Influence of grazing patterns on the stability of soil aggregates in semi-arid grasslands (Postprint)

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Abstract

Global grassland degradation necessitates the identification of sustainable grazing management strategies. In semi-arid regions, grazing exclusion (GE), cold-season grazing (CG), and free grazing (FG) represent common practices in grassland ecosystems, yet the long-term ecological consequences of these patterns on plant community structure and soil aggregate stability remain inadequately elucidated. In this study, we evaluated the effects of GE, CG, and FG on soil organic carbon, soil water content, soil bulk density, soil aggregates, and vegetation indicators in Xilamuren steppe, a semi-arid grassland in northern China through field sampling and laboratory analyses in 2024. Our findings revealed that, compared to CG and FG, GE significantly enhanced aboveground and belowground biomass, species diversity, and soil physical-chemical properties in the 0–30 cm layer. The dominant plant species in GE and CG sites were Stipa krylovii, Leymus chinensis, and Agropyron cristatum, whereas Stipa krylovii, Artemisia frigida, and Leymus chinensis were predominant in FG site. Different grazing patterns led to distinct soil aggregate distributions, with >2.00 and <0.25 mm aggregates exhibiting the highest content in different soil layers depending on the grazing patterns. All grazing management strategies significantly improved soil aggregate stability, with the overall stability following the order: GE>CG>FG. Furthermore, random forest modeling identified plant species diversity, plant growth traits, and grazing patterns as the primary determinants of soil aggregate stability. Collectively, these results offer valuable insights into the sustainable management and ecological restoration of semi-arid grasslands under different grazing pressures.

Full Text

Preamble

J Arid Land (2026) 18(2): 322–338 doi: 10.1016/j.jaridl.2026.02.006; CSTR: 32276.14.JAL.20250296 Influence of grazing patterns on the stability of soil aggregates in semi-arid grasslands LI Haonian1,2, MENG Ruibing1, MENG Zhongju1,2, GE Rile1,2*, WU Xiaolong1 1 College of Desert Control Science and Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China; 2 State Key Laboratory of Water Engineering Ecology and Environment in Arid Area, Inner Mongolia Agricultural University, Hohhot 010018, China Abstract: Global grassland degradation necessitates the identification of sustainable grazing management strategies. In semi-arid regions, grazing exclusion (GE), cold-season grazing (CG), and free grazing (FG) represent common practices in grassland ecosystems, yet the long-term ecological consequences of these patterns on plant community structure and soil aggregate stability remain inadequately elucidated. In this study, we evaluated the effects of GE, CG, and FG on soil organic carbon, soil water content, soil bulk density, soil aggregates, and vegetation indicators in Xilamuren steppe, a semi-arid grassland in northern China through field sampling and laboratory analyses in 2024. Our findings revealed that, compared to CG and FG, GE significantly enhanced aboveground and belowground biomass, species diversity, and soil physical-chemical properties in the 0–30 cm layer. The dominant plant species in GE and CG sites were Stipa krylovii, Leymus chinensis, and Agropyron cristatum, whereas Stipa krylovii, Artemisia frigida, and Leymus chinensis were predominant in FG site. Different grazing patterns led to distinct soil aggregate distributions, with >2.00 and <0.25 mm aggregates exhibiting the highest content in different soil layers depending on the grazing patterns. All grazing management strategies significantly improved soil aggregate stability, with the overall stability following the order: GE>CG>FG. Furthermore, random forest modeling identified plant species diversity, plant growth traits, and grazing patterns as the primary determinants of soil aggregate stability. Collectively, these results offer valuable insights into the sustainable management and ecological restoration of semi-arid grasslands under different grazing pressures.

Keywords: soil aggregate stability; grazing patterns; grazing exclusion; species diversity; soil physical-chemical properties; semi-arid grasslands Citation: LI Haonian, MENG Ruibing, MENG Zhongju, GE Rile, WU Xiaolong. 2026. Influence of grazing patterns on the stability grasslands. https://doi.org/10.1016/j.jaridl.2026.02.006; https://cstr.cn/32276.14.JAL.20250296 aggregates of Arid semi-arid Journal 18(2):

Land,

1 Introduction

Grassland ecosystems are a vital component of the terrestrial biosphere, covering about 40.00% of the Earth’ s land surface and delivering a diverse range of essential ecosystem services and functions (Lewińska et al., 2023). Grazing, as one of the most widespread land-use practices in grasslands, significantly affects regional ecological stability by altering plant species composition and influencing soil processes (Klaus et al., 2018). However, prolonged grazing and unsustainable management have resulted in extensive grassland degradation, marked by reduced vegetation cover, deteriorated soil structure, and diminished ecological function (Kölbl et al., 2011; Sun et al., 2024). To mitigate these adverse trends, a variety of grazing patterns, including grazing exclusion (GE) and cold-season grazing (CG), have been adopted across different regions (Wu et al., 2022). These patterns aim to balance ecological restoration with the sustainable development of animal husbandry (Søndergaard et al., 2025).

