Reasonable Grazing May Balance the Conflict between Grassland Utilization and Soil Conservation in Semi-Arid Hilly Areas of China (Postprint)

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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.

Full Text

Preamble

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

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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 an effective method for addressing this issue. However, some ecological and economic problems, such as slow grassland rejuvenation and limited economic opportunities, have become obstacles to the sustainable utilization of grassland ecosystems. Accordingly, we hypothesized that the conflict between grassland use and soil conservation may be balanced by implementing 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/hm^2, represented by G1–G5, respectively, with no grazing used as control. The results showed that reasonable grazing intensity was conducive to the sustainable utilization of grassland resources. Vegetation biomass under G1–G4 grazing intensities 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 grassland productivity and soil conservation function, we found that both aims were achieved at a low grazing intensity of less than 3.5 goats/hm^2. Therefore, it is recommended that grassland should be moderately utilized with grazing intensity below 3.5 goats/hm^2 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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Introduction

Grassland is a dominant land use type in semi-arid areas, covering approximately 40.0%–45.0% of the total area worldwide [?, ?]. Livestock grazing is the main method of utilizing grassland [?, ?]. Approximately 30.0% of global grassland is used for livestock grazing [?, ?], and grassland is important for livestock production [?, ?]. 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 [?, ?] and often causes severe soil erosion in semi-arid hilly areas [?, ?]. To date, many studies have examined 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 [?, ?, ?]. 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 [?, ?]. In the central arid area of Australia, overgrazing leads to the destruction of grassland surface landscape and degradation, which causes a dramatic increase in soil erosion [?, ?].

To control grassland degradation and soil erosion, governments of many counties have implemented measures to prohibit grazing. For instance, the Chinese government implemented strict grazing prohibition in the hilly Loess Plateau area to control soil erosion and restore the vegetation coverage of grassland [?, ?]. 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 [?, ?]. In addition, long-term grazing prohibition has affected the economic income of residents who rely on animal husbandry [?, ?]. 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 the 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 [?, ?]; the Edward Plateau, Texas, USA [?, ?]; and grassland in southern Queensland, Australia [?, ?], have shown that moderate grazing increases the species diversity and richness of grassland vegetation communities. Moreover, moderate grazing appears to increase plant growth rate [?, ?]. However, the intensity of moderate grazing differs among various areas [?, ?, ?, ?]. 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 [?, ?]. The results of these studies indicated the possibility of balancing soil and water conservation and the health of ecological systems 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 years; however, new challenges have arisen in the rehabilitated grassland, such as the strong consumption of soil water [?, ?], the decreasing species diversity of grasses, the slowing of grassland ecosystem recovery [?, ?], and the risk of wildfires caused by the accumulation of litter over time [?, ?]. On the other hand, the production mode combining agriculture and animal husbandry changed due to the policy of grazing prohibition [?, ?], which caused a decline in farmers' economic incomes [?, ?]. 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.

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 an 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 typical loessial soil. Due to the implementation of the Grain for Green project, a large area of rehabilitated sloping grassland was formed, with coverage of approximately 57.0% [**?**, **?**]. 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 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 measures, the number of free-grazing goats sharply declined, resulting in a 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.

Experimental Design

A typical grassland on a hilly slope that had been rehabilitated for more than 20 years 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 hm^2 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 hm^2 (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/hm^2, respectively, represented by G1–G5 in ascending order, and no grazing (G0) was used as control. The grazing experiment began in early August 2020 and ended in September 2022, with a grazing period of 2 years. The grassland surface vegetation after two years of grazing is shown in Figure 1 [Figure 1: see original paper]. 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; and *P. acaulis* under G5 grazing intensity.

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. The height of vegetation was measured for each plant species in each quadrat, and the 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 [**?**, **?**]. In each grazing plot, 45 gridded quadrats were surveyed from the top to the bottom of the plot to obtain the total biocrust coverage.

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

$$H' = -\sum_{i=1}^{n} P_i \ln P_i$$

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 ith plant to the number of individuals of all species.

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. The 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. The 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.

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):

$$e_k = 0.119 + 0.873 \log i_k, \quad R = EI_{30}$$

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 (MJ/(hm$^2 \cdot$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 (MJ $\cdot$ mm/(hm^2 $\cdot$ h)); and I_{30} is the maximum rain intensity in 30 min (mm/h).

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 [**?**, **?**], 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 [**?**, **?**]. 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.

