Effects of Grazing on the Grassland Vegetation Community Characteristics in Inner Mongolia

Authors: Caiyun, Guo, Dongsheng, Zhao, Du, Zheng, and Yu, Zhu

Source: Journal of Resources and Ecology, 12(3) : 319-331

Published By: Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences

URL: https://doi.org/10.5814/j.issn.1674-764x.2021.03.002

J. Resour. Ecol. 2021 12(3): 319-331
DOI: 10.5814/j.issn.1674-764x.2021.03.002
www.jorae.cn

Effects of Grazing on the Grassland Vegetation Community Characteristics in Inner Mongolia

GUO Caiyun[1,2], ZHAO Dongsheng[1,*], ZHENG Du[1], ZHU Yu[1,2]

1. Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China;
2. University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: The continuous increase of livestock production in Inner Mongolia has caused severe degradation of the grassland ecosystems in recent years. Previous grazing experiments have shown a wide range of vegetation responses between the biome types on a global scale, but there is still a lack of sufficient studies to discern the relative responses of a given biome type. We conducted a meta-analysis of vegetation coverage (VC), plant density (PD), total biomass (TB), above-ground biomass (AGB), under-ground biomass (UGB) and Shannon–Weaver Index (SI) in different grassland types in Inner Mongolia obtained under conditions of different grazing intensities and durations. The results showed that grazing decreased VC, TB, AGB, UGB, and PD significantly. Compared to the global and national average values, the negative effects of grazing to steppe biomass in Inner Mongolia were higher than that on the global scale, while less pronounced than that in China. TB of the meadow steppe in Inner Mongolia increased by 40% under moderate grazing intensity and duration because of compensatory growth. SI of the desert and meadow steppe showed negative linear relationships with the grazing intensity in Inner Mongolia. The percentage changes in AGB, PD, and SI to grazing showed quadratic relationships with the mean annual temperature of the experimental year. With increasing mean annual precipitation, the negative effects of grazing on UGB and SI first decreased and then increased, with that of VC and grazing showing a cubic relationship.

Key words: grazing intensity; grazing duration; vegetation community characteristics; meta-analysis; Inner Mongolia

1 Introduction

Grassland is one of the most widely distributed vegetation types, covering approximately 40% of the global land surface (Simons and Weisser, 2017) and accounting for 20% of terrestrial production (Scurlock and Hall, 1998). Grassland provides numerous ecological services, including species diversity maintenance and soil erosion control, and acts as a carbon sink (Wang et al., 2016; Zhang et al., 2019). In addition, most of the global demands for milk and meat are provided by grassland ecosystem, which is a major objective of grassland husbandry (Boval and Dixon, 2012). Over-grazing damages the vegetation community characteristics of grassland ecosystems and accelerates grassland degradation (Gillson and Hoffman, 2007; Gan et al., 2012), which also threatens grassland ecological health (Fedrigo et al., 2017).

The effects of grazing on grasslands have been widely investigated (Milchunas et al., 2011), and diverse results have been obtained. Some studies reported that grazing induced increases in biomass, as proposed by the grazing optimization hypothesis (McNaughton, 1976; de Mazancourt et al., 1998; Patton et al., 2007). Other studies suggested that grazing may be adverse to the vegetation com-

---

Received: 2020-08-31 **Accepted:** 2021-02-24
Foundaiton: The National Key Research and Development Program of China (2017YFA0604803).
First author: GUO Caiyun, E-mail: guocy.17b@igsnrr.ac.cn
***Corresponding author:** ZHAO Dongsheng, E-mail: zhaods@igsnrr.ac.cn

Citation: GUO Caiyun, ZHAO Dongsheng, ZHENG Du, et al. 2021. Effects of Grazing on the Grassland Vegetation Community Characteristics in Inner Mongolia. *Journal of Resources and Ecology*, 12(3): 319–331.

munity characteristics in most grassland types (Hanke et al., 2014; Jemma et al., 2017). Wang et al. (2002) found that grazing decreased species diversity and increased the spatial heterogeneity of the communities. Dowling et al. (2005) showed that grazing has no apparent benefit to the grassland. The majority of the studies on the effects of grazing on grasslands were performed using controlled grazing experiments (James et al., 2001; McIntyre et al., 2019; Silva et al., 2019) because the grazing experiment was considered as the most effective approach for examining the effects of grazing up to now (Dong et al., 2007). However, various independent experiments on the grazing effects on grasslands have produced divergent results because of (i) different grass types (Yan et al., 2013), (ii) different climate conditions (Ren et al., 2012), and (iii) differences in the duration of grazing treatments (Su et al., 2017). These differences, combined with the complex response of grasslands to disturbances, raise challenges in quantifying the effects of grazing. Therefore, it is necessary to integrate the divergent experiments to provide asynchronous results for a given biome. The meta-analysis method can combine data from various independent studies mathematically, and has emerged as a standard approach for synthesizing research findings (Yang, 2015).