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Different grazing patterns, such as free grazing (FG), GE, and CG, significantly influence both plant communities and soil physical-chemical properties in grassland ecosystems. Although these three grazing patterns differ markedly in their spatial disturbance intensities, they collectively affect key feedback processes within grassland ecosystems (Wei et al., 2022; Xu et al., 2022).

Previous studies have shown that GE can restore biodiversity and improve soil structure, but long-term GE may increase the risk of species simplification (Song et al., 2020; Yang et al., 2023). In contrast, FG can maintain grassland productivity under moderate intensity by promoting compensatory plant growth and nutrient cycling, but long-term over-utilization will lead to biomass decline, soil nutrient loss, and structural degradation (Xun et al., 2018). As an integral grazing strategy, CG has gained increasing attention due to its distinct ecological roles. Studies have suggested that CG considerably alters plant community structure and soil aggregate stability by affecting litter decomposition pathways, regulating freeze–thaw soil dynamics, and modifying microbial activities (Roberts and Johnson, 2021; Santiago et al., 2021; Zweigel et al., 2024).

Compared with grazing in growing seasons, CG primarily consumes litter and dormant plants, thereby reducing canopy cover by 15.00%–30.00%; this reduction enhances surface solar radiation absorption and indirectly promotes early spring germination (Liu et al., 2019a).

Nevertheless, the ecological effects of these management measures are time-heterogeneous, and effective strategies must be tailored according to grazing duration (Liu et al., 2021; Ribeiro et al., 2023). A previous global meta-analysis categorized grazing management lasting 5–10 a as intermediate and extending beyond 10 a as long-term management, with significant differences in plant community impacts depending on duration (Mi et al., 2024). Despite this, the long-term ecological effects of GE, FG, and CG remain underexplored.

Soil aggregates are structural units formed through the binding of soil particles, and their stability is a critical indicator of soil fertility (González-Rosado et al., 2020). Aggregate stability directly influences soil porosity, the coordination of water, nutrients, air, and heat, as well as erosion resistance (Zhang et al., 2019). In grassland ecosystems, soil aggregates and their stability also play vital roles in elemental cycling, water regulation, and biodiversity maintenance (Du et al., 2025). Previous studies have largely focused on the biophysical processes controlling aggregate formation and breakdown under FG with different grazing intensities (Fan et al., 2021; Zhang et al., 2022; Li et al., 2025). However, systematic comparisons of the long-term effects of different grazing patterns remain limited. Stavi et al. (2011) reported that FG disrupts the mechanical stability of large soil aggregates through persistent livestock trampling. Ju et al. (2023) showed that GE reduces soil physical disturbance but alters microbial community composition due to excessive litter accumulation, thereby accelerating soil organic matter decomposition and indirectly affecting aggregate stability.

Grazing patterns play a pivotal role in grassland restoration. However, their effects in the transitional zone between desert steppe and typical steppe in northern China, i.e., semi-arid grasslands, remain poorly understood. Under the dual pressures of global climate change and increasing human activities related to production and infrastructure development, forage resource scarcity has become a key factor influencing the trajectory of plant community succession (Liu et al., 2019b). Over the past two decades, variations in evapotranspiration have altered the surface–atmosphere water and heat balance, while heterogeneous patterns of grassland development have created conditions conducive to wind erosion resembling near-primitive states (Tang et al., 2024). The adoption of seasonal grazing and GE has helped replenish deep soil moisture, enhanced vegetation maintenance, and increased preferential transport of water and nutrients in semi-arid grasslands (Wu et al., 2022). Nevertheless, the effects of different grazing JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 patterns on plant community characteristics and soil physical-chemical properties in the semi-arid grasslands of northern China remain poorly unclear.

In this study, we examined the effects of common grazing patterns (i.e., GE, CG, and FG) in Xilamuren steppe, a semi-arid grassland in northern China. Specifically, we investigated plant communities under long-term management with different grazing patterns and measured soil physical-chemical properties to explore the regulatory mechanisms governing soil aggregates and their stability.

We hypothesized that the formation of soil aggregates is differentially regulated by varying the disturbance intensity of vegetation-soil properties under different grazing patterns.

The research findings can provide a theoretical basis for optimizing grassland management models in regions with similar climatic conditions, aiming to balance ecological conservation with sustainable livestock production.

2.1 Study area

The study area is located in Xilamuren steppe in Inner Mongolia Autonomous Region, China (central coordinates of 111°11$’ 08*Eand*41°23’ $55 N), at an elevation of approximately 1602 m.

