



Reasonable grazing may balance the conflict between grassland utilization and soil conservation in the semi-arid hilly areas, China

SUN Hui¹, ZHAO Yunge², GAO Liqian², XU Mingxiang^{2*}

¹ College of Forestry, Northwest A&F University, Yangling 712100, China;

² College of Soil and Water Conservation Science and Engineering, Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China

Abstract: Soil erosion caused by unsustainable grazing is a major driver of grassland ecosystem degradation in many semi-arid hilly areas in China. Thus, grazing exclusion is considered as an effective method for solving this issue in such areas. However, some ecological and economic problems, such as slow grassland rejuvenation and limited economic conditions, have become obstacles for the sustainable utilization of grassland ecosystem. Accordingly, we hypothesized that the conflict between grassland use and soil conservation may be balanced by a reasonable grazing intensity. In this study, a two-year grazing fence experiment with five grazing intensity gradients was conducted in a typical grassland of the Loess Plateau in China to evaluate the responses of vegetation characteristics and soil and water losses to grazing intensity. The five grazing intensity gradients were 2.2, 3.0, 4.2, 6.7, and 16.7 goats/hm², which were represented by G1–G5, respectively, and no grazing was used as control. The results showed that a reasonable grazing intensity was conducive to the sustainable utilization of grassland resources. Vegetation biomass under G1–G4 grazing intensity significantly increased by 51.9%, 42.1%, 36.9%, and 36.7%, respectively, compared with control. In addition, vegetation coverage increased by 19.6% under G1 grazing intensity. Species diversity showed a single peak trend with increasing grazing intensity. The Shannon-Wiener diversity index under G1–G4 grazing intensities significantly increased by 22.8%, 22.5%, 13.3%, and 8.3%, respectively, compared with control. Furthermore, grazing increased the risk of soil erosion. Compared with control, runoff yields under G1–G5 grazing intensities increased by 1.4, 2.6, 2.8, 4.3, and 3.9 times, respectively, and sediment yields under G1–G5 grazing intensities were 3.0, 13.0, 20.8, 34.3, and 37.7 times greater, respectively, than those under control. This result was mainly attributed to a visible decrease in litter biomass after grazing, which decreased by 50.5%, 72.6%, 79.0%, 80.0%, and 76.9%, respectively, under G1–G5 grazing intensities. By weighing the grassland productivity and soil conservation function, we found that both two aims were achieved at a low grazing intensity of less than 3.5 goats/hm². Therefore, it is recommended that grassland should be moderately utilized with grazing intensity below 3.5 goats/hm² in semi-arid hilly areas to achieve the dual goals of ecological and economic benefits. The results provide a scientific basis for grassland utilization and health management in semi-arid hilly areas from the perspective of determining reasonable grazing intensity to maintain both grassland production and soil conservation functions.

Keywords: fence-controlled grazing; rehabilitated grassland; vegetation community characteristics; soil erosion; sediment; biocrusts; Loess Plateau

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*Corresponding author: XU Mingxiang (E-mail: xumx@nwsuaf.edu.cn)

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1 Introduction

Grassland is a dominant land use type in semi-arid areas, covering approximately 40.0%–45.0% of the total area worldwide (Gong et al., 2023). Livestock grazing is the main method of utilizing grassland (Antal and Huzsvai, 2007). Approximately 30.0% of global grassland is used for livestock grazing (Sara, 2019), and grassland is important in livestock production (Hodgson, 1990). Thus, the sustainable management of grassland is a major concern for many scientists and governments.

Livestock overgrazing is one of the primary causes of grassland degradation and biodiversity decline (Wu et al., 2023) and often causes severe soil erosion in semi-arid hilly areas (Li and Zhao, 2005). To date, many studies have been conducted for the effect of grazing on grassland health, and the results demonstrated that overgrazing is a major driver of ecosystem degradation by causing soil and water losses from sloping grassland (Evans, 2005; Pietola et al., 2005). For example, in Inner Mongolia Autonomous Region, which is a traditional grazing area in China, long-term overgrazing has caused severe soil erosion and grassland degradation (Dong et al., 2023). In the central arid area of Australia, overgrazing leads to the destruction of grassland surface landscape and degradation, which cause a dramatic increase in soil erosion (Tongway et al., 2003).

To control grassland degradation and soil erosion, governments of many counties took measures to prohibit grazing. For instance, strictly prohibiting grazing was implemented in the area of the hilly Loess Plateau of China by Chinese government to control soil erosion and restore the vegetation coverage of grassland (Liu et al., 2008). To date, vegetation coverage has increased greatly, and thus, soil erosion has been controlled because of such policies. However, ecological problems have occurred because of long-term grazing prohibition. Studies have shown that long-term grazing prohibition negatively impacts species diversity and ecosystem stability (Cheng et al., 2014). In addition, long-term grazing prohibition has affected the economic income of residents, who rely on animal husbandry (Wang et al., 2021). Therefore, it is necessary to determine whether it is possible to balance the conflict between grassland utilization and ecological problems, and achieve sustainable development of regional agro-pastoral economy by setting the proper scale of grazing.

Factually, it is believed that moderate grazing will maintain the highest biodiversity and the health of grassland. Studies of typical grassland in Inner Mongolia, China (Na et al., 2018); the Edward Plateau, Texas, USA (Fuhlendorf and Smeins, 1997); and grassland in southern Queensland, Australia (Fensham, 1998), have shown that moderate grazing increases the species diversity and richness of grassland vegetation communities. Moreover, moderate grazing appears to increase plant growth rate (Cheng et al., 2021). However, the intensity of moderate grazing is different among various areas (Fuhlendorf and Smeins, 1997; Fensham, 1998; Na et al., 2018). Thus, it is necessary to determine grazing intensity to maintain the sustainability of grassland.

Although the livestock carrying capacity based on grassland productivity has an important guiding function in grassland animal husbandry, the potential impact of livestock grazing on grassland soil erosion has often been overlooked. For example, Evans (1998) observed that from the viewpoint of livestock carrying capacity, there was enough pasture available for grazing livestock, however, severe soil erosion from grassland indicated that grazing should be limited for soil erosion control. Similarly, in the Loess Plateau of China, light grazing did not increase soil erosion from grassland, and soil erosion unexpectedly reduced on artificial grassland (Yu et al., 2019). The results of these studies indicated the possibility of balancing soil and water conservation and the health of ecological system by setting a suitable grazing intensity.

Large areas of sloping grassland have formed since the implementation of the Grain for Green ecological project in the Loess Plateau of China. This project has been implemented for 24 a, however, new challenges have arisen in the rehabilitated grassland, such as the strong consumption of soil water (Feng et al., 2021), the decreasing species diversity of grasses, the slowing of grassland ecosystem recovery (Cheng et al., 2006), and the risk of wildfires caused by

the accumulation of litter over time (Rodriguez-Lozano et al., 2015). On the other hand, the production mode combining agriculture and animal husbandry changed due to the policy of grazing prohibition (Millennium Ecosystem Assessment, 2005), which caused a decline in farmers' economic incomes (Liang, 2017). Therefore, determining how to reasonably use large areas of rehabilitated grassland to achieve the dual goals of ecological health and economic sustainability is imperative for the utilization of grassland.

