Effects of Long-term Enclosure on Soil Aggregate Stability and Erodibility in Alpine Grasslands: Postprint

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Abstract

To evaluate the effects of long-term enclosure on soil aggregate stability and erodibility, the Bayinbuluke alpine grassland (alpine meadow, alpine meadow steppe, and alpine steppe) with long-term enclosure (fenced in 1984) and free grazing plots were selected as the study sites. Water-stable aggregate fractions, Mean Weight Diameter (MWD), Geometric Mean Diameter (GMD), and soil erodibility (K value) in the 0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm soil layers were analyzed. The results showed: (1) The minimum MWD value occurred in the 0-5 cm soil layer of the alpine meadow under free grazing treatment, with a value of 1.75 mm. There were no significant differences in MWD and GMD in the 20-30 cm soil layer between enclosure and free grazing treatments for alpine meadow and alpine meadow steppe ($P>0.05$), while the differences were significant for alpine steppe ($P<0.05$). (2) The highest K value of 0.136 was found in the 10-20 cm soil layer of the alpine steppe under grazing treatment, showing the weakest erosion resistance among all treatments. (3) Redundancy analysis revealed that total potassium, total phosphorus, pH, and soil organic carbon (SOC) were the most important factors influencing soil erodibility K value and MWD. (4) The 0-10 cm soil layer of the Bayinbuluke alpine grassland was dominated by >2 mm macroaggregates, and long-term enclosure resulted in stronger soil aggregate stability in the 0-10 cm soil layer; moreover, grassland type, enclosure, and soil layer all had significant effects on soil aggregate stability and erodibility, indicating that long-term enclosure can improve the water stability and erosion resistance of soil aggregates.

Full Text

Effects of Long-Term Enclosure on Soil Aggregate Stability and Erodibility in Bayinbuluk Alpine Grassland

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Abstract

To evaluate the effects of long-term enclosure on soil aggregate stability and erodibility, we selected long-term enclosed (fenced in 1984) and free-grazing plots across three alpine grassland types (alpine meadow, alpine meadow steppe, and alpine steppe) in Bayinbuluk as study sites. We analyzed water-stable aggregate composition, mean weight diameter (MWD), geometric mean diameter (GMD), and soil erodibility (K value) in soil layers of 0–5 cm, 5–10 cm, 10–20 cm, and 20–30 cm. The results showed that: (1) The minimum MWD value (1.75 mm) occurred in the 20–30 cm layer of alpine meadow under free grazing. No significant differences were observed in MWD and GMD between enclosure and grazing treatments in the 20–30 cm layer for alpine meadow and alpine meadow steppe ($P > 0.05$), whereas differences were significant for alpine steppe ($P < 0.05$). (2) The K value was highest (0.136) in the 10–20 cm layer under free grazing in alpine steppe, indicating the weakest anti-erosion capacity among all treatments. (3) Redundancy analysis revealed that total potassium, total phosphorus, and pH were the primary factors influencing soil erodibility K values, while soil organic carbon was the most important factor affecting MWD. (4) The 0–10 cm layer in Bayinbuluk alpine grassland was dominated by >2 mm macroaggregates. Long-term enclosure enhanced aggregate stability in the 0–10 cm layer. Moreover, grassland type, enclosure, and soil layer all significantly affected soil aggregate stability and erodibility, demonstrating that long-term enclosure can improve water stability and erosion resistance of soil aggregates.

Keywords: long-term enclosure; alpine grassland; soil aggregate stability; soil erodibility; Bayinbuluk

Introduction

Grassland ecosystems cover 40% of the global terrestrial area and play crucial roles in controlling soil erosion and supporting livestock development. Soil aggregates are porous structural units formed through the synergistic action of mineral particles, organic matter, soil microorganisms, and freeze-thaw cycles. Organic carbon acts as a binding agent that is essential for aggregate formation and composition. Soil aggregates serve as key indicators for evaluating soil quality and are typically divided into macroaggregates (>0.25 mm) and microaggregates (<0.25 mm). As independent structural units, their composition regulates soil physical, chemical, and biological processes. The quantity and stability of water-stable aggregates are critical factors controlling soil erosion resistance.