Statistical Analyses

One-way analysis of variance (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 the 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.

Vegetation Coverage, Height, and Biomass

Vegetation coverage increased under lower grazing intensities (less than 3.0 goats/hm^2) but decreased with increasing grazing intensity (Fig. 2a [Figure 2: see original paper]). 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 differ significantly from control. Vegetation coverage under control did not differ significantly from those under 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 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 [Figure 2: see original paper]). 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 compared 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 [Figure 2: see original paper]). 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.

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 [Figure 3: see original paper]). Litter biomass decreased significantly with increasing grazing intensity (Fig. 3b [Figure 3: see original paper]). 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.

Biocrust Coverage

Biocrust coverage decreased significantly due to grazing (Fig. 4 [Figure 4: see original paper]). 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.

Effects of Grazing on Species Diversity

Moderate grazing promoted an increase in species diversity (Fig. 5 [Figure 5: see original paper]). 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.

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. The 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 [Figure 6: see original paper]), 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 high rainfall erosivity.

Runoff of the grassland increased significantly with increasing grazing intensity (Fig. 7a [Figure 7: see original paper]). 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 runoff depth were related to rainfall patterns (Fig. 7b [Figure 7: see original paper]). 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.

Effects of Grazing on Sediment Yield

Soil loss from sloping grassland increased significantly with increasing grazing intensity (Fig. 8a [Figure 8: see original paper]). 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. The effect of different grazing intensities on soil loss from sloping grasslands was related to rainfall patterns (Fig. 8b [Figure 8: see original paper]). 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/km^2.

SEM Analysis

A SEM was used to explicate the effects of grazing and grassland surface coverage on soil loss (Fig. 9 [Figure 9: see original paper]). 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.

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 [Figure 10: see original paper]). When grazing intensity was 10.5 goats/hm^2, 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/hm^2, where both functional indices were 0.53.

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 [Figure 2: see original paper]), 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 [?, ?]. 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 [Figure 2: see original paper]), 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 [?, ?] or reproductive organs [?, ?] of vegetation, especially tall vegetation. Moreover, grazing trampling causes mechanical damage to tall vegetation [?, ?]. As a result, the dominance of species that occupy environmental and spatial resources such as light and nutrients at their own height is reduced [?, ?], 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 [?, ?].

Surprisingly, vegetation biomass increased after grazing; however, the degree of increase decreased with increasing grazing intensity (Fig. 2c [Figure 2: see original paper]). 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 [?, ?]. 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 [?, ?], and increase surface water retention [?, ?]. To our surprise, litter coverage was not significantly affected by grazing (Fig. 3a [Figure 3: see original paper]), while litter biomass significantly decreased with increasing grazing intensity (Fig. 3b [Figure 3: see original paper]). 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 [Figure 2: see original paper]). 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 [?, ?]. However, biocrusts also have a risk of reducing soil water infiltration [?, ?] and affecting plant seed germination [?, ?]. Due to grazing trampling, biocrusts were fragmented or degraded, resulting in a significant decrease in coverage (Fig. 4 [Figure 4: see original paper]). Soil water infiltration may therefore increase, which in turn promotes vegetation growth [?, ?]. In addition, more plant seeds will be in contact with soil, resulting in an increase in germination rate [?, ?]. This further explains why moderate grazing promotes increases in vegetation coverage, biomass, and diversity (Fig. 5 [Figure 5: see original paper]). 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 [?, ?].

Effects of Grazing on Soil Loss from Sloping Grassland

Grazing is an important factor that induces soil erosion in grassland [?, ?]. Our results also showed that grazing significantly increased soil loss in grassland (Fig. 8 [Figure 8: see original paper]), 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 [?, ?, ?, ?]. 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 [Figure 9: see original paper]). 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 tall plants are eaten by grazing livestock, resulting in a reduction in rainfall interception by the stems [?, ?]. Moreover, vegetation community was dominated by creeping species (Fig. 1 [Figure 1: see original paper]), 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 [?, ?]. 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 [?, ?]. 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 [?, ?]. 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 [?, ?]. 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.