Accordingly, we assumed that reasonable grazing on sloping grassland may solve the problems above. In this study, different grazing intensities were conducted on rehabilitated grassland in the Loess Plateau, aiming to address three questions: (1) how does livestock grazing intensity affect vegetation community in sloping grassland? (2) how do runoff and sediment respond to livestock grazing intensity? and (3) is there a reasonable grazing intensity to mitigate the conflict between grassland utilization and soil erosion? The results of this study can provide scientific guidance for the healthy and sustainable management of grassland in the Loess Plateau of China and other semi-arid areas.

2 Materials and methods

2.1 Study area

This study was conducted on revegetated grassland that was converted from sloping cropland in 1999 in Yan'an City, Shaanxi Province, China, which is in a typical hilly and gully area of the Loess Plateau. Altitude ranges from 1350 to 1780 m a.s.l. The area has a typical semi-arid warm temperate continental monsoon climate, with annual average temperature of 7.8°C and average annual precipitation of 318 mm, almost 70.0% or more of which falls between July and September. The soil is classified as a typical loessial soil. Due to the implementation of the Grain for Green project, a large area of rehabilitated sloping grassland was formed, with the coverage of approximately 57.0% (Gang et al., 2018). The major plant species include *Stipa bungeana* Trin., *Artemisia sacrorum* Weber ex. Stechm., *Potentilla acaulis* Linn., and *Poa sphondylodes* Trin. Moreover, the vegetation gaps are covered with a large area of biological soil crusts (biocrusts), dominated by cyanobacteria, mosses, and lichens, with a coverage of approximately 60.0%. Biocrusts profoundly affect water infiltration, runoff, soil erosion, and so on.

Grazing was used as an important measure of agricultural production in the study area. The grazing livestock were mainly cashmere goats, and the grazing mode was mainly free grazing in sloping grassland. However, with the implementation of the Grain for Green project and grazing prohibition measure, the number of free grazing goats sharply declined, resulting in the combination of free grazing and barn feeding. According to our investigation, goat farmers account for approximately 40.0% of the total number of farmers in the area, with 40–60 goats per household. These goats were allowed to graze freely on sloping grassland for approximately 3 h/d, and the remaining time was for barn feeding.

2.2 Experimental design

A typical grassland on a hilly slope that had been rehabilitated for more than 20 a was selected as the experimental site for fence-controlled grazing experiments. The selected sloping grassland was nearly rectangular, with an area of approximately 4.2 hm² and a slope of 25°. To conduct grazing at different intensities, we divided the grassland into six plots, each with an area of 0.6 hm² (88.4 m×68.3 m). A group of 20 adult cashmere goats weighing approximately 20 kg grazed for 3 h at intervals of 15, 11, 8, 5, and 2 d to obtain a range of grazing intensities, which were 2.2, 3.0, 4.2, 6.7, and 16.7 goats/hm², respectively, represented by G1–G5 in ascending order, and no grazing (G0) was used as control. Grazing experiment began in early August 2020 and ended in September 2022, with a grazing period of 2 a. The grassland surface vegetation after two years of grazing is shown in Figure 1. The dominant species were *Artemisia gmelinii* Web. et Stechm., *S. bungeana*, *Melilotus suaveolens* Ledeb., and *P. sphondylodes* under G0 grazing intensity, *A. gmelinii* under G1 grazing intensity, *A. gmelinii* and *S. bungeana* under G2 and G3 grazing

intensities, *A. gmelinii* and *Potentilla acaulis* Linn. under G4 grazing intensity, *P. acaulis* under G5 grazing intensity.

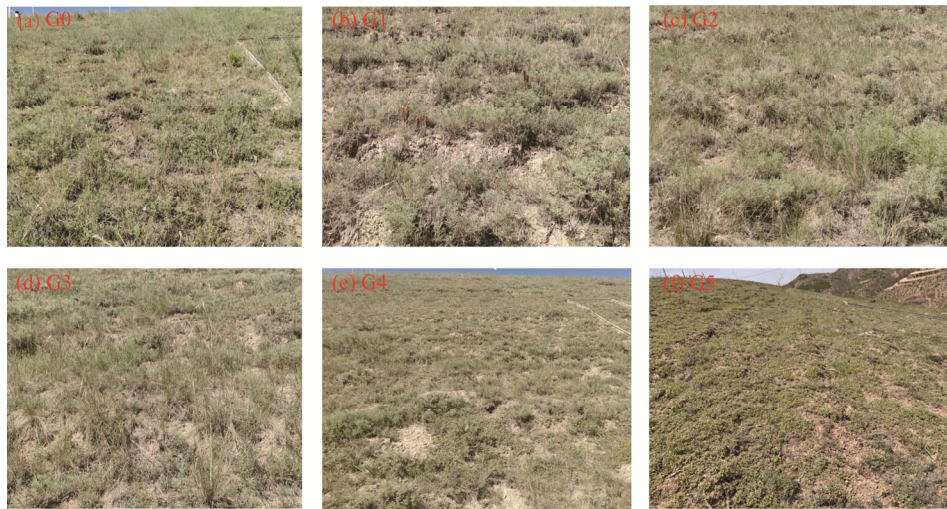


Fig. 1 Vegetation community characteristics of the grasslands along different grazing intensities. (a), G0, 0.0 goats/hm² grazing; (b), G1, 2.2 goats/hm² grazing; (c), G2, 3.0 goats/hm² grazing; (d), G3, 4.2 goats/hm² grazing; (e), G4, 6.7 goats/hm² grazing; (f), G5, 16.7 goats/hm² grazing. The abbreviations are the same in the following figures.

2.3 Investigation of surface cover

Surface cover characteristics of each plot were investigated before (July 2020) and after grazing (September 2022). Three 1 m×1 m quadrats were set in each plot, situated at the upper, middle, and lower positions, to investigate the coverage, biomass, and height of vegetation, and the coverage and biomass of litter. Vegetation coverage was photographed by a camera (SONY A600, Sony Corporation, Tokyo, Japan) and then calculated by ArcGIS v.10.8 software. Height of vegetation was measured for each plant species in each quadrat, and average value was taken as the vegetation height of each quadrat. All vegetation in the quadrats was mowed and dried to a constant weight at 65°C. Dry weight was measured, and vegetation biomass was calculated. After vegetation was mowed, a SONY A600 camera was used to take photographs above the quadrat, and the litter coverage in the quadrat was calculated by ArcGIS software. Then, all the litter in the quadrat was collected and dried to a constant weight at 65°C, after which the litter biomass was calculated. In addition, the biocrust coverage in each grazing plot was investigated with a point-intercept method using a 25 cm×25 cm gridded quadrat (Belnap and Phillips, 2001). In each grazing plot, 45 gridded quadrats were surveyed from the top to the bottom of the plot to obtain the total biocrust coverage.

