Postprint: Vegetation-Soil Response Characteristics under Near-Natural Restoration in Xilamuren Grassland

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Abstract

Through investigating the vegetation community characteristics and soil particle physical properties of grasslands under near-natural conditions in a fenced area at the northern foot of Yinshan Mountain, Inner Mongolia, this study explores the features of grassland communities and soil particle physical properties under natural wind erosion. The results indicate that: (1) Under full grassland coverage, Leymus chinensis and Leymus secalinus are the dominant species; when grassland coverage drops below 40%, Artemisia frigida, an indicator of grassland degradation, becomes dominant; moreover, with decreasing vegetation coverage, the biomass of grassland plant communities shows a declining trend, while both the Shannon-Wiener index and Simpson index exhibit a trend of initially increasing then decreasing; (2) Grassland vegetation coverage significantly affects the fractal dimension of surface soil particles ($P < 0.05$), with the fractal dimension of surface soil particles showing a significant decreasing trend as coverage declines, accompanied by obvious coarsening of surface soil particles; (3) Under near-natural conditions, when grassland vegetation coverage is low, the coarsening of surface 0-1 cm soil particles is particularly pronounced, with cumulative particle size differences reaching 1 mm; vertically, from the 3-5 cm and 1-3 cm soil layers to the 0-1 cm layer, the degree of soil particle coarsening intensifies, with cumulative differences in coarse particle size appearing at 0.1, 0.25, and 1 mm, respectively; (4) Under near-natural conditions, as grassland vegetation coverage increases, the surface soil receives effective protection through plant shading, soil particles gradually become finer, and bulk density slowly decreases. Under near-natural conditions, hierarchical and diverse changes occur in the grassland and soil environment, and the patchy changes in grassland vegetation make natural wind erosion possible in the Xilamuren fenced grassland under near-pristine conditions.

Full Text

Preamble

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Response of Vegetation-Soil Systems Under Almost-Natural Restoration in the Xilamuren Grassland

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Abstract

This study investigated the characteristics of plant communities and soil particle physical properties under almost-natural conditions in enclosed grasslands at the northern foot of the Yinshan Mountains in Inner Mongolia, aiming to explore the response patterns of grassland communities and soil particles under natural wind erosion conditions. The results showed that: (1) Under full vegetation coverage, *Leymus chinensis* and *Leymus secalinus* were the dominant species, while *Artemisia frigida*, an indicator species of grassland degradation, became dominant when vegetation coverage fell below 40%. Plant community biomass decreased significantly with declining vegetation coverage ($P < 0.05$). The Shannon-Wiener and Simpson diversity indices initially increased then decreased with coverage reduction. (2) Vegetation coverage significantly affected the fractal dimension of surface soil particles, which decreased markedly as coverage declined ($P < 0.05$), while sand content in surface soil increased substantially. (3) At low coverage, coarse-grained particles dominated the 0-1 cm soil layer, with cumulative particle differences reaching up to 1 mm, indicating severe surface coarsening. The degree of soil particle coarsening intensified from the 3–5 cm and 1–3 cm layers to the 0–1 cm layer. Cumulative differences for coarse particles appeared at 0.1, 0.25, and 1 mm in the 3–5 cm, 1–3 cm, and 0–1 cm layers, respectively. (4) With increasing vegetation coverage, surface soil received effective protection from plants, soil particles gradually became finer, and bulk density slowly decreased. Under almost-natural conditions, hierarchical and diverse changes occurred in grassland and soil environments, and the patchy vegetation changes in the Xilamuren enclosed area made natural wind erosion possible even under near-pristine conditions. When grassland coverage dropped to 40% and 20%, the Shannon-Wiener and Simpson indices reached their lowest values.

Keywords: enclosed grassland; almost-natural state; fractal dimension; soil particle size

