Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

The multi-dimensional impacts of grazing on grassland ecological quality based on meta-analysis

Shu Jin
National Hulunbuir Grassland Ecosystem Observation and Research Station, Chinese Academy of Agricultural Sciences
Yutong Li
National Hulunbuir Grassland Ecosystem Observation and Research Station, Chinese Academy of Agricultural Sciences
Yi An
National Hulunbuir Grassland Ecosystem Observation and Research Station, Chinese Academy of Agricultural Sciences
Yanzi Xiao
Hulunbuir University
Ruirui Yan
National Hulunbuir Grassland Ecosystem Observation and Research Station, Chinese Academy of Agricultural Sciences
Xiaoyu Zhai
The University of Hong Kong
Xiaoping Xin
National Hulunbuir Grassland Ecosystem Observation and Research Station, Chinese Academy of Agricultural Sciences
Xiaoyu Zhu
zhuxiaoyu@caas.cn

National Hulunbuir Grassland Ecosystem Observation and Research Station, Chinese Academy of Agricultural Sciences

---

Research Article

Keywords: grazing intensity, grassland ecological quality, Meta-analysis, vegetation, soil, species diversity

Posted Date: August 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10464604/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

The multi-dimensional impacts of grazing on grassland ecological quality based on meta-analysis

Shu Jin[1,2 #], Yutong Li [1,2] , Yi An [1] , Yanzi Xiao [3], Ruirui Yan [2], Xiaoyu Zhai[4], Xiaoping Xin [2], Xiaoyu Zhu [1,2 *]

[1] Agro-Environmental Protection Institute, Ministry of Agriculture and Rural Affairs, Tianjin 300191, China

[2] State Key Laboratory of Efficient Utilization of Arable Land in China, National Hulunbuir Grassland Ecosystem Observation and Research Station, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

[3] College of Agriculture, Grass Industry Collaborative Innovation Research Center, Hulunbuir University, Hulunber 021000, China

[4] Faculty of Science, The University of Hong Kong, Hong Kong 999077, China

Abstract: Grasslands, as one of the most widely distributed ecosystems globally, play an irreplaceable role in maintaining ecological security and supporting socio-economic development, with their ecological quality being predominantly regulated by grazing intensity. This meta-analysis synthesizes 585 cases from 53 studies to assess grazing intensity effects on grassland ecological quality. Grazing exerted overall negative effects on vegetation and soil indicators. Aboveground biomass showed the strongest negative response ($P < 0.001$), followed by vegetation cover. Grazing-induced disturbances in soil nutrient cycling were reflected by increased soil pH co-occurring with decreased soil organic carbon and total nitrogen. Although overall species diversity remained statistically unchanged, community composition shifted significantly, with the Margalef index declining and evenness increasing. Subgroup analysis revealed that precipitation and grassland type significantly moderated grazing effects. Under high grazing intensity, both aboveground biomass and vegetation cover declined, while soil organic carbon, belowground biomass, and total nitrogen decreased with increasing intensity. Soil pH increased with grazing intensity. At moderate grazing intensity, soil and vegetation indicators reached their maximum values, supporting the moderate disturbance hypothesis. These findings indicate that controlling grazing at moderate levels is crucial for maintaining grassland ecosystem functions.

Keywords: grazing intensity, grassland ecological quality, Meta-analysis, vegetation, soil, species diversity

1 Introduction

The conflict between human activities and ecosystems has become increasingly prominent with socioeconomic development (Staddon and Faghihinia 2021). As a vital component of global ecosystems, grasslands worldwide face significant challenges from declining productivity and ecological degradation caused by overgrazing (Han et al., 2023). How to achieve sustainable

Shu Jin, Tel: +86-18249038288, E-mail: jinshu0304@163.com
Correspondence, Xiaoyu Zhu, Tel: +86-18502697164, E-mail: zhuxiaoyu@caas.cn

utilization of grasslands and maximize their value has become a major concern for human society (Evans et al., 2023). As an essential part of the global terrestrial ecosystem (Teague, et al., 2011), grasslands not only provide abundant ecological services including carbon sequestration, water and soil conservation, and biodiversity maintenance, but also play key roles in livestock production (Chu et al., 2022). Scholars both domestically and internationally have adopted the concept of "grassland ecological quality" to evaluate the functionality and structure of grassland ecosystems, focusing on their stability and resistance to disturbance since the 1990s (Zhang et al., 2017). Taking into account vegetation growth conditions, soil physicochemical properties, and the overall structure of grassland ecosystems, researchers have explored grassland ecological quality from both single and multi-dimensional perspectives (Shen et al., 2022; Zhang, 2023). Numerous studies have investigated the impact of grazing on grassland ecological quality. Zhou et al. (2018) found that moderate grazing promoted the recovery of grassland biomass and soil physicochemical properties following enclosure through a comprehensive assessment comparing vegetation indicators and soil properties. Zhan et al. (2020) conducted a cross-regional meta-analysis of grasslands in China and found that light grazing improved soil quality and increases belowground biomass, moderate grazing (MG) significantly increased belowground biomass, while heavy grazing significantly reduced soil microbial activity, soil organic carbon, and total nitrogen, resulting in soil nutrient loss. Despite the extensive research on the effects of grazing on grassland ecosystems (Xu et al., 2023), the effects through which different grazing intensities influence grassland ecological quality are still not fully understood. Few studies have addressed the changes in grassland ecological quality under varying grazing intensities, and meta-analyses on grazing-induced changes in soil communities have often lacked standardized bioinformatics processing methods (Qin et al., 2021).

Grazing is the primary utilization method of grassland resources, directly affecting the nutrient status of vegetation and soil through livestock foraging and trampling (Zhou et al., 2024). It influences aboveground biomass, belowground biomass, as well as the composition and structure of soil structure and plant communities, thereby impacting the overall ecological quality of grassland systems (Milchunas and Lauenroth, 1993). Grassland species diversites are frequently disturbed by grazing, which significantly alters their structure. Based on these observations, American ecologist J.H. Connell and others proposed the Intermediate Disturbance Hypothesis in 1978 (Connell, 1978). Only at intermediate disturbance frequencies do the greatest number of species have opportunities to survive, leading to the highest community diversity. Moderate grazing is beneficial for maintaining higher biodiversity, microbial activity, and aboveground productivity. However, most grassland ecosystems lack scientific management and suffer from severe degradation due to overgrazing (Gao et al., 2022). Overgrazing not only reduces vegetation cover and aboveground biomass but also alters the physical structure of grassland soil, decreasing soil permeability and reducing soil carbon storage (Nüsse et al., 2017). This leads to the loss of effective soil nutrients, a decrease in belowground biomass, and a reduction in plant species diversity (Wu et al., 2023; Yang et al., 2023).

This study employs a meta-analysis approach to systematically integrate research data on vegetation, soil, and species diversity to clarify the impact of different grazing intensities on the ecological quality of grasslands. This study put forward three hypotheses: (1) Changes in grazing intensity will affect the sensitivity of vegetation indicators; (2) Soil indicators conform to the appropriate disturbance hypothesis; (3) There is no linear relationship between grazing intensity

and species diversity.