Implications of Grazing for Sustainable Management of Sloping Grassland

Long-term enclosure of grassland is not beneficial for effective vegetation renewal [?, ?] and may lead to grassland degradation [?, ?]. Moreover, long-term accumulation of litter also increases the risk of wildfires [?, ?]. In addition, the production mode in semi-arid hilly areas is mainly based on the combination of agriculture and animal husbandry [?, ?]. Long-term grazing prohibition is not conducive to economic development [?, ?] and will cause large-scale waste of grassland resources. Moderate grazing and utilization of grassland could effectively increase grassland productivity [?, ?] and species diversity [?, ?]. 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/hm^2). 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/hm^2, 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 [?, ?]. 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/hm^2, 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/hm^2, 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 [**?**, **?**]. Chen et al. (2003) defined T value as 200.0 t/(km$^2 \cdot$ a) for grassland 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/hm^2 grazing intensities were 123.3 and 184.4 t/(km$^2 \cdot$ 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/hm^2, the soil loss rate was 194.3 t/(km$^2 \cdot$ a), which was also below the T value, indicating that grazing did not pose a threat to the health of grassland ecosystem.

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/hm^2. 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/hm^2, 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/hm^2 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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References

Antal Z, Huzsvai L. 2007. Grass production model based grazing as the sustainable utilization of protected grasslands. *Cereal Research Communications*, 35(2): 189–192.

Belnap J, Phillips S L. 2001. Soil biota in an ungrazed grassland: Response to annual grass (*Bromus tectorum*) invasion. *Ecological Applications*, 11(5): 1261–1275.

Bleke C A, Gese E M, Roberts S B, et al. 2023. Seasonal shifts in pronghorn antelope (*Antilocapra americana*) diets under a lens: Examining diet composition using a molecular technique. *PloS ONE*, 18(10): 0292725, doi: 10.1371/journal.pone.0292725.

Bronstert A, Daniel N, Gerd R. 2023. Modelling infiltration and infiltration excess: The importance of fast and local processes. *Hydrological Process*, 37(4): e14875, doi: 10.1002/hyp.14875.

Chen Q B, Wang K Q, Qi S, et al. 2003. Soil loss tolerance of sloping field in semiarid hilly-gully area of Loess Plateau. *Bulletin of Soil and Water Conservation*, 23(4): 1–4. (in Chinese)

Cheng H, Jin B C, Luo K, et al. 2021. Vegetation response to goats grazing intensity in semi-arid hilly grassland of the Loess Plateau, Lanzhou, China. *Sustainability*, 13(6): 35–69.

Cheng J M, Wan H E, Hu X M, et al. 2006. Accumulation and decomposition of litter in the semi-arid enclosed grassland. *Acta Ecologica Sinica*, 26(4): 1207–1212. (in Chinese)

Cheng J M, Jing Z B, Jin J W, et al. 2014. Restoration and utilization mechanism of degraded grassland in the semi-arid region of Loess Plateau. *Scientia Sinica Vitae*, 44(3): 267–279. (in Chinese)

Connell J H. 1978. Diversity in tropical rain forests and coral reefs. *Science*, 199(435): 1302–1310.

Dong L, Wang J, Li J R, et al. 2023. Assessing the impact of grazing management on wind erosion risk in grasslands: A case study on how grazing affects aboveground biomass and soil particle composition in Inner Mongolia. *Global Ecology and Conservation*, 40: e02344, doi: 10.1016/j.gecco.2022.e02344.

Dong Y F, Xiong D H, Su Z A, et al. 2018. Effects of vegetation buffer strips on concentrated flow hydraulics and gully bed erosion based on in situ scouring experiments. *Land Degradation & Development*, 29(6): 1672–1682.

Evans R. 1998. The erosional impacts of grazing animals. *Progress in Physical Geography*, 22(2): 251–268.

Evans R. 2005. Curtailing grazing-induced erosion in a small catchment and its environs the Peak District Central England. *Applied Geography*, 25(1): 81–95.

Feng X M, Fu B J, Zhang Y, et al. 2021. Recent leveling off of vegetation greenness and primary production reveals the increasing soil water limitations on the greening Earth. *Science Bulletin*, 66(14): 1462–1471.

Fensham R J. 1998. The grassy vegetation of the Darling Downs, south-eastern Queensland, Australia, floristics and grazing effects. *Biological Conservation*, 84(3): 301–310.

Fuhlendorf S D, Smeins F E. 1997. Long-term vegetation dynamics mediated by herbivores, weather and fire in a *Juniperus quercus* savanna. *Journal of Vegetation Science*, 8(6): 819–828.