Shannon-Wiener diversity index (H') was calculated by the following equation:

$$H' = -\sum_{i=1}^n p_i \ln p_i, \quad (1)$$

where H' is the Shannon-Wiener diversity index; n is the total number of individuals; and P_i is the proportion of the number of individuals of the i^{th} plant to the number of individuals of all species.

2.4 Runoff and sediment data collection

To investigate the effects of grazing on soil and water loss under natural rainfall conditions on sloping grassland, we constructed three 2 m×10 m plots to observe runoff and sediment in the mid-slope position of each grazing plot (88.4 m×68.3 m) with asbestos shingles. A leakage-proof cement seal was used to fill all gaps between asbestos shingles to prevent the leakage of runoff. All the runoff was collected at the lower runoff outlet of the plot and stored in a runoff bucket, with a volume of 90 L. Slope of all runoff and sediment plots was uniform at 25°. Rainfall was

monitored by a HOBOS-RGA-M200 analyzer (Onset Company, Bourne, USA) self-registering tipping bucket rain gauge. When a rainfall event occurred and runoff was generated in the plots, the runoff and sediment yield were collected and measured. Area of the plots was used to calculate the runoff depth and sediment yield of the plots. Considering the time effect and the possible uncertainty in the first year of grazing, runoff and sediment monitoring data from the rainy season of the second year of grazing (June–September 2022) were selected to reflect the impact of grazing on soil and water loss in sloping grassland.

2.5 Calculation of rainfall erosivity

Rainfall erosivity was calculated using rainfall kinetic energy (E) and the maximum rainfall intensity in 30 min (Han et al., 2017):

$$E = \sum_{k=1}^n (e_k P_k), \quad (2)$$

$$e_k = 0.119 + 0.873 \log i_k, \quad (3)$$

$$R = EI_{30}, \quad (4)$$

where E is the rainfall kinetic energy (MJ/hm^2); n is the number of effective rainfall; e_k is the unit rainfall kinetic energy during period k ($\text{MJ}/(\text{hm}^2 \cdot \text{mm})$); P_k is the rainfall amount during period k (mm); i_k is the rainfall intensity during period k (mm/h); R is the rainfall erosivity ($\text{MJ} \cdot \text{mm}/(\text{hm}^2 \cdot \text{h})$); and I_{30} is the maximum rain intensity in 30 min (mm/h).

2.6 Evaluation of reasonable grazing intensity

To evaluate whether there is a reasonable grazing intensity on sloping grasslands, we established the relationship of grazing intensity with grassland productivity function and soil conservation capacity, and then balanced these factors to determine a reasonable grazing intensity. Grassland productivity function was represented by three parameters: grassland productivity, species diversity, and decomposition ability (Noss, 1990), which were respectively expressed by vegetation biomass, Shannon-Wiener diversity index, and litter biomass. Subsequently, the three functions were integrated using the averaging approach to establish a grassland multifunctional index for quantifying the production function of grasslands. To obtain the grassland multifunctional index for each plot, we used Z score transformation to normalize and standardize the three functions. Z scores of grassland functions were then averaged to obtain a grassland multifunctional index for each plot (Maestre et al., 2012). Similarly, we normalized the amount of soil loss and subtracted it from 1 to calculate the grassland soil conservation index, thereby quantifying the soil conservation capacity. Finally, the function relationships of grassland multifunctional index and soil conservation index with grazing intensity were established, and their intersection was defined as a reasonable grazing intensity for maintaining grassland health.

2.7 Statistical analyses

One-way analysis of variation (ANOVA) was used to analyze the differences in land surface coverage, including vegetation coverage, height, vegetation biomass, litter coverage, litter biomass, and biocrust coverage among different grazing intensities before and after two years of grazing. Considering the potential heterogeneity among the plots, we further analyzed the effects of grazing on the indicators mentioned above using difference between before grazing and after two years of grazing at the same grazing intensity, represented by D value. We also used ANOVA to determine the differences in runoff and sediment yield under different grazing intensities during the second year of grazing. Before application of ANOVA, we tested all the data for normality with the Kolmogorov-Smirnov test and for equality of variance using Levene's test. Statistical analyses were completed using SPSS v.19.0 software. In addition, a structural equation model (SEM) using Amos v.21.0 software was constructed to identify direct and indirect effects of grazing on soil loss and to further explain the mechanism by which grazing affects soil loss.

3 Results

3.1 Effects of grazing on grassland surface coverage

3.1.1 Vegetation coverage, height, and biomass

Vegetation coverage increased under lower grazing intensities (less than 3.0 goats/hm²), but decreased with increasing grazing intensity (Fig. 2a). Vegetation coverage under G2, G3, and G5 grazing intensities decreased by 38.5%, 42.0%, and 38.7%, respectively, compared with control. However, G1 and G4 grazing intensities did not significantly differ from that of control. Vegetation coverage under control did not significantly differ with those of grazing. Compared with before grazing, vegetation coverage under G1 grazing intensity increased significantly by 19.6%, while there was no significant difference under G2 grazing intensity. However, vegetation coverage under G3–G5 grazing intensities decreased, and the value decreased significantly by