The region experiences an annual average temperature of 5.5°C and an annual average wind speed of 4.36 m/s. Vegetation in the study area consists mainly of perennial xerophytes adapted to temperate arid and semi-arid climate. Dominant plant species include Stipa krylovii, Leymus chinensis, Artemisia frigida, and Convolvulus ammannii. Over the past two decades, the average annual precipitation has been approximately 281 mm, with rainfall exhibiting pronounced seasonality, mostly concentrated between July and September (Wu et al., 2022). Considering topography, elevation, slope position, and gradient, this study selected three grazing pattern sites for investigation: GE, CG, and FG sites (Fig. 1 [Figure 1: see original paper]).

Fig. 1 Overview of the selected three grazing pattern sites (a–c). GE, CG, and FG represent grazing exclusion, cold-season grazing, and free grazing, respectively. The abbreviations are the same in the following figures.

The three experimental sites are adjacent to each other due to their similar plant communities, parent materials, topography, and climatic conditions (Wu et al., 2022). The GE site has been prohibited with 2.1 m high metal fences since April 2002 to isolate livestock. The CG site is only used for grazing during the cold season from November to April of the next year; it is also prohibited with 2.1 m high metal fences in other months. The FG site is managed under a free-grazing regime. All three site types (GE, CG, and FG) measure an area of 300 m$×$250 m for each. Grazing intensity is determined by pasture supply, which is the relationship between pasture and livestock (Schönbach et al., 2011). The CG site has a grazing intensity of 0.5-1.0 sheep/hm2 from November to April of the next year and no grazing activity from May to October. The FG site has a grazing intensity of 0.5-1.0 sheep/hm2 from November to April of the next year, and 1.5-2.0 sheep/hm2 from May to October.

2.2 Plant community survey

The plant community survey was scheduled in August 2024, during the peak growing season of the grassland. Within each of the GE, CG, and FG sampling areas, three plots (20 m$×20*mforeach*)*wererandomlyselected*.*Ineachplot*, *five*1*m*×$1 m quadrats were randomly established.

Under the three grazing pattern methods, a total of 45 sampling quadrats were set up for LI Haonian et al.: Influence of grazing patterns on the stability of soil aggregates···vegetation surveys, and all plant species within the sampling quadrats were classified.

Specifically, the names of all plant species in the sampling quadrats were recorded, the total number of species in the sampling quadrats was counted, and the plant density was calculated using the number of plants corresponding to each species in the sampling quadrats. The height of the selected plants representing more than 80.00% of the species in each sampling quadrat was recorded, and the vertical projection area of the aboveground portion of the total plant community was compared with the area of the sampling quadrats for the calculation of vegetation cover. At the end of the vegetation survey, the aboveground parts of each species were collected separately, put into envelopes, labeled, and then brought back to the laboratory to be dried at 65.0°C until constant weight was weighed to calculate the aboveground biomass.

During the field sampling, following aboveground biomass measurement, surface debris was removed, and plant roots were collected from soil depths of 0–10, 10–20, and 20–30 cm using a 9-cm diameter root sampler. The root samples were brought back to the laboratory, washed, placed in envelope bags, and oven-dried at 65.0°C to constant weight to determine the belowground biomass.

2.3 Soil sampling and determination of soil physical-chemical properties

In the field, soil samples were collected from the four corners of each 1 m$×1*msamplingquadratusingacuttingring*, *andfoursamplesfromthesamesoillayerweremixedtoformacomp*
onepartwasusedtodeterminethesoilorganiccarbon(*SOC*), *andtheotherpartwasusedtodeterminethesoilwater*−
stableaggregates.*Soilsamplesrequiredfordeterminingsoilwatercontent*(*SWC*), *moisture*−
holdingcapacity(*MC*), *andsoilbulkdensity*(*SBD*)*werecollectedusingacuttingringfromthecenterof*1*m*×$1 m sampling quadrat.

SOC was determined by the dilution calorimetry with potassium dichromate (Li et al., 2023).

SWC and MC were determined by drying at 105.0°C for 24 h, while SBD was measured using the ring knife method after drying at 105.0°C. The content of soil water-stable aggregates was determined using the wet sieving method (Li et al., 2023). Using a soil aggregate analyzer (XY100; Guangzhou Xiangyu Aviation Technology Co., Ltd., Guangzhou, China), wet sieving was performed by shaking vertically in pure water to obtain soil aggregates in five particle size fractions: >2.00, 1.00–2.00, 0.50–1.00, 0.25–0.50, and <0.25 mm. The aggregates of each particle size fraction were dried and weighed. The geometric mean diameter (GWD), content of soil aggregates >0.25 mm, and mean weight diameter

(MWD) were calculated using the methods described in Zhou et al. (2022).

2.4 Data analysis

The method for calculating the importance value of plant species in plant communities is detailed in Zhang et al. (2022). The specific formulas are as follows:

RH RC RB where RH indicates the relative vegetation height; Hi denotes the average height of plant species i (cm); H denotes the average height of all plant species within the quadrat (cm); RC represents the relative vegetation cover; Ci denotes the average cover of plant species i (%); C denotes the sum JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 of all plant species cover within the plot (%); RB signifies the relative aboveground biomass; Bi denotes the average biomass of plant species i (g); B denotes the sum of biomass of all plant species within the plot (g); and IVi denotes the importance value of plant species i within the plot.