Gang C C, Zhao W, Zhao T, et al. 2018. The impacts of land conversion and management measures on the grassland net primary productivity over the Loess Plateau, Northern China. *Science of the Total Environment*, 645: 827–836.

Gong H X, Wang Y Y, Wang G Y, et al. 2023. Quantifying the spatial representativeness of carbon flux footprints of a grassland ecosystem in the semi-arid region. *Journal of Geophysical Research-Atmospheres*, 128(7): e2022JD038269, doi: 10.1029/2022JD038269.

Han Y, Zheng F L, Xu X M. 2017. Effects of rainfall regime and its character indices on soil loss at loessial hillslope with ephemeral gully. *Journal of Mountain Science*, 14(3): 527–538.

He J, Ma L, Sun X, et al. 2023. Water-holding characteristics of litter and soil and the influencing factors after individual rainfall. *Chinese Journal of Applied Ecology*, 34(12): 3169–3176. (in Chinese)

Hodgson J. 1990. *Grazing Management: Science into Practice*. New York: Longman Scientific & Technical.

Lavee H, Imeson A C, Sarah P. 1998. The impact of climate change on geomorphology and desertification along a Mediterranean-arid transect. *Land Degradation and Development*, 9(5): 407–422.

Li Y K, Ouyang J Z, Lin L, et al. 2016. Alterations to biological soil crusts with alpine meadow retrogressive succession affect seeds germination of three plant species. *Journal of Mountain Science*, 13(11): 1995–2005.

Li Y Q, Zhao J B. 2005. Effects of overgrazing on ecological and environmental construction and measurement. *Journal of Desert Research*, 25(3): 404–408.

(in Chinese)

Liang Z. 2017. The relationship between closing hillside to prohibit herding and forestry development. *China Forestry Economics*, 4(145): 68–69. (in Chinese)

Liu J G, Li S X, Ouyang Z Y, et al. 2008. Ecological and socioeconomic effects of China's policies for ecosystem services. *Proceedings of the National Academy of Sciences*, 105(28): 9477–9482.

Maestre F T, Quer J L, Gotelli N J, et al. 2012. Plant species richness and ecosystem multifunctionality in global drylands. *Science*, 335(6065): 214–218.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Desertification Synthesis*. Washington: World Resources Institute.

Morin E, Goodrich D C, Maddox R A, et al. 2006. Spatial patterns in thunderstorm rainfall events and their coupling with watershed hydrological response. *Advances in Water Resources*, 29(6): 843–860.

Muñoz-Robles C, Reid N, Tighe M, et al. 2011. Soil hydrological and erosional responses in patches and inter-patches in vegetation states in semi-arid Australia. *Geoderma*, 160(3–4): 524–534.

Na Y T, Li J X, Hoshino B, et al. 2018. Effects of different grazing systems on aboveground biomass and plant species dominance in typical Chinese and Mongolian steppes. *Sustainability*, 10(12): 10124753, doi: 10.3390/su10124753.

Noss R F. 1990. Indicators for monitoring biodiversity: A hierarchical approach. *Conservation Biology*, 4(4): 355–364.

Oesterheld M, McNaughton S J. 1991. Effect of stress and time for recovery on the amount of compensatory growth after grazing. *Oecologia*, 85(3): 305–313.

Pérez J, Brand C, Alonso A, et al. 2024. Wildfires alter stream ecosystem functioning through effects on leaf litter. *Fire Ecology*, 20(1): 36, doi: 10.1186/s42408-024-00268-w.

Pietola L, Horn R, Yli-Halla M. 2005. Effects of trampling by cattle on the hydraulic and mechanical properties of soil. *Soil and Tillage Research*, 82(1): 99–108.

Pucheta E, Bonamici I, Cabido M, et al. 2004. Belowground biomass and productivity of a grazed site and a neighbouring ungrazed exclosure in a grassland in central Argentina. *Austral Ecology*, 29(2): 201–208.

Quispe C, Ñaupari J, Distel R A, et al. 2021. Feeding selection of sheep and alpaca on Puna tussock rangelands grazed previously by cattle. *Small Ruminant Research*, 197: 106349, doi: 10.1016/j.smallrumres.2021.106349.

Rodriguez-Lozano P, Rieradevall M, Rau M A, et al. 2015. Long-term consequences of a wildfire for leaf-litter breakdown in a Mediterranean stream. *Freshwater Science*, 34(4): 1482–1493.