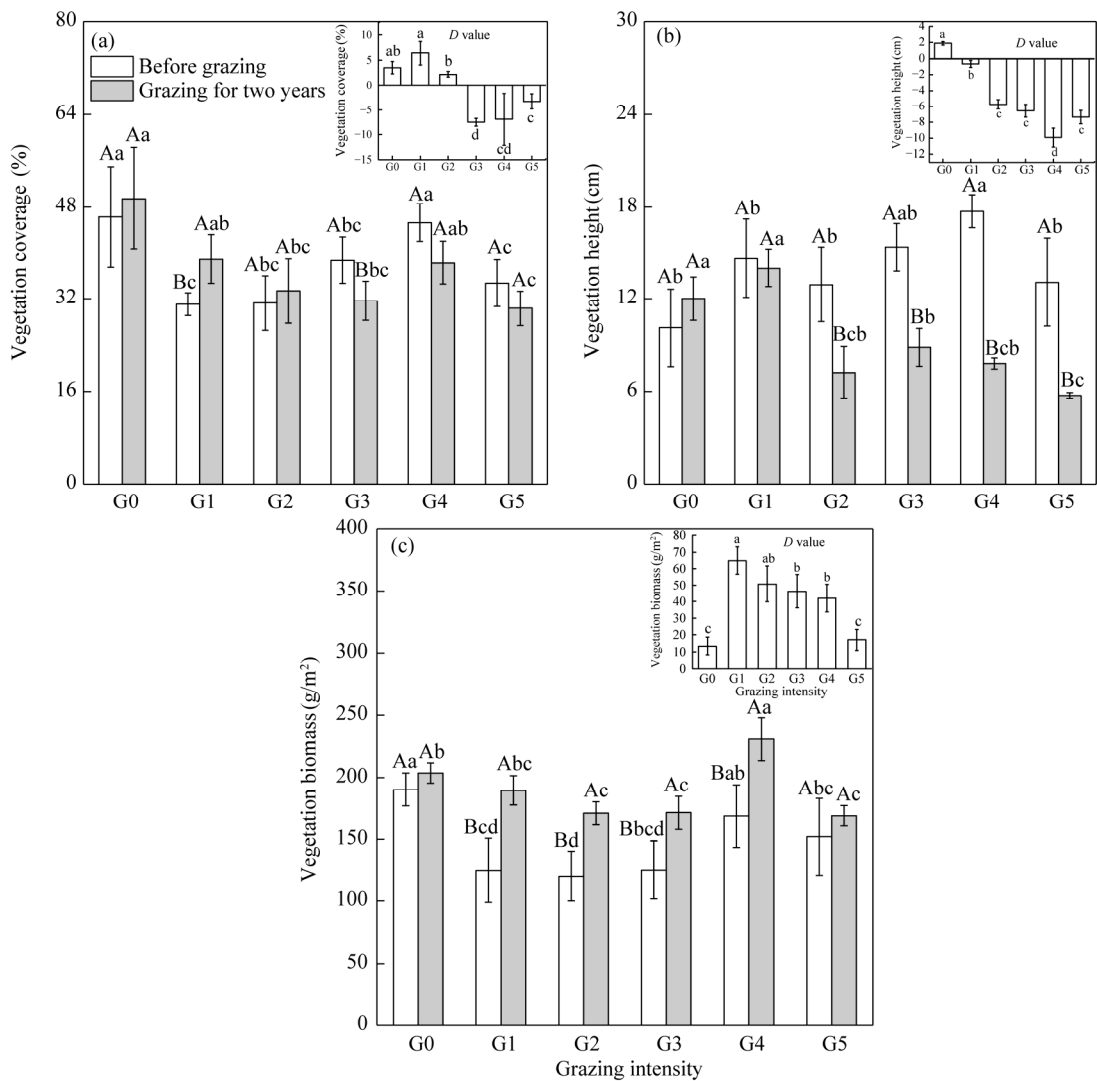


Fig. 2 Effects of grazing on vegetation coverage (a), height (b), and biomass (c). *D* value means the difference between before grazing and after two years of grazing at the same grazing intensity. Different lowercase letters indicate significant differences among different grazing intensities before grazing or after two years of grazing at $P < 0.050$ level, and different uppercase letters indicate significant differences between before and after two years of grazing at the same grazing intensity at $P < 0.050$ level. The meanings of lowercase and uppercase letters are the same in the following figures.

19.2% under G3 grazing intensity compared with before grazing. *D* values showed that vegetation coverage under G1 and G2 intensities increased, while it decreased under other grazing intensities.

Vegetation height decreased significantly with increasing grazing intensity (Fig. 2b). Except for G1 grazing intensity, vegetation heights under G2–G5 grazing intensities decreased by 39.9%, 26.5%, 35.1%, and 52.2%, respectively, compared with control. Vegetation height under G0 and G1 grazing intensities showed no significant difference, while it decreased significantly by 44.2%, 42.5%, 55.9%, and 56.1%, respectively, under G2–G5 grazing intensities compare with those before grazing. *D* value showed that vegetation height decreased with increasing grazing intensity.

Grazing increased vegetation biomass, and the degree of increase in vegetation biomass decreased with increasing grazing intensity (Fig. 2c). There was no significant difference in vegetation biomass between control and G5 grazing intensity compared with that before grazing. Vegetation biomass under G1–G4 grazing intensities increased significantly by 51.9%, 42.1%, 36.9%, and 36.7%, respectively, compared with those before grazing.

3.1.2 Litter coverage and biomass

Grazing did not significantly affect litter coverage, and there was no significant difference in litter coverage before and after grazing under different grazing intensities (Fig. 3a). Litter biomass decreased significantly with increasing grazing intensity (Fig. 3b). Compared with control, litter biomass under G2–G5 grazing intensities decreased significantly by 53.2%, 58.5%, 60.9%, and 64.9%, respectively. Compared with that before grazing, litter biomass under G1–G5 grazing intensities decreased by 50.5%, 72.6%, 79.0%, 80.0%, and 76.9%, respectively.

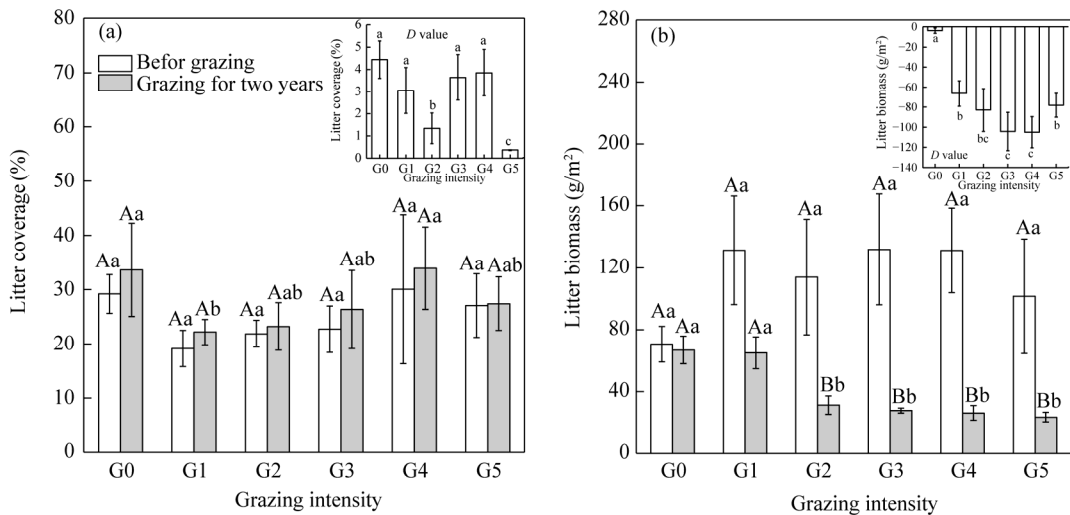


Fig. 3 Effects of grazing on litter coverage (a) and biomass (b)

3.1.3 Biocrust coverage

Biocrust coverage decreased significantly due to grazing (Fig. 4). Compared with control, biocrust coverage under G1–G5 grazing intensities decreased significantly by 20.0%, 41.7%, 43.2%, 41.9%, and 65.3%, respectively. Compared with that before grazing, biocrust coverage decreased by 24.3%, 40.7%, 40.3%, 16.5%, and 57.7%, respectively. *D* values showed that differences in biocrust coverage under all grazing intensities were negative after grazing.

3.2 Effects of grazing on species diversity

Moderate grazing promoted an increase in the species diversity (Fig. 5). Compared with control, the Shannon-Wiener diversity indices under G1–G3 grazing intensities increased significantly by 33.6%, 41.6%, and 32.1%, respectively. Compared with before grazing, there was no significant change in the Shannon-Wiener diversity index under G5 grazing intensity, while it increased significantly by 22.8%, 22.5%, 13.3%, and 8.3%, respectively, under G1–G4 grazing intensities.