The community diversity was mainly expressed as the Shannon-Wiener index, Pielou index, and Simpson index, and the formulas were mainly referred to the study of Gao et al. (2024). $= -' \sum$ where W′ represents the Shannon-Wiener index; S is the total number of plant species within the plot; Pi is the relative abundance of plant species i, i.e., Pi=ni/N (where ni is the number of individuals of plant species i in the sampling plot, and N is the total number of individuals of all plant species in the sampling plot); E′ is the Pielou index; and S′ is the Simpson index.

Soil aggregate stability was measured using the GWD (mm), content of soil aggregates >0.25 mm, and MWD (mm) as follows:

GWD exp where a is the aggregate size group; b is the number of particle size groups in soil aggregates; Wa is the proportion of aggregate size a (%); and aX is the average diameter of aggregate size a (mm).

In this study, the Shapiro-Wilk method was used to test the normal distribution of indicators of soil properties and vegetation characteristics, and the logarithmic transformation or square root transformation was used for non-normally distributed variables. One-way analysis of variance (ANOVA) and Duncan’ s test were applied to analyze the significant differences between indicators of soil properties and vegetation characteristics under different grazing patterns ($P<0.05$). Pearson correlation analysis was used to determine the relationship of environmental factors with soil aggregate content and its stability. Principal component analysis (PCA) was performed using Origin Pro 2021b (OriginLab Corporation, Northampton, the USA) to determine the relationship of environmental factors with soil aggregate content and its stability. Random forest modeling was performed using R software (version 4.4.3) to identify the factors influencing soil aggregate stability. In Pearson correlation analysis, PCA, and random forest analysis, grazing patterns were categorized as follows for data analysis: GE as 1, CG as 2, and FG as 3. In random forest analysis, indicators corresponding to the percentage of increase of mean square error (IncMSE) less than zero were removed.

3.1 Characterization of plant communities under different grazing patterns

The vegetation density, vegetation height, and vegetation cover under different grazing patterns are shown in Figure 2 [Figure 2: see original paper]. Significant differences in vegetation height were observed among the LI Haonian et al.: Influence of grazing patterns on the stability of soil aggregates···grazing patterns (P<0.05), with values decreasing in the order of GE>CG>FG. The mean height of the plant community in GE site was 25.47 cm, which was significantly higher than that in CG and FG sites (P<0.05), while FG site exhibited the lowest value at 11.39 cm. Similarly, vegetation cover also varied significantly across the three grazing patterns (P<0.05), showing a decreasing trend of GE (92.41%)>CG (60.28%)>FG (49.05%). Both vegetation height and vegetation cover demonstrated consistent decreasing trends in response to grazing intensity, whereas vegetation density did not differ significantly among the grazing patterns (P>0.05).

Fig. 2 Vegetation density (VD; a), vegetation height (VH; b), and vegetation cover (VC; c) under different grazing patterns. Note that * and NS indicate significant relationships (P<0.05) and insignificant relationships (P>0.05) between different grazing patterns, respectively. The upper and lower boundaries of the box represent the first and third quartiles, respectively. The line in the middle of the box indicates the median of the data. The upper and lower whiskers represent the first quartile plus 1.5 times the interquartile range and the third quartile minus 1.5 times the interquartile range, respectively. Bars represent standard deviations. The abbreviations are the same in the following figures.

The distribution characteristics of plant species diversity under different grazing patterns are shown in Figure 3 [Figure 3: see original paper]. There was no significant difference in Simpson index and Pielou index of plant community under three grazing patterns (P>0.05; Fig. 3b and c). However, the Shannon-Wiener index under GE was significantly higher than that under CG and FG (P<0.05), while no significant difference of Shannon-Wiener index was detected between CG and FG (P>0.05; Fig. 3a). There were significant differences in aboveground biomass among the three grazing patterns (P<0.05; Fig. 3d). The average aboveground biomass was 97.09 g/m2 under GE, 51.55 g/m2 under CG, and 44.85 g/m2 under FG. Although there was no statistically significant difference in aboveground biomass between CG and FG sites (P>0.05), GE site exhibited significantly higher biomass compared to both CG and FG sites (P<0.05). For belowground biomass in the 0–10 cm layer, values were 328.95 g/m2 under GE, 217.09 g/m2 under FG, and 140.03 g/m2 under CG (Fig. 3e).

A total of 14 plant species were identified across the three grazing pattern sites (Table 1).