Introduction

The low mountainous and hilly grassland region at the northern foot of the Yinshan Mountains in Inner Mongolia serves as both an important ecological barrier and a source of production and living resources for local herders, supporting sustainable regional economic development. Its normal ecological function is irreplaceable for regional and even northern China development. Enclosure for a certain period can help restore degraded grasslands to an almost-natural state, effectively reducing soil wind erosion rates and wind erosion intensity. Previous studies on enclosed grassland community structure and diversity have found that vegetation coverage changes significantly during enclosure and substantially impacts regional ecosystems. After long-term enclosure, community characteristics in arid and semi-arid grasslands show certain fluctuations as vegetation self-regulates to adapt to environmental changes, with height changing significantly. Due to the complexity of grassland ecosystems themselves and the 叠加 effects of grazing history and environmental factors, degraded grassland communities exhibit multi-stable state patterns and hysteresis after enclosure, giving enclosure both positive and negative effects on grasslands. This negative effect may transform uniformly distributed grasslands into patchy grasslands with sparse, low vegetation. Under long-term wind erosion, aboveground vegetation and belowground soil are closely related. Soil water content, silt, and clay particles show significant positive correlations with species richness index and vegetation coverage, making this a key research area in ecology. When surface fine particles lack effective vegetation protection, they are gradually removed, causing surface coarsening and changes in soil particle size distribution. Using fractal characteristics to expand research on soil particle size features has wide application. Soil particle fractal dimension can not only characterize soil particle size composition but also effectively reflect soil texture, fertility, and permeability. Research using soil particle volume distribution to describe fractal dimensions is well-established and can effectively explain soil coarsening phenomena. After years of grassland enclosure reaching an almost-natural state, studying soil particle size characteristics under different vegetation coverage is important for revealing wind erosion features of grassland surfaces under near-natural conditions. This study takes the Xilamuren grassland in Inner Mongolia as the research object, analyzing surface coverage and soil particle parameters of enclosed grasslands to provide a basis for rational grassland development, grazing management, and feasible enclosure strategies to ensure balanced local grassland ecology and economy.

1 Study Area Overview

The experimental site is located in the Xilamuren grassland, Damao Banner, Inner Mongolia (111°00 -111°20 E, 41°12 -41°31 N). This region has a temperate semi-arid continental monsoon climate with an average annual rainfall of approximately 281 mm, concentrated in summer. The area experiences 65 windy days annually, with sandstorm weather occurring mainly in spring and winter. The average annual wind speed is 4.5 m/s. The region is a wind-water composite erosion area where wind erosion dominates, causing surface water loss and particle coarsening. The main soil type is sandy loam with low nutrient content. The dominant constructive species is *Stipa krylovii*, with grassland communities dominated by *Leymus chinensis*, *Leymus secalinus*, and *Stipa krylovii*. Widespread species include *Artemisia frigida*, *Heteropappus altaicus*, and *Convolvulus ammannii*. Due to destructive tourism expansion and mining disturbances, the grassland in this area was severely degraded. Enclosure began in 2002 to exclude grazing and other human disturbances, with an enclosed area of 133 hm^2.

2 Sample Plot Selection and Sample Collection

To investigate characteristics of different coverage grasslands in the Xilamuren enclosed area under natural wind erosion, plant and soil samples were collected in August 2015. August represents the peak of vegetation growth accumulation when biomass reaches its maximum and grassland ecological functions are most active. During enclosure, vegetation self-regulates to adapt to the environment, developing a patchy distribution pattern after years of succession, which is a common and relatively stable vegetation formation in arid and semi-arid regions. Within the enclosed area, typical sampling zones were selected according to vegetation coverage gradients of approximately 0%, 5%, 20%, 40%, 60%, 80%, and 100%. Each sampling zone measured 30 m × 30 m, with three replicate plots per coverage level. In each plot, plant species were counted, heights measured, and aboveground vegetation, standing dead material, and surface litter harvested from 1 m × 1 m quadrats. Fresh weights were measured in the field, then oven-dried in the laboratory to determine dry weights. After vegetation survey completion, soil samples were collected using steel rings at depths of 0–5, 5-10, 10–20, and 20–30 cm to measure bulk density by the drying method. To analyze surface soil coarsening, the 0–5 cm layer was further subdivided into 0–1, 1–3, and 3–5 cm layers. Samples were air-dried and analyzed using a Malvern Mastersizer 3000 laser particle size analyzer to determine soil particle size composition.

3 Methods

3.1 Important Value and Vegetation Community Diversity Index

Vegetation community diversity was assessed using the Shannon-Wiener diversity index, Simpson dominance index, and Pielou evenness index, calculated as follows:

(1) Shannon-Wiener diversity index: $H = -\sum_{i=1}^{S} P_i \ln P_i$, where $P_i = N_i/N$, N_i is the important value of species i in the quadrat, and N is the sum of

important values for all plants in the quadrat.

(2) Simpson dominance index: $D = \sum_{i=1}^{S} P_i^2$

(3) Pielou evenness index: $J = H/\ln S$

3.2 Particle Size Parameters

According to the USDA soil texture classification system, soil particle sizes were divided into: 0-0.002 mm, 0.002-0.05 mm, 0.05-0.1 mm, 0.1-0.25 mm, 0.25-0.5 mm, 0.5-1 mm, 1-2 mm, and 2-2.85 mm.