2 Materials and methods

2.1 Literature retrieval and screening

This study systematically searched the Web of Science (WoS) and China National Knowledge Infrastructure (CNKI) databases using keywords including “grazing” “grassland ecological quality” “species diversity” and “biomass” to identify relevant literature. The literature screening criteria included:

(1) Studies were based on controlled field grazing experiments;

(2) Studies reported grazing intensity and was categorized as light grazing (LG), moderate grazing (MG), and heavy grazing (HG);

(3) The study provided crucial environmental information, including the geographical coordinates (latitude and longitude) of the experimental site, temperature, precipitation, elevation, and grassland type;

(4) The experimental duration was no less than one year;

(5) Literature provided mean values, standard deviations (or standard errors), and sample sizes for target variables in both grazing and control groups;

(6) The publication date of the literature fall between January 2000 and October 2024.

2.2 Data Processing

Data of each variable, including mean values and standard deviations (SD), were directly extracted from eligible literature or digitally obtained from figures using Data Graph Digitizer software. As shown in Figure 1, in the systematic literature screening process, after eliminating duplicate articles and those lacking complete statistical information from the initially retrieved 5890 articles, the final articles that met the inclusion criteria were selected. This process enabled the construction of a robust dataset comprising 585 independent experiments, covering 10 core variables: aboveground biomass (AGB, 118 datasets), vegetation coverage (COV, 102 datasets), soil organic carbon (SOC, 102 datasets), belowground biomass (BGB, 91 datasets), soil pH (33 datasets), soil total nitrogen (TN, 33 datasets), Simpson index (13 datasets), Margalef index (30 datasets), Shannon-Wiener index (33 datasets), and Pielou index (25 datasets).

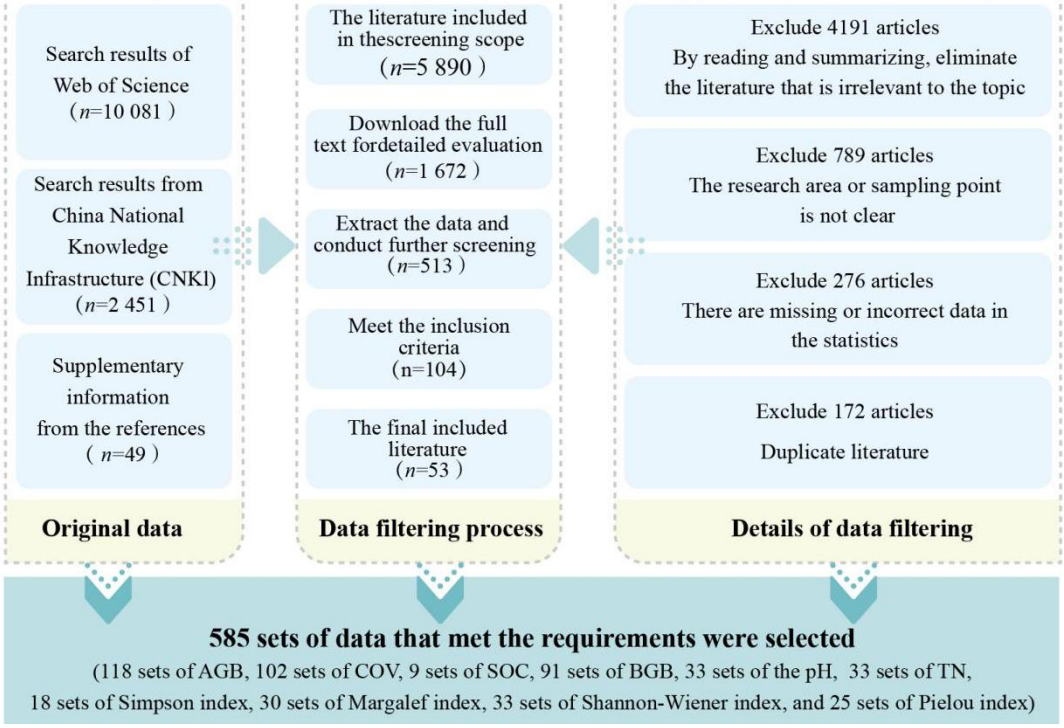


Figure 1. Process of literature search and screening. AGB: Aboveground biomass; COV: Coverage; BGB: Belowground biomass; SOC: Soil organic carbon.

2.3 Meta analysis

This study employed a systematic quantitative meta-analysis approach, using effect sizes to quantitatively synthesize experimental data from multiple studies addressing the same research question. The aim was to systematically analyze the overall effect of the target treatment and its influencing factors (Glass, 1976). A random-effects model was established to calculate the pooled effect size using the meta-analysis software MetaWin 2.1. The response ratio (ln$R$) was used to quantify the magnitude of differences in selected variables between grazing and no-grazing conditions, with the formula as follows:

$$\ln R = \ln\left(\frac{X_e}{X_c}\right) = \ln(X_e) - \ln(X_c) \quad (1)$$

In the formula, X_e represents the mean value of the grazing group, X_c represents the mean value of the no-grazing (control) group.

The variance (ln$R$)of the response ratio (($v_{\ln R}$) was calculated using the following formula:

$$v_{\ln R} = \frac{SD_e^2}{(N_e, X_e^2)} + \frac{SD_c^2}{(N_c, X_c^2)} \quad (2)$$

In the formula, $N_e$and N_c represent the sample sizes of the grazing group and the control group respectively, SD_e^2 and SD_c^2 represent the standard deviations of the target variable in the grazing group and the control group respectively.

The calculation formula for the non-parametric weight factor (w_i) is as follows:

$$w_i = \frac{1}{v_i + \sigma^2} \quad (3)$$

In the formula, v_i is the variance representing a single study, σ^2 is indicates the variance of the combined data, calculate the combined effect value through the weighting factor.

The combined effect size ($\overline{E}$) is calculated through weight factors:

$$\overline{E} = \frac{\sum_{i=1}^{n} w_i E_i}{\sum_{i=1}^{n} w_i} \quad (4)$$

In the formula, E_i represents response ratio of a single study.

To facilitate interpretation, the effect size was converted into a corresponding percentage change using the following formula:

$$\text{Effect size (\%)} = [\exp(\ln R)\text{-}1] \times 100\% \quad (5)$$

2.4 Group heterogeneity analysis

If the influence of a certain explanatory variable on grassland ecological quality is significant, its 95% confidence interval should not include 0. Considering grazing intensity, grassland type, and climatic factors (such as annual average temperature, annual average precipitation, and altitude), this study divides the data into multiple subgroups and the specific grouping criteria are shown in Table 1. To evaluate the heterogeneity of the model, this study used the Q_m statistic. When the P value is less than 0.05, it indicates that the Q_m statistic has reached statistical significance, thereby suggesting that the explanatory variable has a significant contribution to the heterogeneity of the effect size.

Table 1 The classification criteria of explanatory variables used in subgroup analysis

Variable	Unit	Classification		
Grazing intensity		Light grazing	Moderate grazing	Heavy grazing
Temperature	℃	1~3	3.1~5	≥5.1
Precipitation	mm	＜300	300~500	＞500
Elevation	m	＜1500	1500~2500	＞2500
Grassland type		Typical steppe	Desert steppe	High-cold steppe

Note: The classification is based on the national meteorological data standards.