Specifically, 13 species were recorded in GE site, 9 species were recorded in CG site, and 10 species were recorded in FG site. Stipa krylovii was the dominant species in all sites, consistently exhibiting the highest importance value, which reflects its strong adaptability to different grazing patterns. The dominant species in GE site included Stipa krylovii, Leymus chinensis, and Agropyron cristatum. CG site exhibited a species composition similar to GE site, whereas the dominant species in FG site were Stipa krylovii, Artemisia frigida, and Leymus chinensis. The importance values of Allium mongolicum, Astragalus membranaceus, Cleistogenes squarrosa, Agropyron cristatum, and Heteropappus hispidus remained relatively consistent across the three grazing pattern sites. Artemisia frigida, a known indicator of grassland degradation, was present in all sites, showing the greatest abundance in FG site, followed by GE site and CG site. This pattern suggests varying degrees of vegetation degradation across the grazing pattern sites, with the highest risk of degradation associated with FG.

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 3 Distribution characteristics of Shannon-Wiener index (W′; a), Simpson index (S′; b), Pielou index (E′; c), aboveground biomass (AGB; d), and belowground biomass (BGB; e) under different grazing patterns. Note that * and NS indicate significant relationships ($P<0.05$) and insignificant relationships ($P>0.05$) between different grazing patterns, respectively. The upper and lower boundaries of the box represent the first and third quartiles, respectively. The line in the middle of the box indicates the median of the data. The upper and lower whiskers represent the first quartile plus 1.5 times the interquartile range and the third quartile minus 1.5 times the interquartile range, respectively. Different lowercase letters indicate significant differences between grazing patterns at the same soil layer depth ($P<0.05$). Bars represent standard deviations. The abbreviations are the same in the following figures.

3.2.1 Distribution characteristics of SOC, SWC, MC, and SBD

As shown in Figure 4a [Figure 4: see original paper], significant differences in SOC were observed among the three grazing patterns in the 0-10 and 10-20 cm layers ($P<0.05$), whereas no significant differences were observed in the 20-30 cm layer ($P>0.05$). Specifically, SOC in GE site was significantly higher than that in CG and FG sites in the 0-10 cm layer ($P<0.05$), and significantly higher than that in FG site in the 10-20 cm layer ($P<0.05$). MC showed no significant differences among the three grazing patterns in the 0-10 and 20-30 cm layers (Fig. 4b). However, in the 10-20 cm layer, MC under GE was significantly higher than that under FG ($P<0.05$), while no significant differences of MC were observed between CG and the other two patterns ($P>0.05$). SWC in GE site was significantly higher than that in CG and FG sites in the 0-10 and 10-20 cm layers ($P<0.05$; Fig. 4c). SBD did not differ significantly among the three grazing patterns in the 0-10 cm layer (Fig. 4d). In contrast, within the 10-20 and 20-30 cm layers, SBD under GE was significantly lower than that under

FG (P<0.05).

LI Haonian et al.: Influence of grazing patterns on the stability of soil aggregates···Table 1 Dominant plant species and the corresponding importance values in sampling sites with different grazing patterns Species name Stipa krylovii Artemisia frigida Leymus chinensis Allium mongolicum Artemisia annua Astragalus membranaceus Cleistogenes squarrosa Agropyron cristatum Heteropappus hispidus Convolvulus ammannii Juncus effusus Medicago Sativa Ptilotricum canescens Caragana stenophylla Importance value GE site CG site FG site Note: GE, CG, and FG represent grazing exclusion, cold-season grazing, and free grazing, respectively.

Fig. 4 Distribution characteristics of soil organic carbon (SOC; a), moisture-holding capacity (MC; b), soil water content (SWC; c), and soil bulk density (SBD; d) in the 0–30 cm soil layer under different grazing patterns.

Different lowercase letters indicate significant differences between grazing patterns at the same soil layer depth (P<0.05). Bars mean standard deviations. The abbreviations are the same in the following figures.

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2

3.2.2 Distribution characteristics of soil aggregates under different grazing patterns

Figure 5a [Figure 5: see original paper]–c represents the soil aggregate content in the 0–10, 10–20, and 20–30 cm layers, respectively. In the 0–10 cm soil layer, the proportions of soil aggregates with particle sizes >2.00 and <0.25 mm were the highest across all three grazing patterns (Fig. 5a). The content of >2.00 mm soil aggregates was significantly higher under GE and CG compared to FG (P<0.05). No significant differences were observed among the three grazing patterns for the 1.00–2.00 and 0.25–0.50 mm soil aggregates (P>0.05). However, the content of <0.25 mm soil aggregates differed significantly among GE, CG, and FG (P<0.05). In the 10–20 cm soil layer, no significant differences were found among grazing patterns for soil aggregates larger than 0.25 mm (P>0.05; Fig. 5b). In contrast, the content of <0.25 mm soil aggregates under CG and FG was significantly higher than that under GE (P<0.05). In the 20–30 cm soil layer, the content of >2.00 mm soil aggregates was significantly higher in GE site than in CG and FG sites, whereas the content of 0.50–1.00 mm soil aggregates was significantly higher in FG site than in GE and CG sites (P<0.05; Fig. 5c).

