for data level. The arithmetic mean is susceptible to extreme values in a dataset, while the median, being less affected by extremes, is often used to describe central tendency. For each large sample plot, the mean and median values of ground measurement gravel coverage, measuring disk method gravel coverage, and surface gravel mass per unit area were calculated. Standard deviation, coefficient of variation, skewness, and correlation with surface gravel mass per unit area were analyzed to determine the optimal evaluation method for large

sample plot and sample site gravel coverage.

Standard deviation (σ), the most commonly used measure of statistical distribution, is defined as the square root of the arithmetic mean of squared deviations from the sample mean. It reflects dispersion among individuals within a group and is affected by extreme values. Smaller standard deviation indicates more concentrated data, while larger standard deviation indicates more dispersed data. The calculation formula is:

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \mu)^2}$$

where $\{x_1, x_2, \dots, x\}$ is a sample set; n is sample size; μ is the sample mean.

Coefficient of variation (C), also known as relative variability, is a normalized measure of probability distribution dispersion, defined as the ratio of standard deviation to mean. Thus, it eliminates the influence of units or mean values when comparing variability across one or more datasets. The calculation formula is:

$$C_v = \frac{\sigma}{\mu}$$

Skewness (Sk), also called skewness coefficient, measures the direction and degree of distribution asymmetry, characterizing the degree of asymmetry of the probability density curve relative to the mean. It is defined as the third standardized moment of the sample. Generally, when data shows right-skewed distribution, $Sk > 0$, with larger Sk values indicating greater right skewness; when data shows left-skewed distribution, $Sk < 0$, with smaller Sk values indicating greater left skewness; when data shows symmetric distribution, $Sk = 0$. The calculation formula is:

$$Sk = \frac{1}{n} \sum_{i=1}^n \left(\frac{x_i - \mu}{\sigma} \right)^3$$

Kurtosis (K), also called kurtosis coefficient, describes the steepness of the distribution shape relative to the normal distribution. When $K = 0$, the data distribution has the same steepness as normal distribution; when $K > 0$, the distribution is steeper (leptokurtic); when $K < 0$, the distribution is flatter (platykurtic) than normal distribution. Larger absolute kurtosis values indicate greater deviation from normal distribution shape. The calculation formula is:

$$K = \frac{1}{n} \sum_{i=1}^n \left(\frac{x_i - \mu}{\sigma} \right)^4 - 3$$

Correlation coefficient (r) measures the degree of linear correlation between variables. While various definitions exist depending on research objectives, Pearson correlation coefficient is most commonly used. The calculation formula is:

$$r = \frac{\sum_{i=1}^n (x_i - \mu_x)(y_i - \mu_y)}{\sqrt{\sum_{i=1}^n (x_i - \mu_x)^2 \sum_{i=1}^n (y_i - \mu_y)^2}}$$

where $\{x_1, x_2, \dots, x\}$ and $\{y_1, y_2, \dots, y\}$ are two different sample sets; and are their respective means.

2.1 Small Sample Plot Gravel Coverage Measurement Results

Statistical values for ground measurement gravel coverage, measuring disk method gravel coverage, and surface gravel mass per unit area from 66 small sample plots are presented in Table 1. The results show extremely uneven distribution of gravel coverage and surface gravel mass per unit area within the study area. Particularly, surface gravel mass per unit area shows large differences between minimum and maximum values due to variations in gravel particle size and composition, causing the data distribution to exhibit peaked characteristics. However, since surface gravel mass per unit area was measured using an electronic balance, it is preliminarily determined to have the smallest error. The difference between ground measurement method and measuring disk method results is minimal, with correlation coefficients with surface gravel mass per unit area of 0.961 and 0.965, respectively, both passing significance tests at $\alpha = 0.01$, indicating that the measuring disk method has slightly higher measurement precision than the ground measurement method.

The minimum ground measurement gravel coverage is greater than that of the measuring disk method, likely due to sand particle contamination during ground measurement, while the maximum ground measurement value is smaller than the measuring disk method value, probably because the ground measurement method more easily causes gravel stacking. The measuring disk method results show slightly larger standard deviation, coefficient of variation, skewness, and kurtosis than ground measurement results, indicating more concentrated data distribution with relatively concentrated positions skewed more leftward. From the probability density distribution (Fig. 4 [Figure 4: see original paper]), samples are mainly distributed within the 20%-50% gravel coverage interval.