Table 2 Group heterogeneity test results

Response variable	Factor	Degree of Freedom(df)	Q_m	P value	I^2%	R^2
AGB	Temperature	2	2.92	0.23	31.5	1.46
	Precipitation	2	8.04	0.018	75.1	4.02
	Elevation	2	1.12	0.56	0	0.56
	Grassland type	2	3.9	0.81	48.7	1.95
COV	Temperature	2	3.66	0.83	45.6	1.68
	Precipitation	2	3.9	0.14	48.7	1.95
	Elevation	2	0.9	0.34	0	0.45

SOC	Grassland type	2	6.32	0.04	68.4	3.16
	Temperature	2	0.47	0.78	0	0.235
	Precipitation	2	5.05	0.07	60.4	2.525
	Elevation	2	8.76	0.01	77.2	4.38
BGB	Grassland type	2	16.28	0.002	87.7	8.14
	Temperature	2	1.29	0.52	0	0.645
	Precipitation	2	26.71	0.01	92.5	13.355
	Elevation	2	3.1	0.21	35.5	1.55
pH	Grassland type	2	2.29	0.31	12.7	1.14
	Temperature	2	1.16	0.51	0	0.58
	Precipitation	2	4.5	0.22	55.6	2.25
	Elevation	2	2.8	0.1	28.57	1.4
TN	Grassland type	2	1.3	0.59	0	0.65
	Temperature	2	4.2	0.51	52.4	2.1
	Precipitation	2	0.6	0.98	0	0.3
	Elevation	2	5.8	0.04	65.52	2.9
	Grassland type	2	4.2	0.5	52.4	2.1

Note: Q_m is the statistic for inter-group heterogeneity; I^2 represents the proportion of heterogeneity; R^2 is the proportion of variance explained by the moderating variable.

2.5 Publication bias assessment

Meta-analysis was conducted using Rsoftware with the Metafor package. Funnel plots were generated, and publication bias was assessed through Egger's test and visual inspection of funnel plot asymmetry. In addition, the fail-safe number method was used in conjunction with funnel plot asymmetry tests to examine the potential influence of publication bias on the robustness of the findings. As shown in Table 3, the fail-safe numbers for all variables exceeded the critical threshold of 5K + 10 (If the fail-safe numbers is greater than 5K + 10, where k represents the number of subjects included in the study, it is generally considered that the results are relatively stable.) (Li et al., 2019). This indicated that a substantial number of unpublished non-significant results would be required to overturn the current conclusions, suggesting that publication bias was negligible and the results were robust.

Table 3 Fail safe numbers for various indicators of grassland ecological quality

Variables	K	5K+10	Fail-safe	Egger's test
AGB	118	600	327197	0.3812
COV	102	520	106983	0.9008
SOC	102	520	33372	0.8628
BGB	91	465	16603	0.2481
pH	33	175	489	0.3889
TN	33	175	545	0.4320
Simpson index	13	75	123	0.0041
Margalef index	30	160	1819	0.0209
Shannon-Wiener index	33	175	593	0.4540
Pielou index	25	135	426	0.3660

The funnel plots (Figure 2) exhibited an approximately symmetric distribution of standard errors (SE). Furthermore, Egger's regression test results were non-significant ($P > 0.05$), providing additional evidence that no substantial publication bias was present and supporting the reliability of the meta-analysis findings. Nevertheless, given the inherent heterogeneity among the original studies, such as differences in environmental contexts, management practices, and experimental methods, the interpretation of the results remains appropriately cautious.

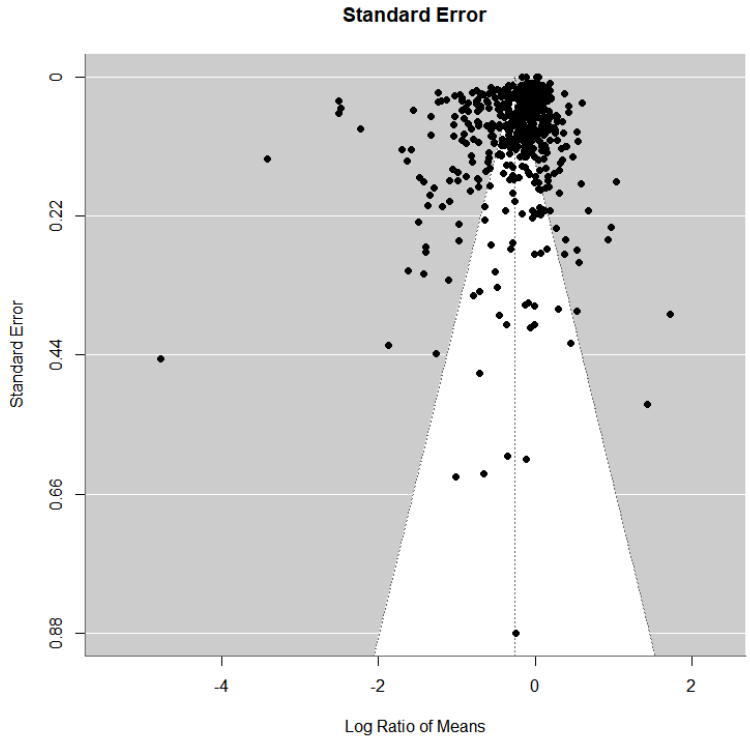


Figure 2. Publication bias assessment of grazing effects on grassland ecological quality.

3 Results

3.1 Subgroup analysis of grazing effects across environmental gradients

The influence of AGB on grassland ecological quality (Figure 3a), under different rainfall conditions, was tested for heterogeneity and reached a significant level ($P < 0.05$). Subgroup analysis further revealed that when the rainfall was less than 300mm, AGB had a negative effect, reducing by 24%. In terms of COV (Figure 3b), the heterogeneity test for different grassland types reached a significant level ($P < 0.05$).

The heterogeneity test also showed that the influence of SOC (Figure 3c) on grassland ecological quality reached a significant level in different grassland types ($P < 0.01$), and also showed a significant effect at different elevations ($P < 0.01$). Subgroup analysis indicated that at altitudes less than 1500 m and between 1500 m and 2500 m, it had a negative effect, each reducing by 31%, while at elevations above 2500 m, it had a positive effect, increasing by 39%. When the grassland types were typical grassland, desert grassland, and alpine meadow, it decreased by 2%, 3%, and 3% respectively.

Through the heterogeneity test analysis of BGB (Figure 3d), none of the classifications

reached a significant level. Subgroup analysis indicated that when the grassland type was typical grassland, BGB had a negative effect, reducing by 29%, while when the grassland type was desert grassland and alpine meadow, it decreased by 24% in both cases.

For the influence of pH (Figure 3e) on grassland ecological quality, the heterogeneity test results did not reach a statistically significant level. Subgroup analysis indicated that overall it had a positive effect. When the rainfall was less than 300 mm, it reduced by 35%; when the temperature was between 3.1℃ and 5.0℃, it reduced by 36%.

For the influence of TN on grassland ecological quality (Figure 3f), the heterogeneity test results did not reach a statistically significant level. Subgroup analysis indicated that overall it had a negative effect. When the rainfall was less than 300 mm, it increased by 35%; when the rainfall was between 300 and 500 mm, it increased by 33%; when the temperature was between 1℃ and 3℃, it increased by 33%; when the temperature was between 3.1℃ and 5.0℃, it decreased by 36%.