Soil erodibility reflects the susceptibility of soil to erosion forces and represents the sensitivity of soil to detachment and transport by erosive agents. It is an intrinsic factor affecting soil erosion rates and forms the basis for quantitative soil erosion research. Bayinbuluk alpine grassland, located on the southern slope of the central Tianshan Mountains, is China' s largest subalpine grassland and second largest alpine grassland. This typical arid alpine ecosystem is highly sensitive and vulnerable to climate change. Climate change and human activities have intensified freeze-thaw cycles and desertification, causing widespread grassland degradation that destroys soil structure. Livestock trampling particularly alters soil structural properties and reduces erosion resistance.

Enclosure is an effective approach for restoring degraded grassland ecosystems, including recovery of aboveground biodiversity, biomass, soil structure, and nutrient cycling. Previous studies have shown that enclosure enhances carbon sequestration capacity, with plant carbon storage increasing by 1.5–2.5 times and soil carbon pools increasing by 1.2–1.8 times after 6–8 years of grazing exclusion. Enclosure also improves soil aggregate water stability and erosion resistance. This study investigates how enclosure affects soil aggregate stability and erodibility across three grassland types to provide scientific basis for understanding the response mechanisms between grazing and soil aggregate characteristics, and to inform ecological restoration strategies for degraded grasslands like Bayinbuluk.

Materials and Methods

1.1 Study Area The study area is located in Bayinbuluk alpine grassland on the southern slope of the central Tianshan Mountains, with geographic coordinates of 83°42 E, 42°43 -43°58 N, and elevation of 2400–3500 m. The region has a typical alpine climate with mean annual temperature of -4.8 °C (minimum -48 °C), annual precipitation of 276.2 mm, annual evaporation of 1247.5 mm, and snow cover for 150–180 days. There is no absolute frost-free period. Dominant species include *Carex tristachya*, *Festuca ovina*, *Stipa purpurea*, and *Poa pratensis*.

1.2 Sample Plot Setup and Soil Collection In August 2019, we selected long-term enclosed plots (fenced in 1984, 20 m × 20 m) within three grassland types (alpine meadow, alpine meadow steppe, and alpine steppe) as study sites. Each enclosed plot had a corresponding free-grazing control plot outside the fence. Within each plot, we established three 2 m × 2 m subplots with intervals >20 m. Undisturbed soil samples were collected from depths of 0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm in each subplot [Figure 2: see original paper]. Samples were transported to the laboratory and air-dried while removing plant roots and stones.

1.3 Sample Analysis Water-stable aggregates were separated using the wet sieving method. A 100 g soil sample was placed on a nest of sieves (2 mm, 0.25 mm, 0.053 mm) and immersed in distilled water. The sieves were manually oscillated for 3 minutes with 3 cm amplitude at 30 cycles per minute. After drying at 65 °C, water-stable aggregates of different sizes were obtained. Mean weight diameter (MWD) and geometric mean diameter (GMD) were calculated using:

$$MWD = \sum_{i=1}^{n} W_i \times d_i$$

$$GMD = \exp\left(\sum_{i=1}^{n} W_i \times \log d_i\right)$$

where d_i is the mean diameter of aggregates in the ith size fraction and W_i is the mass percentage of aggregates in that fraction.

Soil erodibility K value was calculated following Shirazi and Boerama (1984):

$$K = 7.954 \times \left[0.0017 + 0.0494 \times \exp(-0.5 \times (\log GMD + 1.675)^2)\right]$$

Soil organic carbon was determined by the potassium dichromate external heating method. Total nitrogen was measured by the Kjeldahl method. Total phosphorus was determined colorimetrically after $HClO_4$-H_2SO_4 digestion. Total potassium was measured by flame photometry. Soil pH was measured in a 1:2.5 soil-water ratio.