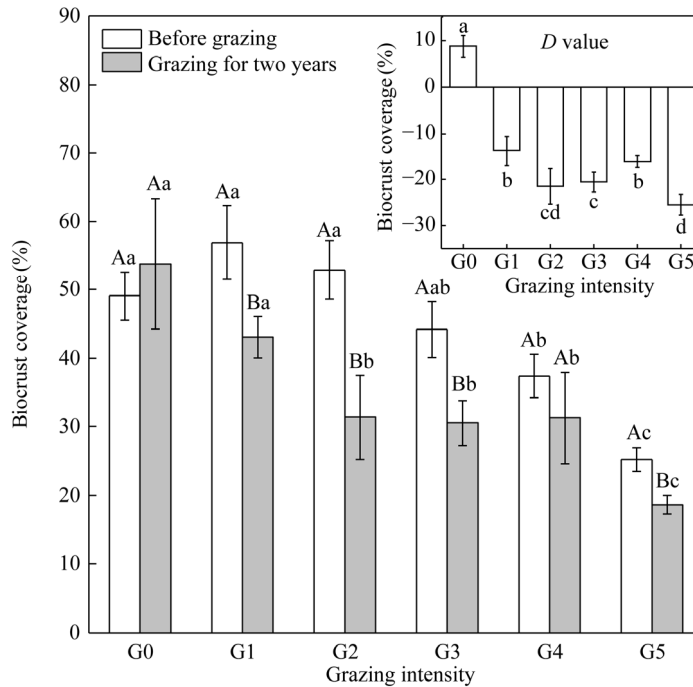


Fig. 4 Effect of grazing on biocrust coverage

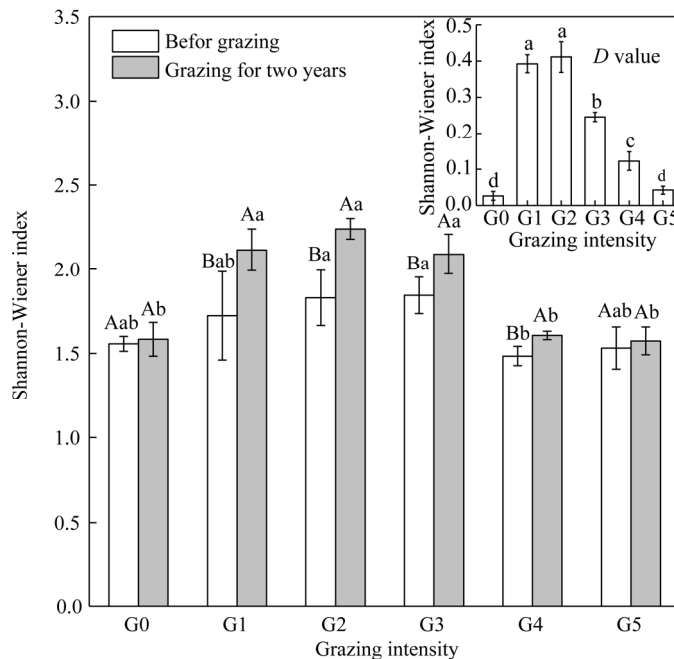


Fig. 5 Effect of grazing on the Shannon-Wiener index of vegetation community

3.3 Rainfall characteristics and response of runoff yield to grazing

During the experimental period in the second year of grazing, a total of 38 rainfall events occurred, with a cumulative rainfall amount of 380 mm. Among them, six rainfall events generated runoff between May and August 2022, accounting for 15.8% of the total rainfall frequency. Cumulative amount of the six rainfall events was 191 mm, accounting for 50.2% of the total rainfall amount. The details of the six rainfall events are shown in Table 1.

Rainfall is an important influencing factor of runoff and soil erosion. Thus, to reveal the effects of grazing on soil and water loss under different rainfall conditions, we classified the six rainfall events into three groups according to rainfall erosivity and rainfall duration (Fig. 6), represented by R1, R2, and R3, respectively. R1 was characterized by a long rainfall duration and low rainfall erosivity, R2 was characterized by a short rainfall duration and moderate rainfall erosivity, and R3 was characterized by a high rainfall erosivity.

Table 1 Rainfall characteristics

Rainfall pattern	Rainfall amount (mm)	Duration of rainfall (h)	Mean rainfall intensity (mm/h)	Maximum rainfall intensity in 30 minutes (mm/h)	Rainfall erosivity (MJ·mm/(hm ² ·h))
R1	23.40	6.97	3.36	10.80	28.84
	14.00	7.97	1.76	7.60	89.60
R2	43.20	4.38	9.86	30.40	306.74
	23.00	3.20	7.19	36.80	220.43
R3	41.20	3.23	12.74	56.00	572.88
	46.00	6.58	6.99	68.00	805.12

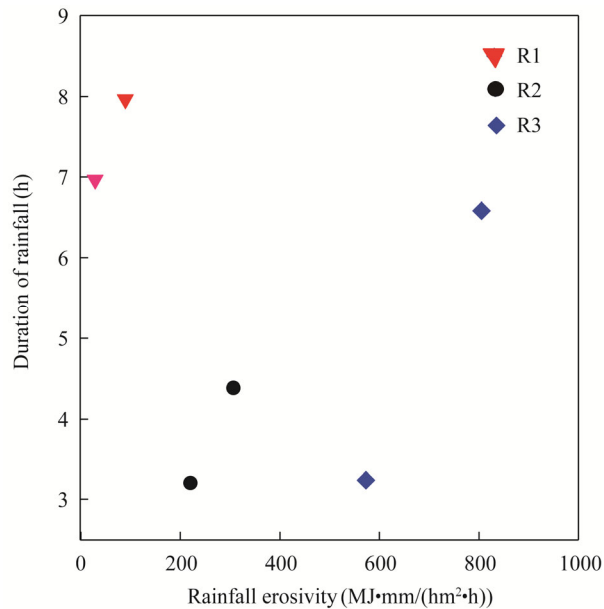


Fig. 6 Cluster analysis of rainfall. R1, R2, and R3 are three patterns of rainfall.

Runoff of the grassland increased significantly with increasing grazing intensity (Fig. 7a). Runoff depths under G1–G5 grazing intensities were 2.6, 3.0, 3.3, 4.2, and 4.0 times higher than that of control, respectively, and there was no significant difference between G4 and G5 grazing intensities.

Effects of different grazing intensities on the runoff depth were related to rainfall patterns (Fig. 7b). Under R1 rainfall pattern, runoff depths were less than 2 mm. Under R2 rainfall pattern, runoff depth under G1–G5 grazing intensities increased by 1.4, 2.6, 2.8, 4.3, and 3.9 times higher than that of control, respectively. However, under R3 rainfall pattern, runoff depth under G1–G5 grazing intensities increased sharply by 3.5, 3.4, 3.9, 4.3, and 4.3 times higher than that of control, respectively.