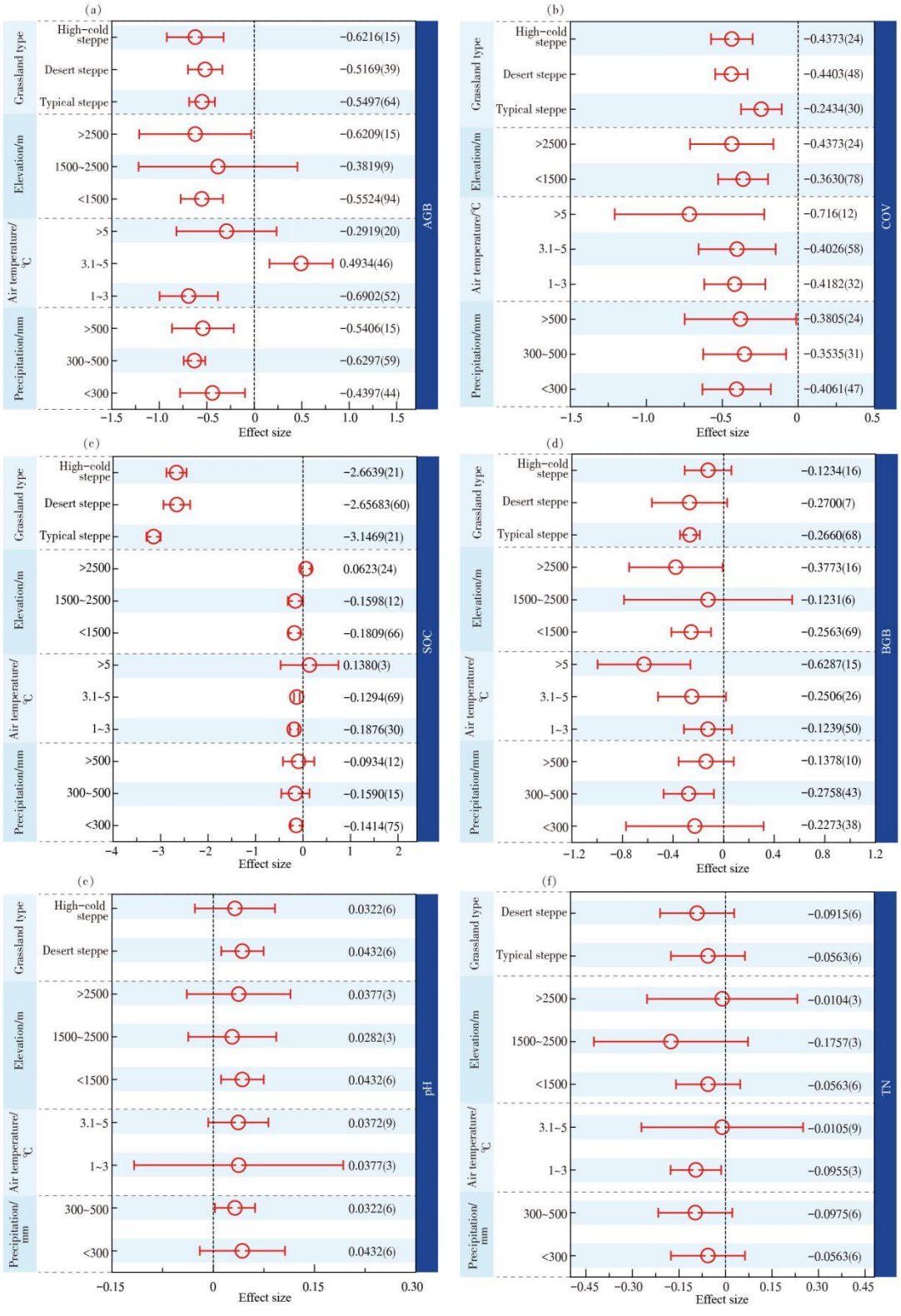


Figure 3. Subgroup analysis of different influencing factors.

3.2 Differential effects of grazing on grassland ecological quality

The differential effects of grazing on key indicators of grassland ecological quality are shown in Figure 4. Regarding vegetation-related indicators, grazing had the most significant impact on

AGB ($P < 0.001$), followed by COV ($P < 0.01$). Among soil indicators, grazing showed varying degrees of significant effects on BGB ($P < 0.01$) and TN ($P < 0.05$), while its influence on SOC ($P < 0.01$) and pH ($P < 0.05$) was relatively weak. No significant overall effect of grazing was observed on species diversity metrics.

Overall, the negative effects of grazing dominated across the grassland ecosystem. Seven of the ten evaluated indicators exhibited negative responses, with AGB showing the most pronounced negative effect (effect size: -0.512), indicated a significant suppression of vegetation. In addition, the increase in soil pH co-occurred with decreases in SOC and TN, reflected grazing-induced disturbances in soil nutrient cycling. Regarding species diversity, the overall impact of grazing was relatively weak. The Shannon-Wiener, Margalef, and Simpson indices all exhibited slight negative trends, whereas the Pielou index showed a marginal positive effect (0.019), which may suggest that moderate grazing could enhance species evenness by reducing competitive pressure among certain species.

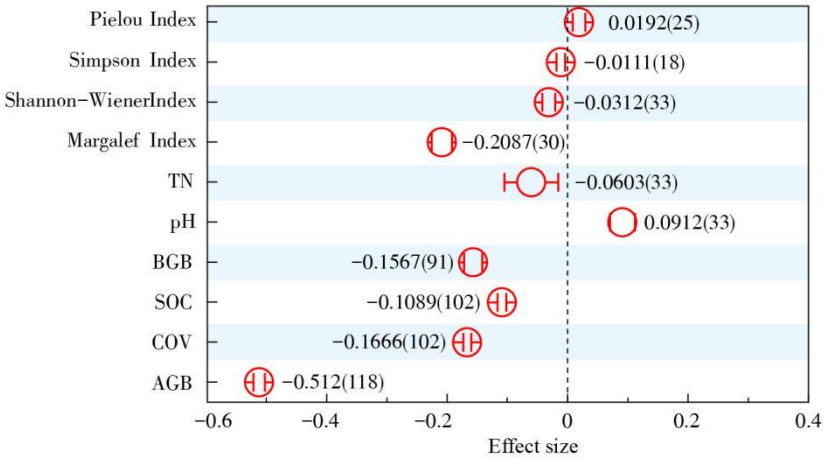


Figure 4. The impact of grazing on grassland ecological quality.

3.3 Gradient effects of grazing intensity on vegetation and soil indicators

The relationship between different grazing intensities and vegetation, as well as soil. (Figure 5 and Figure 6). Compared to no-grazing conditions, AGB significantly decreased by 39.01% ($P < 0.01$), 67.78% *(*$P < 0.001$), and 93.18% ($P < 0.001$) under light, moderate, and heavy grazing,. Similarly (Figure 5a), COV demonstrated a sharp decreasing trend, with reductions of 16.32% ($P < 0.05$), 48.02% ($P < 0.01$), and 83.12% ($P < 0.001$) under the three grazing intensities(Figure 5b) .

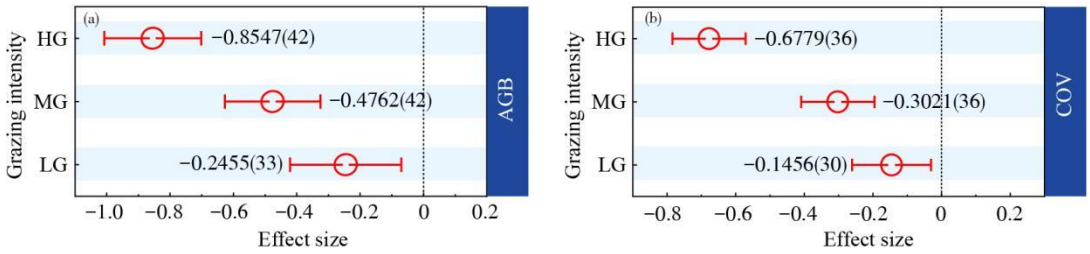


Figure 5. The effects of different grazing intensities on AGB (a) and COV (b). LG: light grazing; MG: moderate grazing; HG: heavy grazing. The same below.