1.4 Data Analysis Data were analyzed using SPSS 25.0 with one-way ANOVA and Duncan' s multiple comparison tests. Origin software was used for plotting. Redundancy analysis (RDA) was performed to examine relationships between aggregate characteristics, K values, and environmental factors.

Results

2.1 Effects of Long-Term Enclosure on Soil Organic Carbon Content Soil organic carbon (SOC) content decreased with soil depth across all grassland types [Figure 3: see original paper]. SOC content under enclosure was significantly higher than under free grazing ($P < 0.05$). The highest SOC content

(20.91 $g \cdot kg^{-1}$) occurred in the 0–5 cm layer of alpine meadow under enclosure, significantly higher than other treatments ($P < 0.05$). In alpine meadow steppe and alpine steppe, SOC content in the 20–30 cm layer was significantly lower than in other layers ($P < 0.05$). No significant differences in SOC content were observed between enclosure and grazing treatments in the 20–30 cm layer of alpine meadow steppe and alpine steppe ($P > 0.05$).

2.2 Effects of Long-Term Enclosure on Water-Stable Aggregate Distribution, Stability, and Erodibility The distribution of water-stable aggregates is shown in [Figure 5: see original paper]. In the 0–5 cm layer of alpine meadow, the >2 mm aggregate content under enclosure (67.58%) was significantly higher than under grazing ($P < 0.05$). No significant differences were observed in other layers. In alpine meadow steppe, the >2 mm aggregate content in the 0–5 cm layer was significantly higher under enclosure (48.73%) compared to grazing ($P < 0.05$). In alpine steppe, enclosure significantly increased >2 mm aggregate content in the 0–5 cm layer.

MWD and GMD values under different treatments are presented in . In the 0–5 cm layer of alpine meadow, MWD under enclosure (4.22 mm) was significantly higher than under grazing (1.75 mm) ($P < 0.05$). Similar patterns were observed in other grassland types. The minimum MWD (1.75 mm) occurred in the 20–30 cm layer of alpine meadow under grazing. No significant differences in MWD and GMD were found between treatments in the 20–30 cm layer for alpine meadow and alpine meadow steppe ($P > 0.05$), but differences were significant for alpine steppe ($P < 0.05$).

Soil erodibility K values are shown in [Figure 6: see original paper]. K values were significantly higher under grazing than enclosure across all layers in alpine steppe. The highest K value (0.136) occurred in the 10–20 cm layer under grazing in alpine steppe, indicating the weakest anti-erosion capacity. No significant differences in K values were observed between treatments in alpine meadow and alpine meadow steppe ($P > 0.05$).

2.3 Correlations Between Aggregate Composition, MWD, GMD, K Values, and Soil Chemical Properties Correlation analysis revealed that >2 mm aggregate content was extremely significantly positively correlated with MWD and GMD ($P < 0.01$), and extremely significantly negatively correlated with K value ($P < 0.01$). Conversely, <0.053 mm aggregate content showed extremely significant negative correlations with MWD and GMD ($P < 0.01$), and extremely significant positive correlation with K value ($P < 0.01$). The 2–0.25 mm aggregate content was significantly positively correlated with MWD and GMD ($P < 0.05$), and significantly negatively correlated with K value ($P < 0.05$).

Redundancy analysis [Figure 8: see original paper] showed that for alpine meadow, environmental factors explained 46.43% of variation in aggregate stability and K values, with total phosphorus, total potassium, and pH being the most important factors influencing K value. For alpine meadow steppe, environmental factors explained 54.52% of variation, with soil organic carbon being the most important factor affecting aggregate stability. For alpine steppe, environmental factors explained 59.62% of variation, with soil organic carbon having the greatest influence.