2.2 Large Sample Plot Gravel Coverage Evaluation

First, means and medians of ground measurement gravel coverage, measuring disk method gravel coverage, and surface gravel mass per unit area were calculated for each of the 22 large sample plots. Then standard deviation, coefficient

of variation, skewness, and kurtosis were computed for each set of means and medians, with results shown in Table 2 .

Similarly, large sample plots may contain locations with average gravel coverage state but significantly different gravel particle sizes and masses, leading to substantial mass differences among several samples within the same large plot. Since the mean is affected by extreme values in a dataset, its standard deviation, coefficient of variation, skewness, and kurtosis are significantly larger than those of the median. Therefore, this study concludes that calculating surface gravel mass per unit area for large sample plots using sample medians avoids influence from extreme values, providing greater stability and better reflecting the general state of gravel mass presence.

Standard deviation, coefficient of variation, skewness, and kurtosis show minimal differences between means and medians of ground measurement gravel coverage and measuring disk method gravel coverage, with means showing slightly smaller dispersion and skewness, and more platykurtic distribution compared to medians. However, since areas with extremely low and high gravel coverage were excluded during measurement following the secondary average state principle, this study concludes that calculating large sample plot gravel coverage using sample medians better reflects the overall gravelization level of the study area.

Correlation coefficients were calculated between means and medians of ground measurement gravel coverage and measuring disk method gravel coverage and means and medians of surface gravel mass per unit area, with results presented in Table 3 . The lowest correlations were found between means of ground measurement gravel coverage and measuring disk method gravel coverage and the mean of surface gravel mass per unit area (0.940 and 0.944, respectively), while the highest correlations were between medians of both methods and the median of surface gravel mass per unit area (0.950 and 0.956, respectively). This further demonstrates that gravel coverage and surface gravel mass per unit area calculated using sample medians show more consistent spatial distribution patterns, with measuring disk method gravel coverage showing higher correlation with surface gravel mass per unit area.

In summary, when evaluating gravel coverage and surface gravel mass per unit area for each large sample plot, the median evaluation method is superior to the mean method, and the measuring disk method provides higher precision data than the ground measurement method.

2.3 Sample Site Gravel Coverage Evaluation

This study used medians of measuring disk method gravel coverage and surface gravel mass per unit area to represent large sample plot values, then further calculated means and medians for sample site gravel coverage and surface gravel mass per unit area. Standard deviation, coefficient of variation, skewness, and kurtosis were analyzed, with results shown in Table 4 . Unlike large sample plot

results, medians showed slightly smaller dispersion and skewness, with more pronounced platykurtic distribution characteristics. Therefore, this study concludes that calculating sample site gravel coverage and surface gravel mass per unit area using means of large sample plot values better adheres to the secondary average state principle.

Correlation coefficients were calculated between sample site gravel coverage means and medians and surface gravel mass per unit area means and medians, with results presented in Table 5. Similarly, using means of large sample plot gravel coverage and surface gravel mass per unit area to calculate sample site values yielded the highest correlation (0.994), with scatter distribution shown in Fig. 5 [Figure 5: see original paper]. Sample points are basically distributed on both sides of the linear regression line with minimal dispersion, indicating that when sample site gravel coverage or surface gravel mass per unit area data are missing in practical work, interpolation using their linear relationship is feasible. This also demonstrates that surface gravel mass per unit area is an effective indicator for monitoring land gravelization degree.