Soil indicators also exhibited significant responses to grazing intensity. The response of SOC was complex, which decreased by 6.42% and 7.01% ($P < 0.05$) under light and moderate grazing (Figure 6a), respectively, while showing a sharp decline of 73.52% ($P < 0.001$) under heavy grazing ($P < 0.05$). BGB exhibited a continuous decline with increasing grazing intensity, showing reductions of 37.71% ($P < 0.01$), 40.67% ($P < 0.01$), and 54.06% ($P < 0.001$) under light, moderate, and heavy grazing (Figure 6b). TN was significantly reduced by 16.3% ($P < 0.05$) under heavy grazing, indicating its sensitivity to high-intensity disturbance(Figure 6c) . In contrast, soil pH showed a positive correlation with grazing intensity, increasing significantly by 4.37% and 4.97% ($P < 0.05$) under moderate and heavy grazing, respectively, which reflected the alkalinizing effect associated with the accumulation of livestock excreta(Figure 6d).

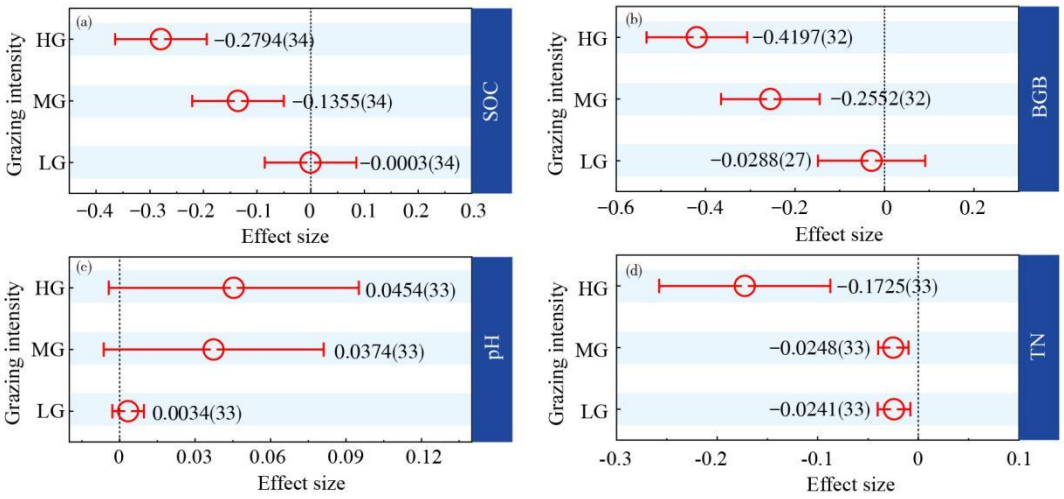


Figure 6. Effects of different grazing intensities on SOC (a), BGB (b), TN (c) and pH (d).

3.4 Effects of grazing intensity on species diversity indicators

In contrast to vegetation and soil indicators, the effects of different grazing intensities on species diversity indices did not reach statistical significance (Figure 7). Nevertheless, several meaningful trends were observed. The Margalef index showed a continuous declining trend with increasing grazing intensity, suggesting a potential suppression of species richness (Figure 7a). The Shannon-Wiener index and Simpson index exhibited minimal changes and weak responses across grazing intensities (Figure 7b and 7c) . The Pielou index fluctuated only slightly under different grazing intensities (Figure 7d). These findings indicated that species diversity

composition demonstrated a degree of resistance to grazing disturbance in the grassland ecosystems of this study and its response might lag behind changes in vegetation and soil indicators, or be modulated by other factors such as grassland type or successional stage which could obscure overall significant trends.

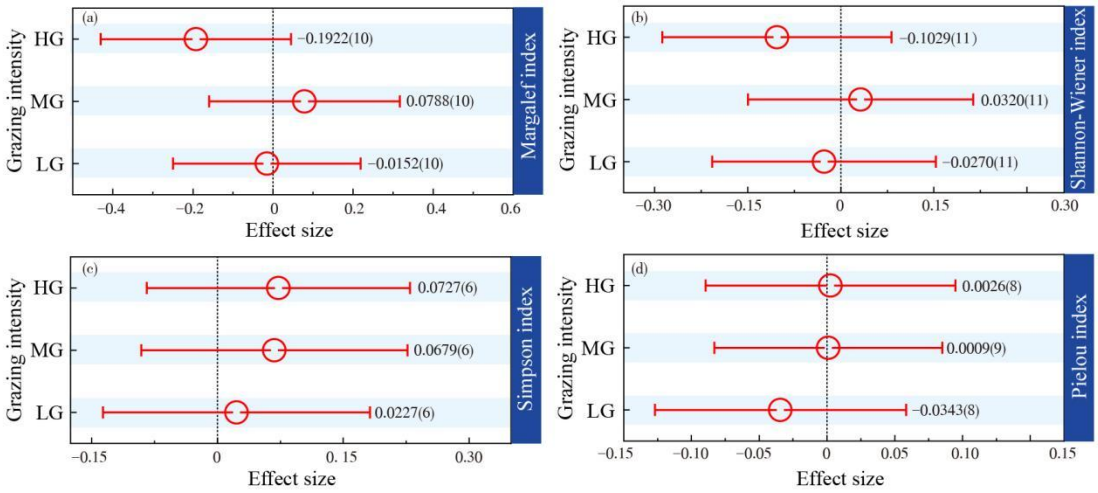


Figure 7. The effects of different grazing intensities on Simpson index (a), Margalef index (b), Shannon-Wiener index (c), and Pielou index (d).

4 Discussions

4.1 Impact of grazing on grassland ecological quality

Grazing acts as a primary grassland disturbance that indirectly influences vegetation, soil, and species diversity via foraging, trampling, and excretion, thereby regulating ecosystem structure and function. Overall, grazing exerts a negative effect on grassland ecological quality, most significantly inhibiting vegetation ; reductions inAGB, which is highly sensitive to livestock consumption, along with COV and BGB, directly reflect suppressed plant production due to damaged meristems and altered resource allocation. Soil indicators show differentiated responses: significant declines in SOC and TN suggest nutrient loss from reduced litter input and accelerated decomposition, while a slight pH increase likely results from urine-induced alkalinization, indicating soil buffer resistance. Notably, species diversity does not exhibit significant overall changes, likely because most regions experienced moderate grazing that did not exceed the ecosystem's threshold, maintaining community stability; these findings align with Aryal et al. (2018) and Zhang et al. (2021), identifying overgrazing as a major cause of grassland degradation (Shao, 1988). Grazing directly impacts vegetation function but affects soil primarily indirectly through changes in vegetation; SOC content, dependent on aboveground litter and root turnover (Johansen et al., 2019, decreases with increasing grazing intensity (Xiao et al., 2024), though moderate grazing can enhance it (Xiong et al., 2016).

Regarding diversity, the Margalef index initially rises then falls with grazing intensity, as light-moderate grazing reduces dominant species advantage and temporarily boosts diversity(Ford et al., 2013), while high intensity causes habitat disturbance and diversity decline (Cui et al., 2005). (Sandoval-Calderon et al., 2024; Hou et al., 2020); consistent with Chen et al. (2023), the

Shannon-Wiener and Simpson indices show higher sensitivity, supporting that moderate grazing is more conducive to maintaining population diversity and ecosystem stability(Fuhlendorf and Smeins, 1997).