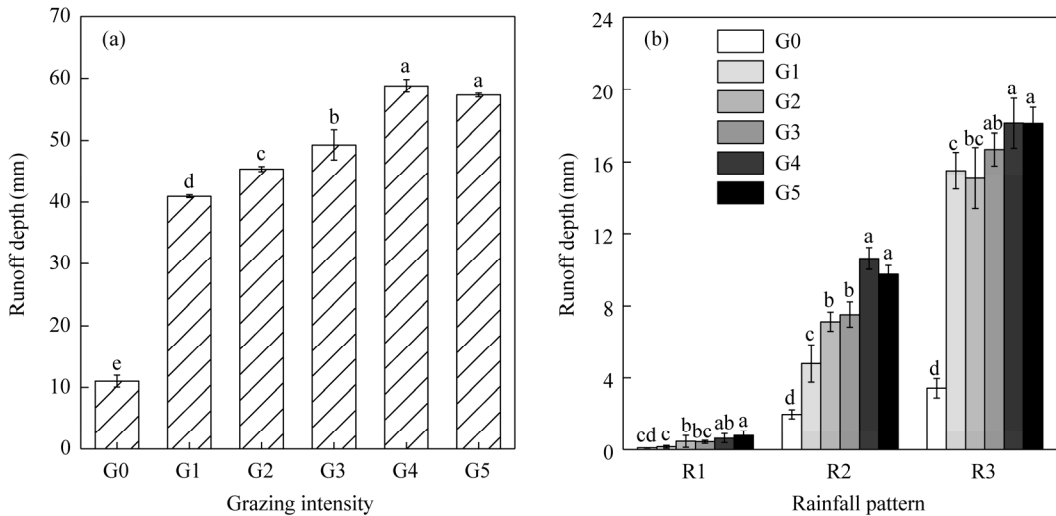


Fig. 7 Changes of runoff depth under different grazing intensities (a) and rainfall patterns (b). Different lowercase letters indicate significant differences among different grazing intensities or different rainfall patterns at $P < 0.050$ level. R1, R2, and R3 are three patterns of rainfall with low, moderate, and high rainfall erosivities, respectively. The meanings of lowercase letters and abbreviations are the same in the following figure.

3.4 Effects of grazing on sediment yield

Soil loss from sloping grassland increased significantly with increasing grazing intensity (Fig. 8a). Soil loss under G1–G5 grazing intensities was 3.0, 13.0, 20.8, 34.3, and 37.7 times higher than that of control, respectively. Effect of different grazing intensities on soil loss from sloping grasslands was related to rainfall patterns (Fig. 8b). Under R1 rainfall pattern, there was no significant difference in soil loss under G1–G4 grazing intensities and control, while soil loss under G5 grazing intensity increased by 8.3 times higher than that of control. Under R2 rainfall pattern, soil loss under G2–G5 grazing intensities was 7.5, 15.6, 21.0, and 27.7 times higher than that of control, respectively, and there was no difference between G1 grazing intensity and control. Under R3 rainfall pattern, soil loss increased significantly with increasing grazing intensity, and soil loss under G1–G5 grazing intensities increased by 4.7, 5.6, 9.0, 11.0, and 14.0 times, respectively, compared with that of control. The sediment yield per year from the five grazing intensities ranged from 123.32 to 491.64 t/km².

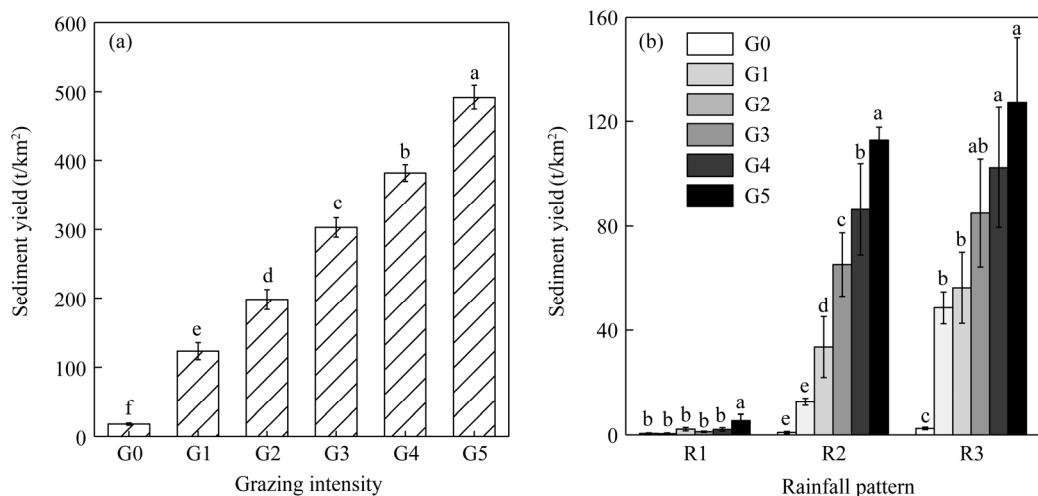


Fig. 8 Changes of sediment yield under different grazing intensities (a) and rainfall patterns (b)

3.5 SEM analysis

A SEM was used to explicate the effects of grazing and grassland surface coverage on soil loss (Fig. 9). Results of the model showed that grazing had strong direct effects on vegetation height and litter biomass, and thereby indirectly affected soil loss. Among them, the effect of litter biomass on soil loss was the primary effect, with an estimated path coefficient of -0.79 , followed by that of vegetation height, with an estimated path coefficient of 0.18 . Moreover, grazing had a strong direct effect on soil loss, with an estimated path coefficient of 0.45 . Furthermore, grazing exerted a significant direct influence on biocrust coverage (-0.78), whereas the impact of biocrust coverage on soil loss was slight. Although vegetation coverage had a significant impact on soil loss, the effect of grazing on vegetation coverage was not significant.

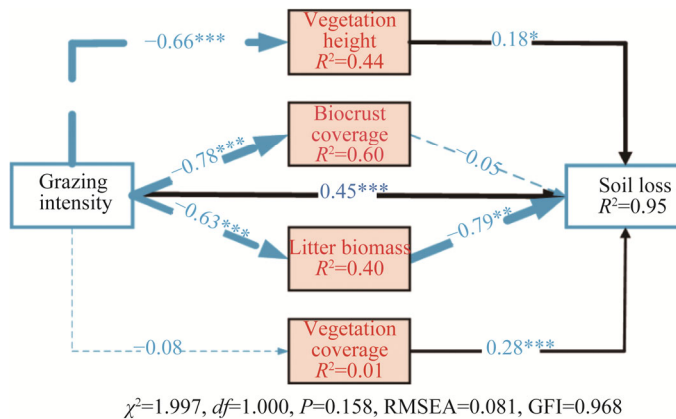


Fig. 9 A structural equation model (SEM) demonstrating the effects of grazing and land surface coverage on soil loss. Black solid arrows indicate positive effects, and blue dashed lines indicate negative effects. *, $P<0.050$ level; **, $P<0.010$ level; ***, $P<0.001$ level; *df*, degree freedom; RMSEA, root mean square error of approximation; GFI, goodness of fit index.