Soil particle volume fractal dimension (D_v) can reflect soil particle composition and texture information. Using fractal theory, the fractal model was established with the expression:

$$\log\left(\frac{V(r<\bar{R}_i)}{V_t}\right) = (3 - D_v)\log\left(\frac{\bar{R}_i}{R_{\max}}\right)$$

where $\bar{R}_i$ is the average diameter between sieve sizes R_i and R_{i+1}, $V(r < \bar{R}_i)$ is the cumulative volume of particles smaller than $\bar{R}_i$, V_t is the total volume of all particle sizes, and $R_{\max}$ is the average diameter of the largest particle size. During calculation, log values of both sides were obtained and linearly fitted using Origin 8.0 to determine the slope and thus the fractal dimension.

Soil particle size parameters were calculated using the Φ scale, where $d = -\log_2 D$, with D being the particle diameter in mm. d_{50} represents the median particle diameter corresponding to 50% volume percentage.

3.3 Data Analysis

Excel was used for preliminary data organization. SPSS 17.0 was used for one-way ANOVA to test differences in plant indicators among sample plots, and Pearson correlation analysis was performed between vegetation characteristics, biomass, and soil particle fractal dimension. Origin 8.0 was used for plotting and analysis.

4 Results

4.1 Vegetation Coverage Status

After 13 years of enclosure, the grassland in this area had recovered to a near-primary community type. Changes in coverage presented a typical succession pattern under natural conditions. Dominant species shifted from *Leymus chinensis* and *Leymus secalinus* to *Stipa krylovii*, then to *Stipa krylovii* and *Artemisia frigida* communities. Aboveground community biomass and litter changed significantly with coverage. Biomass showed a significant decreasing trend with reduced coverage ($P < 0.05$), while litter showed no significant differences. When vegetation coverage was 40% and 20%, dominant constructive species like *Leymus* no longer appeared, while indicator species of degradation such as *Artemisia frigida* and *Convolvulus ammannii* emerged and increased in importance value. *Artemisia frigida* reached its maximum importance value at 20% coverage, while *Convolvulus ammannii* and unpalatable plants like *Euphorbia fischeriana* increased in importance at lower coverage levels.

Steppe vegetation condition under enclosure

4.2 Vegetation Diversity Characteristics

Vegetation diversity, evenness, and dominance in the study area were significantly influenced by vegetation coverage under long-term enclosure. The Shannon-Wiener index, which integrates evenness and richness, is the best index for expressing species diversity. Both the Shannon-Wiener and Simpson indices showed initial increases followed by decreases with declining coverage, indicating that community composition was most complex and stable at 40% and 20% coverage. At full coverage, species diversity was lowest, suggesting that excessive vegetation coverage under near-pristine conditions leads to simplified community composition and reduced stability. The intermediate coverage levels (40% and 20%) showed the highest diversity and dominance indices, with *Artemisia frigida* as a distinct indicator species, demonstrating that higher vegetation coverage is not always better for community structural stability.

Species diversity in different vegetation coverage

4.3 Soil Fractal Dimension Characteristics Under Different Coverage

Data showed no significant differences in fractal dimension of deep soil layers (20-30 cm) under different coverage levels, as these layers share similar parent material and initial conditions. However, vegetation coverage significantly affected surface soil fractal dimension (0-1, 1-3, and 3-5 cm), which decreased significantly with reduced coverage ($P < 0.05$). Fractal dimension showed significant positive correlation with clay and silt content and negative correlation with sand content. As coverage increased, fine particle content increased and soil gradually refined. At low coverage (<40%), surface soil showed obvious coarsening with relatively low fractal dimensions. Vertically, significant differences existed among 0-1, 1-3, and 3-5 cm layers, with fractal dimension gradually decreasing from deeper to surface layers. At 100% coverage, no differences existed among surface layers, indicating complete soil structure recovery. At 0% coverage, no vertical differences were observed among 0-1, 1-3, and 3-5 cm layers, showing the most severe coarsening.