Sara G. 2019. FAO SOFA report 2019: New insights into food loss and waste. IFPRI (International Food Policy Research Institute) Blog: Issue Markets, Trade, Institutions (MTID). [2023-09-10]. https://www.ifpri.org/blog/fao-sofa-report-2019-new-insights-food-loss-and-waste/.

Sun H, Zhao Y G, Liu G L, et al. 2022. Effects of grazing intensity on the grassland vegetation community characteristics in the hilly Loess Plateau region. *Acta Agrestia Sinica*, 30(4): 810–817. (in Chinese)

Tongway D J, Sparrowb A D, Friedelc M H. 2003. Degradation and recovery processes in arid grazing lands of central Australia. Part I: Soil and land resources. *Journal of Arid Environments*, 55(2): 301–326.

Wang G J, Wang S P, Hao Y B, et al. 2005. Effect of grazing on the plant functional group diversity and community biomass and their relationship along a precipitation gradient in Inner Mongolia Steppe. *Acta Ecologica Sinica*, 25(7): 1649–1656. (in Chinese)

Wang S P, Wang Y F. 2001. Study on over-compensation growth of *Cleistogenes squarrosa* population in Inner Mongolia steppe. *Acta Botanica Sinica*, 43(4): 413–418. (in Chinese)

Wang Z T, Yang L, Li G, et al. 2021. Long-term response of the rural economic structure changes between suburban and rural areas to Grain-for-Green Project in the Loess Plateau of central Gansu, Northwest China. *Acta Ecologica Sinica*, 14(6): (in Chinese)

Wu Y, Du Y B, Liu X, et al. 2023. Grassland biodiversity response to livestock grazing, productivity, and climate varies across biome components and diversity measurements. *Science of the Total Environment*, 878: 162994, doi: 10.1016/j.scitotenv.2023.162994.

Xu M Y, Zhu W Y, Yang C, et al. 2023. Effects of different grazing intensities on the soil seed bank in an alpine meadow. *Pratacultural Science*, 40(6): 1461–1471. (in Chinese)

Yang C Q, Cai Q G, Fan H M. 2004. Process of soil loss tolerance research—in the Phaeozem region of Northeast China. *Research of Soil and Water Conservation*, 11(4): 66–69. (in Chinese)

Yang K, Zhao Y G, Gao L Q. 2022. Biocrust succession improves soil aggregate stability of subsurface after “Grain for Green” project in the hilly Loess Plateau, China. *Soil & Tillage Research*, 217: 105290, doi: 10.1016/j.still.2021.105290.

Yang Z P, Li X Y, Sun Y L, et al. 2008. Characteristics of rainfall interception and stemflow for *Salix psammophila* in Maowusu Sandland, Northwest China. *Advances in Water Science*, 19(5): 693–698. (in Chinese)

Yao J J, Cheng J H, Zhou Z D, et al. 2018. Effects of herbaceous vegetation coverage and rainfall intensity on splash characteristics in northern China. *Catena*, 167: 411–421.

Yu H Q, Li Y, Oshunsanya S O, et al. 2019. Re-introduction of light grazing reduces soil erosion and soil respiration in a converted grassland on the Loess Plateau, China. *Agriculture Ecosystems & Environment*, 280: 43–52.

Zhang H, Liu N, Yang G W, et al. 2022. Diet selection of sheep shifted from quality to quantity characteristics of forages as sward availability decreased. *Animal*, 16(6): 100546, doi: 10.1016/j.animal.2022.100546.

Zhang M N, Delgado B M, Li G Y, et al. 2023. Experimental impacts of grazing on grassland biodiversity and function are explained by aridity. *Nature Communications*, 14: 5040, doi: 10.1038/s41467-023-40809-6.

Zhao Y G, Xu M X, Wang Q J, et al. 2006. Impact of biological soil crust on soil physical and chemical properties of rehabilitated grassland in hilly Loess Plateau, China. *Journal of Natural Resources*, 21(3): 441–448. (in Chinese)

Zheng W. 2012. Effects of enclosure on storage and allocation of carbon and nutrient elements in *Seriphidium transiliense* population. *Pratacultural Science*, 6(10): 1503–1511. (in Chinese)

Zönnchen C, Schaaf W, Esperschutz J. 2014. Effect of plant litter addition on element leaching in young sandy soils. *Journal of Plant Nutrition and Soil Science*, 177(4): 585–595.

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