4.2 Response of grassland ecological quality to different grazing intensities

In this study, AGB showed a decreasing trend with increasing grazing intensity. Under no-grazing conditions, vegetation exhibited significant recovery due to the absence of livestock trampling (Dong et al., 2022). As grazing intensity intensified, large-scale leaf loss occurred (Zhou et al., 2019), inhibiting plant photosynthesis and reducing compensatory growth of aboveground biomass. These changes led to widespread plant mortality and a significant decline in grassland AGB (Zhao et al., 2018). SOC, which is closely related to soil fertility (Chen et al., 2017), plays a critical role in the grassland carbon cycle. The study found that higher grazing intensities resulted in lower SOC content. This reduction is primarily attributed to grazing-induced changes in plant functional group distribution and soil microbial communities, which collectively diminish the input of organic carbon into the soil (Dong et al., 2021). Ma et al. (2017) suggested that as grassland degradation intensifies, the total community biomass declines markedly.

Increased grazing pressure not only reduces overall grassland community biomass but also leads to a decrease in individual plant biomass. In contrast, moderately grazed grasslands maintain highly stable ecological quality (Veen et al., 2014), with soil moisture conditions and physicochemical properties remaining optimal. Under such conditions, plants experience rapid growth and development, community species richness is high, and dominant species achieve greater density (Harris, 2010). In heavily grazed grassland communities, changes in AGB do not directly lead to redistribution or altered growth patterns of belowground root systems (Xiao et al., 2024). As a result, the effects of grazing on plant root systems exhibit a certain lag (Wen et al., 2016; Li et al., 2016), in their study on root distribution characteristics and their relationship with grassland degradation in Hulunbuir, found that different grassland plant species exhibit distinct vertical root distribution patterns. Furthermore, the sensitivity of belowground biomass to grazing intensity varies depending on these root architectural traits.

4.3 Relationship between grazing intensity and soil properties

A dynamic and complex interaction exists between grazing pressure, soil degradation, Moderate grazing can enhance nutrient cycling in grassland ecosystems, as livestock foraging behavior and excreta accelerate organic matter decomposition and nutrient redistribution, thereby helping to maintain soil fertility (Matinizadeh et al., 2024). However, when grazing pressure exceeds the ecological carrying capacity of the ecosystem, it triggers a series of chain reactions: livestock trampling disrupts soil physical structure, increasing bulk density and reducing porosity; decreased vegetation cover exposes topsoil to wind and water erosion (Premsuriya et al., 2024); and reduced input of organic matter further weakens soil aggregate stability. These changes significantly impact nutrient cycling processes. On one hand, soil erosion leads to the loss of key nutrients such as nitrogen and phosphorus through runoff. On the other hand, deterioration of the soil microenvironment inhibits microbial activity (Yang et al., 2022), reducing the efficiency of organic matter decomposition and nutrient mineralization. More critically, this degradation process can form a positive feedback loop: declining soil quality reduces vegetation productivity, and weakened vegetation recovery capacity increases grazing pressure on the remaining plants (Sunil et al., 2023), potentially leading to irreversible degradation of grassland ecosystem services. Therefore, implementing adaptive grazing management based on ecological carrying capacity

such as seasonal rotational grazing and stocking rate regulation coupled with artificial vegetation restoration and nutrient supplementation measures, is essential for maintaining soil health and balanced nutrient cycling in grasslands.

4.4 Effects of grazing intensity on species diversity

Grazing activities influence grassland species diversity across multiple scales by altering habitat heterogeneity, exhibiting typical nonlinear responses. Empirical results indicate that although comprehensive diversity indices did not show significant changes, subgroup analyses revealed that species richness (e.g., the Margalef index) tended to decline with increasing grazing intensity. This suggests that grazing, particularly at high intensities, may lead to local loss of rare or sensitive species (Sandoval-Calderon et al., 2024). However, due to the persistence of the advantageous species that can withstand grazing, species diversity is difficult to be maintained.. This pattern "compositional change without net diversity loss" highlights that relying solely on diversity indices may obscure underlying species turnover within communities (Chen et al., 2017). Finally, the response of biodiversity to grazing exhibits significant scale dependence. At the local scale, heavy grazing may reduce diversity through overconsumption and trampling. In contrast, at the regional scale, moderate grazing heterogeneity can maintain or even promote species diversity by creating varied microhabitats, such as grass-bare ground mosaics (Fuhlendorf and Smeins, 1997; Chen et al., 2023).

5 Conclusions

The continuous intensification of grazing has become the main anthropogenic factor leading to the degradation of grassland ecosystems and the weakening of soil carbon storage functions. Based on a comprehensive analysis of 585 sets of data from 53 studies, this research systematically evaluated the impact of different grazing intensities on the ecological quality of grasslands. The conclusions are as follows: (1) Grazing exerts an overall negative effect on grassland ecological quality, with seven of the ten evaluated indicators exhibiting negative responses. The most pronounced inhibition is observed on vegetation, as evidenced by the significant negative effect on aboveground biomass; (2) Grazing-induced disturbances in soil nutrient cycling are reflected by increased soil pH co-occurring with decreased soil organic carbon and total nitrogen. At moderate grazing intensity, soil and vegetation indicators reach their maximum values, verifying the moderate interference hypothesis; (3) While overall species diversity remained statistically unchanged, with the Margalef richness index declining and evenness increasing. This indicates that grazing alters community structure even without reducing species count, highlighting the need to monitor compositional changes to prevent adverse succession. Therefore, controlling the grazing intensity at a moderate level or below it is crucial for protecting soil carbon storage functions, and preventing adverse succession of species diversity structure.

CRediT authorship contribution statement: Jin Shu & Yutong Li: Conceptualization, Writing - original draft. **Yanzi Xiao & Xiaoyu Zhai**: Data curation, Validation. **Xiaoyu Zhu & Xiaoping Xin**: Supervision, Writing - review & editing. **Yi An & Ruirui Yan**: Writing – editing.

Declaration of competing interest: The authors declare that they have no conflict of interest.

Data Availability Statement: The data presented in this study are available on request from the

corresponding author.

Acknowledgments: This research was supported by the National Natural Science Foundation of China (32130070, 32101446); the National Key Research and Development Program of China (2021YFD1300500); the Special Funding for the Modern Agricultural Technology System from the Chinese Ministry of Agriculture (CARS-34); and the open project of State Key Laboratory of Efficient Utilization of Arable Land in China (EUAL-2025-12). We thank the anonymous reviewers for their valuable comments and suggestions on our manuscript.