Soil fractal dimension in different vegetation coverage

4.4 Surface Soil Particle Size Parameter Characteristics

Vegetation coverage is associated with wind erosion intensity. Evaluating soil surface coarsening requires considering both horizontal coverage and vertical depth dimensions. As vegetation coverage decreased, average particle size increased continuously, with bare sand showing the coarsest particles. The rate of coarsening was highest at 5% and 0% coverage. Particle size generally became finer with depth, though the overall trend was not obvious. The maximum average distance between soil particle cumulative frequency curves of different coverage levels appeared at 0–1 cm, with cumulative differences occurring at 0.1, 0.25, and 1 mm. Coarse particles (>1 mm) increased most significantly at low coverage. Fine particles (<0.25 mm) showed a decreasing trend with reduced coverage, while the proportion of coarse particles increased gradually. The increase rate of >0.25 mm particles was 11.78% in the 0–1 cm layer and 5.63% in the 1–3 cm layer, demonstrating strong protective effects of vegetation coverage on soil particles.

Soil particle parameters in different vegetation coverage
[Figure 1: see original paper] Soil particle size characteristics in 0–1 cm layer
[Figure 2: see original paper] Soil particle size characteristics in 1–3 cm layer
[Figure 3: see original paper] Soil particle size characteristics in 3–5 cm layer

4.5 Relationship Between Soil Bulk Density and Vegetation Coverage

Soil bulk density characterizes soil structure condition. Correlation analysis revealed a highly significant negative correlation between soil bulk density and vegetation coverage ($r = -0.964$, $P < 0.001$). As grassland coverage increased after years of enclosure, soil bulk density gradually decreased, indicating that soil fertility and structure gradually recovered toward a pristine state. The anti-erodibility of grassland increased significantly with coverage.

[Figure 4: see original paper] Relationship between vegetation coverage and 0–5 cm soil bulk density

5 Discussion

Previous studies in debris flow-prone areas found positive correlations between grassland coverage and soil surface fractal dimension. This study similarly found that fractal dimension decreased with declining coverage. The study area has sandy loam soil, and research shows that fractal dimension effectively reflects soil texture, being significantly negatively correlated with medium-coarse sand and fine sand content, and positively correlated with silt and clay content. No significant differences in fractal dimension were found in deep soil layers (20–30 cm) because these layers have similar parent material. However, significant differences appeared in surface layers (0–1, 1–3, and 3–5 cm) under different coverage levels. At 100% coverage, no vertical differences existed among surface layers, indicating complete recovery of soil structure. At 0% coverage, no differences existed among 0–1, 1–3, and 3–5 cm layers, showing the most severe coarsening. This pattern is consistent with research on grassland enclosure duration.

The relationship between vegetation coverage and soil particle fractal dimension can be analyzed from positive and negative perspectives. The negative direction shows that decreasing coverage leads to reduced fractal dimension and soil coarsening, with natural wind erosion causing increased coarse particles on the surface. Bare land shows more severe coarsening than vegetated areas. The positive direction shows that increasing coverage leads to gradual fractal dimension increase, with fine particle content increasing and soil refining. During grassland restoration after grazing prohibition, fine particles are preserved and recovered, gradually improving soil structure.

This study used finer sampling methods than previous research, subdividing the 0–5 cm layer into 0–1, 1–3, and 3–5 cm layers because soil below the crust tends to refine. Cumulative particle differences appeared at 0.1, 0.25, and 1 mm, with the most severe coarsening in the 0–1 cm layer. The increase rate of coarse particles was 11.78% under vegetation protection and 5.63% without protection, demonstrating the significant protective effect of vegetation coverage.

After enclosure, the grassland showed overall improvement. When vegetation coverage exceeded 60%, dominant species were *Leymus chinensis* and *Stipa krylovii* with good soil texture but low diversity indices, consistent with research on typical grasslands. However, during vegetation succession, patchy coverage changes caused wind erosion on sparsely vegetated surfaces, leading to surface coarsening. Sparse vegetation and degradation indicator species like *Artemisia frigida* and *Convolvulus ammannii* tend to aggregate, causing soil structure damage and increased bulk density during wind erosion.

6 Conclusion

After 13 years of enclosure, the Xilamuren grassland recovered to a near-natural state with typical steppe characteristics and *Stipa krylovii* as the dominant species. Aboveground plant communities changed significantly, with biomass decreasing as vegetation coverage declined. The Shannon-Wiener and Simpson indices showed initial increases followed by decreases. Under near-natural conditions, natural wind erosion occurred even in enclosed grasslands, with surface soil coarsening significantly due to vegetation differences. Vertically, soil particle coarsening intensified from deeper to surface layers, with cumulative differences for coarse particles appearing at 0.1, 0.25, and 1 mm in the 3–5 cm, 1–3 cm, and 0–1 cm layers, respectively. Enclosure played a positive role in restoring grassland soil structure.

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