3.6 Evaluation of effect of a reasonable grazing intensity on grassland

Grassland multifunctional index showed an open downward quadratic relationship with increasing grazing intensity (Fig. 10). When grazing intensity was 10.5 goats/hm², grassland multifunctional index reached its maximum. However, soil conservation index sharply decreased with increasing grazing intensity. Functions of vegetation multifunctional and soil conservation indices with grazing intensity intersected at a grazing intensity of 3.5 goats/hm², where both functional indices were 0.53 .

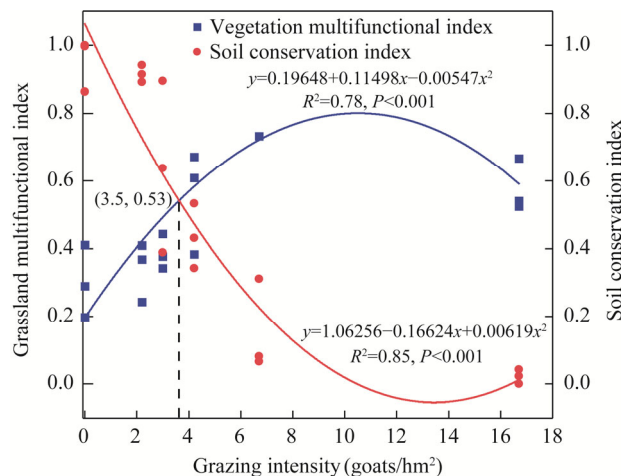


Fig. 10 Relationship of grassland multifunctional and soil conservation indices with grazing intensity

4 Discussion

4.1 Response of grassland surface coverage to grazing

Grazing is an important utilization pathway for grassland. Vegetation coverage, biomass, and height of the grassland were affected by grazing and varied with grazing intensity. Our results showed that vegetation coverage under G2, G3, and G5 grazing intensities was significantly lower than that of control, while there was no significant difference under G4 grazing intensity (Fig. 2a), which was inconsistent with our expectations. This may be due to the heterogeneity of grazing plots with different intensities before grazing. To eliminate the uncertainty caused by heterogeneity and accurately analyze the response of vegetation coverage to grazing intensity, vegetation coverage before grazing was used as a control too. Results showed that vegetation coverage under G1 grazing intensity increased significantly compared with that before grazing, while it decreased under G3–G5 grazing intensities. This means that low and moderate grazing intensities will promote an increase in vegetation coverage, while high grazing intensity will lead to a decrease in vegetation coverage. The reason may be that nutrient cycling in grassland ecosystem is promoted under low-intensity grazing, which in turn promotes resource redistribution and leads to the over-compensatory growth of grassland vegetation (Oesterheld and McNaughton, 1991). With increasing grazing intensity, the feed intake of vegetation by grazing livestock increases and the damage to photosynthetic and growth tissues of vegetation also increases, making it more difficult to restore, resulting in undercompensated growth of vegetation.

Notably, vegetation height was significantly reduced by grazing (Fig. 2b), which may have been related to the alteration of spatial structure of vegetation community induced by grazing through foraging and trampling. Grazing livestock selectively forage for fresh and nutritious apical growth points (Bleke et al., 2023) or reproductive organs (Zhang et al., 2022) of vegetation, especially tall vegetation. Moreover, grazing trampling causes mechanical damage to tall vegetation (Quispe et al., 2021). As a result, the dominance of species that occupy environmental and spatial resources such as light and nutrients at their own height is reduced (Zheng, 2012), which provides more space and resources for species distributed at the bottom to grow better, resulting in a decrease in the height of the overall vegetation community. In other words, grazing causes changes in the dominant species and life forms of the grassland vegetation communities. According to our investigation, the dominant species of the vegetation community changes from the upright species *A. gmelinii* and *Stipa capillata* Linn to the creeping species *P. acaulis* with increasing grazing intensity, resulting in a significant decrease in vegetation height. Similar results were obtained in a study on the impact of long-term grazing on the vegetation community characteristics of grassland (Sun et al., 2022).

Surprisingly, vegetation biomass increased after grazing; however, the degree of increase decreased with increasing grazing intensity (Fig. 2c). Therefore, in terms of vegetation biomass, the productivity of grassland was not reduced by grazing. Nevertheless, there may be a risk of poor palatability of vegetation communities for livestock as grazing intensities increase over time. Furthermore, compensatory vegetation growth may occur under low grazing intensity (Wang and Wang, 2001). Consequently, in terms of vegetation biomass, moderate grazing was beneficial for the sustainable utilization of grassland.

Litter, as a product of plant metabolism, is also an important surface cover in grassland ecosystem, can enhance soil fertility (Zönnchen et al., 2014), and increase surface water retention (He et al., 2023). To our surprise, litter coverage was not significantly affected by grazing (Fig. 3a), while litter biomass significantly decreased with increasing grazing intensity (Fig. 3b). This meant that litter layer decreased in thickness. This may be due to the reduction in vegetation coverage and height under the influence of grazing and the transformation of dominant species in vegetation community into species with low litter yields (Fig. 2). Moreover, the spatial distribution of litter changed due to grazing and soil erosion, and some were carried out in plots, resulting in a decrease in litter biomass.

Biocrusts are ubiquitous living covers in dryland ecosystem and are important in improving soil structure and maintaining soil surface stability (Yang et al., 2022). However, biocrusts also have a risk of reducing soil water infiltration (Zhao et al., 2006) and affecting plant seed germination (Li et al., 2016). Due to grazing trampling, biocrusts were fragmented or degraded, resulting in a significant decrease in coverage (Fig. 4). Soil water infiltration may therefore increase, which in turn promotes vegetation growth (Lavee et al., 1998). In addition, more plant seeds will be in contact with soil, resulting in an increase in germination rate (Xu et al., 2023). This further explains why moderate grazing promotes increases in vegetation coverage, biomass, and diversity (Fig. 5). Our results also showed that grassland species diversity increased under all grazing intensities except for under heavy grazing (G5), which was consistent with the theory of moderate disturbance (Connell, 1978).

4.2 Effects of grazing on soil loss from sloping grassland

Grazing is an important factor that induces soil erosion in grassland (Pietola et al., 2005). Our results also showed that grazing significantly increased soil loss in grassland (Fig. 8), and the increasing effect was determined by grazing intensity and land cover characteristics. Grazing caused changes in vegetation coverage, vegetation biomass, height, litter biomass, and biocrust coverage. Vegetation coverage is a key factor in preventing and controlling soil erosion. It reduces soil erosion by intercepting rainfall, mitigating the impact of raindrops on soil, decelerating flow velocity, enhancing infiltration, and diminishing the erosive force of runoff (Muñoz-Robles et al., 2011; Dong et al., 2018; Yao et al., 2018). We also found that vegetation coverage had a significant impact on soil erosion, however, different intensities of grazing had no significant impact on vegetation coverage (Fig. 9). Nevertheless, vegetation height decreased in response to grazing intensities, which consequently had a positive effect on soil erosion (0.18). This may be because the leaves of high plants are eaten by grazing livestock, resulting in a reduction in rainfall interception by the stems (Yang et al., 2008). Moreover, vegetation community was dominated by creeping species (Fig. 1), which act as "protective films" to buffer rainfall and runoff erosion. Biocrusts serve as a vital ground cover for grassland in the loess hilly areas, significantly enhancing soil erosion resistance. With a coverage of 40.0%, biocrusts can control more than 80.0% of soil loss (Yang et al., 2022). Unexpectedly, despite a significantly decreased response to grazing, biocrust coverage exerted minimal and insignificant impact on soil erosion in grazed grassland. This might be attributed to the increase in creeping species after grazing, which offsets the reduction in biocrust coverage.