Based on comprehensive analysis, sample site gravel coverage in the study area ranges from 11% to 88%, with a mean value of 39.15%. Following the threshold range and classification of gravelization degree based on surface gravel coverage by Miao et al. [11], sample sites were classified into gravelization levels (Table 6). Since areas with extremely low and high gravel coverage were excluded during sampling, selected sample sites mainly concentrated in moderate and severe gravelization levels, accounting for 40.9% and 59.1% of total sites, respectively. The distribution of sample site gravelization levels is shown in Fig. 6 [Figure 6: see original paper]. Moderate gravelization is primarily located in fine-gravel gobi on alluvial-proluvial plains at the southern foothills of the Badain Jaran stone residual mountains, with decreasing gravel coverage near desert areas. Severe gravelization is scattered across various alluvial or medium-gravel gobi areas, mainly consisting of gravel-sand mixtures where surface fine materials have been blown away by strong wind erosion, leaving gravel residues. Extreme gravelization is mainly located in the northern Yinshan Basin and near mountain bodies, representing typical denudation residual hill-type stone coarse-gravel gobi composed of denudation-eluvial materials [13].

3 Discussion

Previous studies on land gravelization degree evaluation primarily assessed land gravelization through surface gravel coverage [11, 13], with measurement methods mainly divided into three categories: visual estimation, ground measurement, and digital image methods. However, this study found that surface gravel mass per unit area is also an effective indicator for evaluating land gravelization degree, and that at the same surface gravel coverage level, greater surface gravel mass per unit area indicates more severe gravelization. Therefore, future work should develop more precise land gravelization monitoring and evaluation by constructing a comprehensive land gravelization assessment index through

normalization or dimensionless processing of surface gravel coverage and surface gravel mass per unit area.

Furthermore, although ground survey methods currently represent the primary approach for surface gravel coverage monitoring and offer higher accuracy than remote sensing interpretation methods, they are often limited by high costs and can only be implemented in key areas. Therefore, how to reasonably and efficiently integrate ground surveys with remote sensing interpretation represents a future research priority for gravelization land monitoring and evaluation [15].

As land gravelization degree intensifies and gravelization land area increases, the negative ecological effects of land gravelization become increasingly apparent, adversely impacting ecology, production, and daily life. The restoration of gravelization ecosystems (gravelization land) has become necessary and urgent, emerging as another important topic in ecological research. Its main content involves the restoration of artificial gravelization ecosystems and human-natural gravelization ecosystems. For gravelization land restoration and ecological construction, this study argues for the necessity of proposing and constructing the disciplinary system of “imitative ecology.” Imitative ecology is a discipline based on profound understanding of natural ecosystem composition, structure, dynamics, and characteristics and patterns of geological, hydrological, and meteorological elements. It involves mimicking the composition, structure, and functions of natural ecosystems for degraded land restoration (including gravelization) and ecological construction, enabling ecological engineering projects or human activities to achieve superior ecological effects. Gravelization ecosystem restoration must uphold ecological governance concepts that respect natural laws, prioritize natural recovery, combine natural recovery with artificial restoration, adapt measures to local conditions, determine vegetation based on natural precipitation, implement category-specific strategies, and adopt systematic and comprehensive approaches. Using “imitative ecology” as the theoretical foundation and methodological guide for gravelization ecosystem restoration and ecological construction practice can promote improved and sustainable high-quality development of ecological construction effects.

4 Conclusions

- 1) The secondary average state method retains the advantages of the measuring disk method—including ease of operation, low environmental requirements, and suitability for field applications—while enhancing sample representativeness by reducing sample plot size and increasing sample quantity. The reduction in sample plot size enables corresponding reduction in measuring disk dimensions, allowing more meticulous arrangement of gravel fragments and effectively reducing overlapping and gaps between fragments, thereby achieving higher measurement precision.
- 2) Although surface gravel mass per unit area is significantly affected by extreme values, it shows good correlation with surface gravel coverage,

with correlation strength following the order: sample site > large sample plot > small sample plot. Therefore, surface gravel mass per unit area is also an effective indicator for monitoring land gravelization degree.

- 3) From small sample plots to large sample plots and then to sample sites, data dispersion progressively decreases while right-skewed and peaked distributions become more prominent, making the overall characteristics of gravelization in the study area increasingly distinct.
- 4) Evaluating gravel coverage for large sample plots using sample medians and for sample sites using means of large sample plots better highlights the secondary average state principle followed during sample selection and shows good consistency with evaluation results of surface gravel mass per unit area. This demonstrates that land gravelization monitoring based on secondary average state sampling achieves high precision and stability, which can be used to improve land gravelization monitoring procedures and accuracy while enhancing fieldwork efficiency.

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