References

Aryal, D. R., Morales Ruiz, D. E., Tondopó Marroquín, C. N., Pinto Ruiz, R., Guevara Hernández, F., Venegas Venegas, J. A., Ponce Mendoza, A., Villanueva López, G., Casanova Lugo, F., Rodríguez Larramendi, L. A., Ley de Coss, A., Hernández López, A., Medina Jonapá, F. J., Velázquez Sanabria, C. A., Alcudia Aguilar, A., & Euán Chi, I., (2018). Soil organic carbon depletion from forests to grasslands conversion in mexico: a review. *Agriculture (Basel)*, 8(11), 181. https://doi.org/10.3390/agriculture8110181

Chen, C., Jing, C., Zhao, W., & Xu, Y., (2022). Grassland quality response to climate change in Xinjiang and predicted future trends. *Acta Prataculturae Sinica*, 31(12), 1-16. https://kns.cnki.net/kcms/detail/62.1105.S.20220929.1204.027.html

Chen, C., Zhang, L., Zhao, W., Ye, H., Xie, H., & Lai, W., (2023). The response of degraded grasslands to different types of restoration measures in western China: A Meta-analysis. *Pratacultural Science*, 40(12), 3048-3061. https://next.cnki.net/middle/abstract

Chen, T., Christensen, M., Nan, Z., & Hou, F., (2017). The effects of different intensities of long-term grazing on the direction and strength of plant-soil feedback in a semiarid grassland of Northwest China. *Plant Soil*, 413(1/2), 303-317. https://doi.org/10.1007/s11104-016-3103-y

Chu, L., Hou, M., & Jiang, Z., (2022). How does the fragmentation of pasture affect grassland ecology?——Evidence from typical pastoral areas in China. *Ecological indicators*, 136, 108701. https://doi.org/10.1016/j.ecolind.2022.108701

Connell, J. H., (1978). Diversity in Tropical Rain Forests and Coral Reefs. *Science*, 199(4335), 1302-1310. http://www.jstor.org/stable/1745369

Cui, X., Wang, Y., Niu, H., Wu, J., Wang, S., Schnug, E., Rogasik, J., Fleckenstein, J., & Tang, Y., (2005). Effect of long-term grazing on soil organic carbon content in semiarid steppes in Inner Mongolia. *Ecological research*, 20(5), 519-527. https://doi.org/10.1007/s11284-005-0063-8

Dong, L., Li, J., Chen, S., Zhang, R., Sun, J., & Ma, M., (2021). Changes in soil organic carbon content and their causes during the degradation of alpine meadows in Zoigê *Wetland Chinese Journal of Plant Ecology*, 45(05), 507-515. https://link.cnki.net/urlid/11.3397.Q.20210401.1237.006

Dong, L., Wang, J., Li, J., Wu, Y., Zheng, Y., Zhang, J., Li, Z., Yin, R., & Liang, C., (2022). 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. https://doi.org/10.1016/j.gecco.2022.e02344

Evans, A. W., Woodward, B. D., Wyckoff, A. C., Toledo, D., Duke, S., Fischer, C., Núñez, C., & Sierra-Corona, R., (2023). Livestock grazing is an effective conservation tool for Californian coastal

grassland ecology: An eight-year study on vegetation dynamics. *Applied Vegetation science*, 26(3). https://doi.org/10.1111/avsc.12736

Ford, H., Rousk, J., Garbutt, A., Jones, L., & Jones, D. L., (2013). Grazing effects on microbial community composition, growth and nutrient cycling in salt marsh and sand dune grasslands. *Biol Fertil Soils*, 49(1), 89-98. https://doi.org/10.1007/s00374-012-0721-2

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. https://doi.org/10.2307/3237026

Gao, C., Qi, Z., Zheng, H., Chen, X., Qin, J., Hao, J., Zhang, N., Wang, C., & Dong, K., (2022). Response of soil available nutrients and microbial characteristics to Short-Term grazing intensities. *Acta Agrestia Sinica*, 30(07), 1641-1650. https://kns.cnki.net/kcms/detail/11.3362.s.20220323.2004.004.html

Glass, G. V., (1976). Primary, secondary, and meta-analysis of research. *Educational researcher*, 5(10), 3-8. https://doi.org/10.3102/0013189X005010003

Guo, J., Zhao, G., Jia, S., Dong, J., Chen, L., & Wang, S., (2020). Comprehensive evaluation of effects of fertilization on grassland quality index and soil properties in alpine steppe. *Acta Prataculturae Sinica*, 29(09), 85-93. https://doi.org/10.11686cyxb2019513

Harris, R. B., (2010). Rangeland degradation on the Qinghai-Tibetan plateau: A review of the evidence of its magnitude and causes. *Journal of arid environments*, 74(1), 1-12. https://doi.org/10.1016/j.jaridenv.2009.06.014

Hou, D., Guo, K., & Liu, C., (2020). Asymmetric effects of grazing intensity on macroelements and microelements in grassland soil and plants in Inner Mongolia Grazing alters nutrient dynamics of grasslands. *Ecol Evol*, 10(16), 8916-8926. https://doi.org/10.1002/ece3.6591

Ji, B., He, J., Wu, X., Wang, Z., Xie, Y., & Jiang, Q., (2021). Characteristics of soil organic carbon and active organic carbon in typical natural grassland in Ningxia. *Acta Prataculturae Sinica,* 30(01), 24-35. https://kns.cnki.net/kcms2/article/abstract.

Johansen, L., Taugourdeau, S., Hovstad, K. A., & Wehn, S., (2019). Ceased grazing management changes the ecosystem services of semi-natural grasslands. Ecosystems and people (Abingdon, England), 15(1), 192-203. https://doi.org/10.1080/26395916.2019.1644534

Li, J., Liu, L., Li, Z., Bao, Y., Sun, Z., Yang, B., Zhang, J., & Baoyin, T., (2016). The root distribution characteristics and its relationship with functional groups and steppe degradation in Hulunbuir Grassland. *Chinese Journal of Grassland*, 38(04), 55-62. https://doi.org/10.16742/j.zgcdxb.2016-04-09

Li, X., & Qu, Q., (2002). Soil microbial biomass carbon and nitrogen in Mongolian Grassland. *Acta Pedologica Sinica,* (01), 91-98.

Liu, R.-t., Zhao, H.-l., Zhao, X.-y., & Zhu, F., (2013). Effects of cultivation and grazing exclusion on the soil macro-faunal community of semiarid sandy grasslands in northern china. *Arid land research and management*, 27(4), 377-393. https://doi.org/10.1080/15324982.2013.787470

Ma, W., Wang, H., Li, G., Shi, W., Zhao, J., Luo, Y., Nie, Z., & Xue, J., (2017). Changes in plant biomass and its seasonal dynamics during degradation succession in the Gahai wetland. *Acta Ecologica Sinica*, 37(15), 5091-5101. https://kns.cnki.net/kcms/detail/11.2031.q.20170322.1921.060.html

Milchunas, D. G., & Lauenroth, W. K., (1993). Quantitative effects of grazing on vegetation and soils over a global range of environments. *Ecological monographs*, 63(4), 327-366. https://doi.org/10.2307/2937150

Matinizadeh, M., Nouri, E., Bayranvand, M., Kolarikova, Z., Janousková, M., (2024). Arbuscular mycorrhiza and rhizosphere soil enzymatic activities as modulated by grazing intensity and plant species identity in a semi-arid grassland. *Rhizosphere*, 30: 100893. https://doi.org/10.1016/j.rhisph.2024.100893

Nüsse, A., Linsler, D., Kaiser, M., Ebeling, D., Tonn, B., Isselstein, J., & Ludwig, B., (2017). Effect of grazing intensity and soil characteristics on soil organic carbon and nitrogen stocks in a temperate long-term grassland. *Archiv für Acker- und Pflanzenbau und Bodenkunde*, 63(12), 1776-1783. https://doi.org/10.1080/03650340.2017.1305107

Premsuriya, J., Leerach, N., Laosena, P., Hinthong, W., (2024). The effects of livestock grazing on physicochemical properties and bacterial communities of perlite-rich soil. *PeerJ*, 12: e18433. https://doi.org/10.7717/peerj.18433

Qin, Y., Xiaofang, Z., Adamowski, J. F., Biswas, A., Holden, N. M., & Hu, Z., (2021). Grassland grazing management altered soil properties and microbial β-diversity but not α-diversity on the Qinghai-Tibetan Plateau. *Applied soil ecology a section of Agriculture*, *ecosystems & environment*, 167, 104032. https://doi.org/10.1016/j.apsoil.2021.104032