Fig. 5 Distribution characteristics of soil aggregates with different particle sizes in the 0–10 cm (a), 10–20 cm (b), and 20–30 cm (c) soil layers under different grazing patterns. Different lowercase letters indicate significant differences between grazing patterns at the same soil layer depth (P<0.05). Bars mean standard deviations.

MWD, content of soil aggregates >0.25 mm, and GWD in the 0–30 cm soil layer under different grazing patterns are shown in Figure 6 [Figure 6: see original paper]. The results indicated that in the 0–10 cm layer, the proportion of soil aggregates >0.25 mm was 78.10% under GE, 70.28% under CG, and 50.32% under FG (Fig. 6b). This proportion was significantly higher under GE and CG than under FG ($P<0.05$). Across the 0–30 cm soil profile, GE site exhibited significantly greater soil aggregate stability than the other two grazing pattern sites. In particular, MWD under GE was consistently higher than that under CG and FG (Fig. 6a). Within the 0–10 cm soil layer, MWD values under GE and CG were significantly greater than that under FG ($P<0.05$), while in the 20–30 cm soil layer, GE site had significantly higher MWD value than both CG and FG sites ($P<0.05$). The GWD showed a similar trend to MWD across all grazing patterns. GWD values in the 0–10 and 20–30 cm layers were significantly higher under GE than under CG and FG (Fig. 6c). Notably, the highest GWD value (1.94 mm) was recorded in the 10–20 cm layer under GE.

Overall, the distribution of MWD, content of soil aggregates >0.25 mm, and GWD within the 0–30 cm soil layer suggests that GE significantly enhances soil aggregate stability.

3.3 Correlation between soil aggregate distribution characteristics and environmental

factors Pearson correlation analysis was conducted to assess the relationships among the distribution of soil aggregates, vegetation characteristics, and soil physical-chemical properties. As shown in Figure 7 [Figure 7: see original paper], the contents of soil aggregates with particle sizes of <0.25, 0.25–0.50, and 0.50–1.00 mm exhibited distinct correlations with basic vegetation indices and soil physical- chemical properties. Specifically, these smaller aggregate fractions (<0.25, 0.25–0.50, and 0.50–1.00 mm) LI Haonian et al.: Influence of grazing patterns on the stability of soil aggregates···Fig. 6 Mean weight diameter (MWD; a), proportion of soil aggregates >0.25 mm (b), and geometric mean diameter (GWD; c) in the 0–30 cm soil layer under different grazing patterns. Different lowercase letters indicate significant differences between GE, CG, and FG at the same soil layer depth ($P<0.05$). Bars mean standard deviations. The abbreviations are the same in the following figures.

Fig. 7 Correlation analysis between soil aggregates and environmental factors. *, P$ 0.05*level*; ∗∗, *P* $0.01 level. Red circle indicates a positive correlation, and blue circle indicates a negative correlation; the larger the circle area, the stronger the correlation. showed highly significant positive correlations with grazing patterns and SBD ($P<0.01$), and significant negative correlations with vegetation height, vegetation cover, aboveground biomass, and SWC ($P<0.05$). In contrast, >2.00 mm soil aggregates displayed an opposite trend. Their content was significantly negatively correlated with grazing patterns and SBD ($P<0.01$), while showing significant positive correlations with other vegetation characteristics and soil properties, excluding belowground biomass. Similarly, MWD, content of soil aggregates >0.25 mm, and GMD exhibited consistent variations. These indicators were negatively correlated with grazing patterns and SBD ($P<0.01$), and positively correlated with other vegetation characteristics and soil properties ($P<0.05$), except for belowground biomass and SOC.

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 As shown in Figure 8 [Figure 8: see original paper], the variance explained by the PC1 (the first principal component) and PC2 (the second principal component) axes were 53.30% and 12.70%, respectively, representing a total of 66.00% of the overall variance. The distribution characteristics of the confidence ellipses revealed significant differences between GE and FG ($P<0.05$). This study further explored the drivers of three metrics (i.e., MWD, content of soil aggregates >0.25 mm, and GMD) characterizing soil aggregate stability using a random forest model. The random forest model for MWD was statistically significant ($P<0.05$), with the R2 value of 0.8189 (Fig. 9a [Figure 9: see original paper]), indicating that the model explained 81.89% of the variance and demonstrated good performance. MWD was significantly affected by grazing patterns, vegetation height, vegetation cover, belowground biomass, SWC, >2.00 mm soil aggregates, 0.50–1.00 mm soil aggregates, and <0.25 mm soil aggregates. Similarly, the random forest model for the content of soil aggregates >0.25 mm was also significant ($P<0.05$), with the R2 value of 0.8116 and an explanatory power of 81.16% (Fig. 9b), confirming its robustness. The content of soil aggregates >0.25 mm was significantly affected by grazing patterns, vegetation height, vegetation cover, belowground biomass, MC, >2.00 mm soil aggregates, and <0.25 mm soil aggregates. The random forest model for GMD was significant ($P<0.05$), with the R2 value of 0.6615 (Fig. 9c). The model explained 66.15% of the variance in GMD, supporting its applicability. GMD was significantly influenced by grazing patterns, vegetation height, Simpson index, Shannon-Winner index, aboveground biomass, >2.00 mm soil aggregates, and <0.25 mm soil aggregates.