Multivariate analysis of variance showed that grassland type, enclosure, and soil layer had highly significant effects on MWD, GMD, and K values ($P < 0.01$).

Discussion

3.1 Effects of Enclosure on Aggregate Composition and Water Stability The 0–10 cm soil layer in all three grassland types was dominated by >2 mm macroaggregates, with higher contents under enclosure than grazing. This enhanced stability occurs because enclosure reduces disturbance from livestock trampling, allowing greater accumulation of plant residues and root secretions that provide energy for microbial activity. Increased microbial activity, particularly fungal growth, promotes formation of microaggregates within macroaggregates, enhancing their stability. The long-term accumulation of organic residues under enclosure maintains microbial activity in the surface soil, facilitating macroaggregate formation and structural stability. Different vegetation types produce varying quantity and quality of litter inputs, affecting soil organic carbon content and the binding agents that form macroaggregates, ultimately leading to differences in aggregate composition characteristics.

Previous studies have demonstrated that enclosure is an important pathway for restoring soil organic carbon pools in degraded grasslands. Our results align with Zhang et al.' s findings on the Loess Plateau, which showed that enclosure promotes vegetation recovery and increases aggregate stability, thereby enhancing resistance to soil erosion. The significantly higher MWD and GMD values under enclosure indicate greater aggregate stability, as these indices reflect larger mean aggregate diameters and stronger aggregation.

3.2 Effects of Enclosure on Soil Erodibility Soil erodibility represents the difficulty with which soil is eroded, reflecting its sensitivity to detachment and transport by erosive forces. The significantly higher K values under grazing in alpine steppe indicate weaker anti-erosion capacity compared to enclosed plots. This difference likely arises because enclosure increases vegetation cover and organic matter inputs, improving soil physicochemical properties and promoting new aggregate formation. Enhanced aggregate stability subsequently improves erosion resistance, consistent with findings from Dou et al. on the Loess Plateau.

The highest K value (0.136) in the 10–20 cm layer under grazing suggests that subsurface soils are particularly vulnerable to erosion when surface protection is removed. Enclosure mitigates this vulnerability by increasing organic carbon inputs and reducing physical disturbance, thereby strengthening soil structure throughout the profile.

3.3 Correlations Between Aggregate Characteristics and Soil Properties Our analysis revealed that K value was extremely significantly positively correlated with <0.053 mm aggregate content and extremely significantly negatively correlated with >2 mm aggregate content. This demonstrates that soils with more small aggregates have weaker erosion resistance, while macroaggregate-dominated soils are more resistant. Soil organic carbon was the primary factor influencing aggregate stability, as it serves as the binding agent that cements small aggregates into larger, more stable units. The formation of >0.25 mm aggregates requires cementing substances, and organic carbon content directly affects this process.

Total phosphorus, total potassium, and pH were identified as the main factors affecting K values. These physicochemical properties influence aggregate formation and stability through their effects on microbial activity and mineral-organic interactions. The multivariate analysis confirmed that grassland type, enclosure treatment, and soil layer all significantly influence aggregate stability and erodibility, highlighting the complex interactions between management practices and inherent soil characteristics.

Conclusion

Based on our analysis of soil aggregate stability, erodibility, and chemical properties in Bayinbuluk alpine grassland, we conclude:

1. Long-term enclosure increased the mass fraction of >2 mm macroaggregates and enhanced aggregate stability in the 0–10 cm soil layer across all grassland types.
2. Free grazing in alpine steppe resulted in significantly higher K values compared to other treatments, indicating the weakest soil anti-erosion capacity.
3. Soil total phosphorus, total potassium, and pH were the primary factors influencing soil erodibility K values, while soil organic carbon was the most important factor affecting aggregate stability.
4. Grassland type, enclosure treatment, and soil layer all significantly affected soil aggregate stability and erodibility, demonstrating that long-term enclosure effectively improves water stability and erosion resistance of soil aggregates in alpine grassland ecosystems.

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