Sandoval-Calderon, A. P., Rubio Echazarra, N., Kuijk, M., Verweij, P. A., Soons, M., & Hautier, Y., (2024). The effect of livestock grazing on plant diversity and productivity of mountainous grasslands in South America – A meta-analysis. *Ecol Evol*, 14(4), e11076-n/a. https://doi.org/10.1002/ece3.11076

Kumar, S., Dixit, AK., Prasad, M.,Rai, SK.,Mahanta, SK.,Singh, S.,Radotra, S.,Ghosh, PK., (2023). Effects of grazing intensity and pasture type on soil organic carbon stock in the semi-arid tropics of India. *Tropical grasslands-forrajes tropicales*, 11(1): 41-51. https://doi.org/10.17138/TGFT(11)41-51

Shao, L., Dong, G., & Lu, F., (1988). Developmental and adverse processes of steppe desertification and law of vegetation succession in Gonghe Basin. *Journal of Desert Research*, (1), 33-43. https://next.cnki.net/middle/abstract

Shen, T., Wang, Y., & Han, G., (2022). Response of Stipa breviflora desert steppe ecosystem stability to grazing. *Grassland and Turf*, 42(06), 88-94. https://doi.org/10.13817/j.cnki.cyycp.06.012

Staddon, P. L., & Faghihinia, M., (2021). Grazing intensity is key to global grassland carbon sequestration potential. *Sustainable Environment*, 7(1). https://doi.org/10.1080/27658511.2021.1895474

Teague, W. R., Dowhower, S. L., Baker, S. A., Haile, N., DeLaune, P. B., & Conover, D. M., (2011). Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. *Agriculture, ecosystems & environment*, 141(3), 310-322. https://doi.org/10.1016/j.agee.2011.03.009

Veen, G. F., de Vries, S., Bakker, E. S., van der Putten, W. H., & Olff, H., (2014). Grazing-induced changes in plant–soil feedback alter plant biomass allocation. *Oikos*, 123(7), 800-806. https://doi.org/10.1111/j.1600-0706.2013.01077.x

Wen, D., He, N., & Zhang, J., (2016). Dynamics of soil organic carbon and aggregate stability with grazing exclusion in the inner mongolian grasslands. *PLoS One*, 11(1), e0146757-e0146757. https://doi.org/10.1371/journal.pone.0146757

Wu, S., Hao, J., Diao, H., Ju, X., Ning, Y., Su, Y., Dong, K., & Wang, C., (2023). Response of grassland biomass to Short-term grazing intensities in the agro-pastoral ecotone in Northern Shanxi. *Acta Agrestia Sinica*, 31(8), 2446-2454. https://kns.cnki.net/kcms/detail/11.3362.S.20230712.1418.002.html

Xiao, L., Leng, M., Greenwood, P., Zhao, R., Xie, Z., You, Z., & Liu, J., (2024). Temporal and vertical dynamics of carbon accumulation potential under grazing-excluded grasslands in China: The role of soil bulk density. *J Environ Manage*, 351, 119696-119696. https://doi.org/10.1016/j.jenvman.2023.119696

Xiong, D., Shi, P., Zhang, X., & Zou, C. B., (2016). Effects of grazing exclusion on carbon sequestration and plant diversity in grasslands of China—A meta-analysis. *Ecological Engineering*, 94, 647-655. https://doi.org/10.1016/j.ecoleng.06.124

Xu, H., You, C., Tan, B., Xu, L., Liu, Y., Wang, M., Xu, Z., Sardans, J., & Peñuelas, J., (2023). Effects of livestock grazing on the relationships between soil microbial community and soil carbon in grassland ecosystems. *Sci Total Environ*, 881, 163416-163416. https://doi.org/10.1016/j.scitotenv.163416

Yang, L.-F., Kong, D.-Y., Diao, J.-W., & Guo, P., (2023). Meta-analysis on the effects of nitrogen addition on soil organic carbon content in terrestrial ecosystems. *Huanjing kexue*, 44(11), 6226-6234. https://doi.org/10.13227/j.hjkx.202211126

Yang, Y., Z. Yang, & J. Guo, (2022). Effects of Grazing Intensity on Features of Vegetation, Soil and Its Erosion in a Steppe Desert. *Shuitu baochi tongbao*, 42(4): 66-73

Zhan, T., Zhang, Z., Sun, J., Liu, M., Zhang, X., Peng, F., Tsunekawa, A., Zhou, H., Gou, X., & Fu, S., (2020). Meta-analysis demonstrating that moderate grazing can improve the soil quality across China's grassland ecosystems. *Applied soil ecology : a section of Agriculture, ecosystems & environment*, 147, 103438. https://doi.org/10.1016/j.apsoil.103438

Zhang, L., (2023). Study on construction and applicati on of evaluation index system of grassland ecological management efficiency .*Master, Inner Mongolia University Of Technology*. https://doi.org/10.27225/d.cnki.gnmgu.000002

Zhang, M., Zhai, Y., Zhang, Z., Tang, W., Ma, Y., Nie, X., & Ding, L., (2017). Quality and dynamic changes of grassland ecosystems in the Three-River Headwater Region. *Research of Environmental Sciences*, 30(01), 75-81. https://doi.org/10.13198/j.issn.1001-6929. 01.48

Zhang, Q., Liu, K., Shao, X., Li, H., He, Y., Sirimuji, & Wang, B., (2021). Microbes require a relatively long time to recover in natural succession restoration of degraded grassland ecosystems. *Ecological indicators*, 129, 107881. https://doi.org/10.1016/j.ecolind. 107881

Zhang, W., Guan, S., & Li, Y., (2000). Effect of graxing capacity on water content, nutrient and biomass of steppe soil. *Journal of Arid Land Resources and Environment,* (04), 62-65. https://doi.org/10.13448/j.cnki.jalre. 04.011

Zhao, L., Zhong, H., Zhao, M., & Zhang, J., (2018). Effect of enclosure and grazed management on aboveground biomass and species diversity in sandy grasslands of Horqin Sandy Land, Eastern Inner Mongolia, China. *Ecology and Environmental Sciences*, 27(10), 1783-1790. https://doi.org/10.16258/j.cnki.1674-5906.2018.10.001

Zhou, G., Luo, Q., Chen, Y., He, M., Zhou, L., Frank, D., He, Y., Fu, Y., Zhang, B., & Zhou, X., (2019). Effects of livestock grazing on grassland carbon storage and release override impacts associated with global climate change. *Glob Chang Biol*, 25(3), 1119-1132. https://doi.org/10.1111/gcb.14533

Zhou, T., Gao, J., Wang, J., Sun, J., Xu, B., Xue, J., He, J., Xie, Y., & Wu, Y., (2018). Effects of 7 一 year enclosure on an alpine meadow at the south—eastern margin of Tibetan Plateau based on community structure and soil physico—chemical properties. *Acta Prataculturae Sinica*, 27(12), 1-11. https://doi: <Go to ISI>://CABI:20193072043

Zhou, Y., Batelaan, O., Guan, H., Liu, T., Duan, L., Wang, Y., & Li, X., (2024). Assessing long-term trends in vegetation cover change in the Xilin River Basin: Potential for monitoring grassland degradation and restoration. *Journal of Environmental Management*, 349, 119579-119579. https://doi.org/10.1016/j.jenvman.119579.