Fig. 8 Principal component analysis (PCA) of environmental factors and soil aggregate stability. PC1 and PC2 represent the first principal component and the second principal component, respectively.

4 Discussion

Understanding the influence of grazing patterns on plant community composition remains a central question in ecological research (Yu et al., 2020). This study compared the effects of GE, CG, and FG on grassland vegetation characteristics. The results demonstrated that grazing patterns significantly affect vegetation height and vegetation cover, although their influence on vegetation density is not statistically significant. These findings highlight the selective impact of grazing on grassland ecosystems and suggest that grazing patterns directly shape the vertical structure and surface coverage of plant communities. In this study, vegetation height and vegetation cover were significantly greater under GE than under CG and FG, consistent with previous research in Inner Mongolian grasslands (Wang et al., 2017; Liu et al., 2018).

Furthermore, perennial herbaceous plants expand their populations by vegetative reproduction, LI Haonian et al.: Influence of grazing patterns on the stability of soil aggregates···Fig. 9 Exploring the environmental factors of MWD (a), content of soil aggregates >0.25 mm (b), and GMD (c) based on the random forest model. IncMSE, percentage of increase of mean square error; *, P$ 0.05*level*; ∗∗, *P* $0.01 level. forming dense aboveground biomass that substantially increases vegetation cover (Özüdoğru et al., 2021). In contrast, vegetation height (11.39 cm) and vegetation cover (49.05%) were lowest in FG site, reflecting the dual inhibitory effects of continuous grazing on plants and soil. Vegetation characteristics under CG were intermediate, indicating that seasonal rest of grasslands provides a critical recovery period for plants. Moreover, the retention of leaf litter helps maintain a favorable soil microenvironment, thereby facilitating plant growth and vegetation development during the warm season (Zhang et al., 2025). At this stage, grazing patterns profoundly influence soil aggregate formation and stability by regulating vegetation characteristics. Under GE, higher vegetation cover and vegetation height effectively mitigate direct surface damage from external forces such as hydrodynamic and wind erosion. Combined with dense root networks, these factors significantly promote soil aggregate formation and stability (Yang et al., 2024).

The Shannon-Winner index was significantly higher under GE than under CG and FG (P<0.05), while no significant differences were observed for the Simpson index or Pielou index (P>0.05), indicating that GE increases species richness but does not markedly altering species evenness. This is consistent with the results of Arévalo et al. (2022). In this study, we found that SOC was higher, SBD was lower, and SWC was higher under GE compared to FG and CG, suggesting that GE effectively improves soil physical-chemical properties. This finding is consistent with the results reported by Zhu et al. (2021). Under GE, plants need to allocate more biomass to root systems to efficiently absorb water and nutrients. The belowground biomass in the 0–10 cm soil layer reached 328.95 g/m2, indicating that in the absence of grazing pressure, JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 plants tend to allocate more root biomass in surface soils to rapidly acquire water and nutrients (Dai et al., 2019). SOC content in both the 0–10 and 10–20 cm layers was significantly higher under GE than under FG and CG (P<0.05), demonstrating that GE substantially enhances carbon sequestration in grassland ecosystems. SOC also plays a crucial role in mediating the relationship between the duration of GE and aboveground biomass responses (Wan et al., 2024). Our findings support the widely held view that grazing patterns strongly influence soil aggregate stability by regulating vegetation community structure. Specifically, GE not only promotes the recovery of vegetation species diversity but also significantly enhances ecosystem organic carbon storage.

The sustained increase in organic carbon input drives soil aggregate formation and stability.

Conversely, FG and CG lead to losses in species diversity and depletion of SOC (Zhu et al., 2021).

Land use can induce significant changes in the evolution of soil physical properties (Sun et al., 2018; Zhang et al., 2021). SBD is strongly influenced by grazing patterns, such as GE, CG, and FG. Overgrazing or excessive livestock numbers can lead to soil compaction in grasslands (Pulido et al., 2017). Under FG, livestock trampling frequently applies ground pressure through hooves, resulting in soil deformation and compaction (Warren et al., 1986). Soil compaction is primarily associated with reductions in soil volume, increases in SBD, and changes in pore connectivity including the disintegration of soil aggregates (Zhao et al., 2010; Alaoui et al., 2011). In contrast, GE minimizes overgrazing and hoof trampling, thereby alleviating soil compaction and decreasing SBD. The stabilized pore structure under GE promotes water infiltration and storage, leading to higher SWC and saturated water holding capacity (He et al., 2025). By improving MC, these factors ultimately work together to promote the formation and long-term stability of soil aggregates.