Due to the long-term closure of grassland, there is a considerable amount of litter on the ground surface. Litter could form a "buffer layer" on the surface of grassland, reducing the impact of rainfall on the surface soil. Moreover, litter has a high water-holding capacity, which can reduce runoff and flow velocity. However, litter biomass decreased significantly in response to grazing, resulting in a weakened ability to protect the soil. Moreover, litter biomass exerted the greatest impact on soil loss among all surface cover factors. Overall, grazing mainly reduced the litter biomass, leading to an increase in soil erosion.

Rainfall is a dynamic factor influencing soil erosion, including rainfall intensity and duration. Rainfall erosivity represents the potential capacity for rainfall to induce soil erosion. It frequently characterizes erosive rainfall and stands as a crucial factor influencing soil erosion (Morin et al., 2006). We found significant differences in the response of soil erosion to grazing intensity under different rainfall erosivity patterns. Under R1 pattern, minimal soil loss occurred across various grazing intensities, with no significant differences observed. This could be attributed to the low rainfall intensity and extended duration, and the rainfall intensity may be lower than the soil infiltration capacity (Bronstert et al., 2023). The majority of rainfall had enough time to infiltrate the soil, thereby providing insufficient erosive forces to cause substantial soil loss. Under R2 pattern, soil loss on grazed grassland significantly increased compared with non-grazed grassland. Significant variations were observed across different grazing intensities, indicating a high sensitivity of soil loss on grassland to grazing intensity within this rainfall pattern. Under R3

pattern, although soil loss on grazed grassland increased sharply compared with non-grazed grassland, its sensitivity to grazing intensity was lower than that under R2 pattern. In the loess hilly area, short duration and high intensity rainfall is the primary rainfall pattern causing soil loss, and soil loss from high rainfall intensity is less influenced by ground surface conditions than that of low rainfall intensity (Bronstert et al., 2023). Therefore, under high rainfall erosive conditions, the impact of rainfall on soil loss might exceed the grassland surface differences caused by grazing, which likely accounts for the lower sensitivity of soil loss to grazing intensity in this rainfall pattern. In the context of global climate change, the frequency of extreme rainfall events is likely to increase, so even light grazing may increase the risk of soil erosion in grassland.

4.3 Implications of grazing for sustainable management of sloping grassland

Long-term enclosure of grassland is not beneficial for effective vegetation renewal (Cheng et al., 2006) and may lead to grassland degradation (Cheng et al., 2014). Moreover, long-term accumulation of litter also increases the risk of wildfires (Pérez et al., 2024). In addition, the production mode in semi-arid hilly areas is mainly based on the combination of agriculture and animal husbandry (Millennium Ecosystem Assessment, 2005). Long-term grazing prohibition is not conducive to economic development (Liang, 2017) and will cause large-scale waste of grassland resources. Moderate grazing and utilization of grassland could effectively increase grassland productivity (Pucheta et al., 2004) and species diversity (Wang et al., 2005). Our results also revealed that vegetation biomass and species diversity increased by 42.1% and 34.0%, respectively, under moderate grazing (below 3.0 goats/hm²). However, vegetation and litter coverage did not change significantly or increased slightly.

To comprehensively reflect the grassland production function, we established a vegetation multifunctional index by selecting vegetation biomass, diversity, and litter biomass. We found that under grazing intensities below 10.5 goats/hm², vegetation multifunctional index increased with increasing grazing intensity. This may be related to the enhancement of species diversity due to grazing, as studies have shown a positive correlation between vegetation species diversity and grassland multifunctionality (Zhang et al., 2023). This implies that reasonable grazing practices will not pose a threat to grassland productivity and may even enhance it. In contrast, soil conservation function sharply decreased with increasing grazing intensity. This further confirms the conflict between grassland utilization and soil conservation. To balance this conflict, it is necessary to maintain both grassland productivity and soil conservation. With increasing grazing intensity, grassland multifunctionality and soil conservation indices converged at the grazing intensity of 3.5 goats/hm², at which point the indices were both 0.53, indicating that grassland productivity and soil conservation both maintained at high levels. Therefore, we believe that grassland can be grazed with an intensity of less than 3.5 goats/hm², ensuring both functions of grassland productivity and soil conservation.

Soil loss tolerance refers to the maximum soil loss that maintains soil fertility and basic stability of soil productivity over a long period, commonly represented by the *T* value (Yang et al., 2004). Chen et al. (2003) defined *T* value as 200.0 t/(km²·a) for grassland was based on soil formation rate of loess in the loess hilly areas of China. In this study, the soil loss rates under 2.2 and 3.0 goats/hm² grazing intensities were 123.3 and 184.4 t/(km²·a), respectively, which were both lower than the *T* value. According to the relationship between soil conservation index and grazing intensity, when grazing intensity was 3.5 goats/hm², the soil loss rate was 194.3 t/(km²·a), which was also below the *T* value, indicating that grazing did not pose a threat to the health of grassland ecosystem.

5 Conclusions

In this study, the effects of grazing intensity on vegetation coverage, biomass, diversity, and soil erosion were analyzed from the perspective of balancing grassland utilization and soil conservation in the semi-arid loess hilly areas. Reasonable grazing is beneficial for the

sustainable utilization of grassland resources. Vegetation biomass, coverage, and diversity were significantly improved under grazing intensities below 3.5 goats/hm². Moreover, grazing increased the risk of soil erosion, which increased noticeably with increasing grazing intensity. This can be mainly attributed to a visible decrease in litter biomass after grazing. Under low grazing intensity of less than 3.5 goats/hm², both grassland productivity and soil conservation function were maintained at high levels. Therefore, it is recommended that grassland should be moderately utilized with grazing pressure below 3.5 goats/hm² in semi-arid hilly areas to achieve dual goals of ecological and economic benefits. The results provide a scientific basis for grassland utilization and health management in semi-arid hilly areas from the perspective of determining reasonable grazing intensity to maintain both grassland production and soil conservation functions.

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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Author contributions

Conceptualization: ZHAO Yunge, XU Mingxiang, SUN Hui, GAO Liqian; Formal analysis and investigation: SUN Hui, GAO Liqian; Methodology: SUN Hui, ZHAO Yunge; Writing - original draft preparation: SUN Hui; Writing - review and editing: SUN Hui, GAO Liqian, ZHAO Yunge, XU Mingxiang; Funding acquisition: GAO Liqian, ZHAO Yunge; Resources: XU Mingxiang, ZHAO Yunge; Supervision: ZHAO Yunge, XU Mingxiang. All authors approved the manuscript.

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