In this study, we compared the effects of GE, CG, and FG on the distribution of soil aggregates.

In the 0–10 cm layer, the content of soil aggregates with particle size >2.00 mm was significantly higher in GE and CG sites than in FG site ($P<0.05$), which is consistent with previous findings on the damage of soil physical structure caused by grazing (Yang et al., 2025). Continuous livestock treading under FG may reduce the stability of large soil aggregates through mechanical fragmentation (Romero-Ruiz et al., 2023), resulting in higher contents of soil aggregates with particle sizes >2.00 and <0.25 mm compared to GE and CG. In contrast, GE and CG promote vegetation restoration and root secretion accumulation by limiting grazing frequency and seasonal rest, which in turn facilitates the formation of macroaggregates through organic matter cementation (Baumert et al., 2018; Wu et al., 2024). In this study, grazing management significantly affects the stability of soil aggregates. GE significantly increased MWD, content of soil aggregates >0.25 mm, and GWD, whereas FG resulted in increased aggregate fragmentation, particularly in the 0–10 and 20–30 cm soil layers. This phenomenon may be related to SWC in different soil layers. Vogelmann et al. (2017) found that increased soil moisture enhances the adsorption properties of soil aggregates in natural grasslands. The significant relationships of MWD, content of soil aggregates >0.25 mm, and GMD with vegetation cover, vegetation height, and vegetation density indicated that vegetation communities play an important role in regulating the stability of various soil aggregates (Garcia et al., 2019).

Pearson correlation analysis showed that soil aggregates with particle sizes of <0.25, 0.25–0.50, and 0.50–1.00 mm were significantly positively correlated with grazing patterns and SBD ($P<0.01$), and significantly negatively correlated with vegetation height, vegetation cover, aboveground biomass, and SWC ($P<0.05$). These results support the notion that grazing reduces vegetation cover and weakens root retention of aggregates, while increasing SBD and promoting the fragmentation of large aggregates (>2.00 mm) into fine-grained fractions (Roberts and Johnson, 2021). The random forest model explained 81.89% of the variance in MWD, 81.16% of the variance in the content of soil aggregates >0.25 mm, and 66.15% of the variance in GMD ($P<0.05$), indicating that the selected indicators are effective in revealing the driving mechanisms LI Haonian et al.: Influence of grazing patterns on the stability of soil aggregates···of soil aggregate stability. The models identified grazing patterns and vegetation parameters (i.e., vegetation cover, vegetation height, and aboveground biomass) as the most important variables influencing MWD and GMD, consistent with traditional linear analyses. However, nonlinear modeling further helped identify key drivers of soil aggregate stability. Through random forest modeling, the primary drivers of soil aggregate stability have been elucidated, offering a scientific basis for grassland management and conservation.

However, the study also has some limitations. Only some environmental variables were considered in this study, and other potential factors may also have important effects on soil aggregate stability. Future research could incorporate more environmental variables to comprehensively assess the drivers of soil aggregate stability.

5 Conclusions

In semi-arid grasslands, grazing management plays a crucial role in shaping vegetation community characteristics and soil physical-chemical properties. This study focused on GE, CG, and FG that are prevalent in the grassland regions of the semi-arid zone. Compared to FG, both CG and GE promoted plant community development and improved soil quality. Variations in grazing patterns led to distinct differences in plant community structure. In GE site, the dominant species included Stipa krylovii, Leymus chinensis, and Agropyron cristatum. CG site shared similar species with GE, while FG site was dominated by Stipa krylovii, Artemisia frigida, and Leymus chinensis. Compared to FG, GE and CG significantly enhanced soil aggregate formation and stability. Under GE and CG, the proportion of large soil aggregates (>0.25 mm) increased significantly, improving soil texture structure. Conversely, FG led to an increase in the content of soil aggregates <0.25 mm, resulting in soil structure degradation under sustained grazing pressure. GE significantly improved soil aggregate stability, and CG was more stable than FG due to its seasonality. The restoration of plant communities and improvement of soil quality through litterfall are crucial for promoting soil aggregate stability. Despite seasonal limitations, CG maintains relatively stable aggregate structure, highlighting its potential as a balanced management strategy. Random forest modeling revealed that plant species diversity, growth characteristics, and grazing patterns significantly drive soil aggregate stability. Overall, this study confirms that appropriate grazing patterns (i.e., GE and CG) effectively enhance soil aggregate stability in semi-arid grasslands, thereby improving soil quality. The research elucidates the regulatory mechanisms governing soil aggregates' response to grazing patterns, providing scientific evidence for the sustainable management and ecological restoration of degraded grassland ecosystems.

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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