The grassland of Inner Mongolia is one of the major parts of the Eurasian steppes, comprising meadow, typical, and desert steppes distributed along a gradient of decreasing precipitation from northeast to southwest. Meanwhile, it is one of the grasslands with the most frequent human activities in the world since it has served as a key resource for supporting the subsistence of local people for thousands of years. The introduction and expansion of livestock production pose major challenges to the grasslands in this region. Currently, the area of degraded grassland is approximately 50% of the total land area of Inner Mongolia, of which 20% is seriously degraded. Numerous individual grazing experiments have been undertaken to ascertain the effects of grazing on grassland productivity and plant community diversity in Inner Mongolia (Silletti and Knapp, 2002; Focht and Pillar, 2003; Mike et al., 2012). Based on the data from these individual grazing experiments, several meta-analyses have examined the responses of grassland productivity and plant community diversity to grazing at the biome scale. For example, Ren et al. (2012) analyzed the effect of grazing intensity on species diversity of typical steppe in Inner Mongolia, and demonstrated that species diversity had a neutral response to grazing intensity. Su (2017) quantified the AGB response to grazing in Inner Mongolia grassland. Yan et al. (2013) revealed the response of grassland production to grazing in China based on a transect survey and published data. However, these studies only examined the effects of grazing on individual indexes, but neglected the comprehensive responses of the grassland ecosystem. Furthermore, the limited data on grazing experiments have also prevented the examination of the heterogeneity of the effect size. One example is the study of Yan, which used transect survey data to compensate for the insufficient grazing experiment data. Therefore, high uncertainties remain in the effects of grazing on vegetation community characteristics at the biome scale. A comprehensive analysis based on more extensive experimental data is needed to examine the effects of grazing on grassland vegetation community characteristics in a given biome type.

In this study, we compiled data from 433 observations in 61 studies to quantify the effect of grazing on the vegetation coverage (VC), plant density (PD), total biomass (TB), above-ground biomass (AGB), under-ground biomass (UGB), and Shannon-Weaver Index (SI) in different grassland types in Inner Mongolia for conditions of different grazing intensities and durations. Our objectives were to: 1) examine the patterns of the vegetation community characteristics of the grassland ecosystem in response to grazing; and 2) investigate the regulatory effects of environmental factors on productivity and species diversity in response to grazing.

2 Materials and methods

2.1 Data

We compiled peer-reviewed studies published before May 2018 using the resources of the Web of Science (WOS), Google Scholar, and China National Knowledge Infrastructure (CNKI). The extensive searches were conducted using combinations of the keywords: grazing intensity, grazing experiment, vegetation coverage, plant density, Shannon-Weaver Index, and Inner Mongolia. To find additional relevant studies, we consulted the reference lists of the papers found in the databases.

Figure 1 shows a flow diagram detailing the procedure for the selection of the studies used in the meta-analysis. We included only those studies meeting the following criteria in the meta-analysis: 1) The studies were carried out in the grassland ecosystem of Inner Mongolia, and data for at least one of the variables VC, PD, AGB, UGB, TB, and SI was reported; 2) The data for replicates, means, standard errors, standard deviations and the sample sizes of both control and grazing groups were available; and 3) Grazing intensity, grassland type, and grazing duration were provided in the study. A list of the data sources used in the study is provided as “Supplementary Data”①.

Since publication bias is inevitable in any meta-analysis, the standard method used to identify publication bias currently is a funnel plot (Mavridis and Salanti, 2014), which makes a corresponding scatter plot using the estimated effect value of a single study as the X-axis and the sample size of each study as the Y-axis. Because the accuracy of effect

---

① Please log in the journal’s website: www.jorae.cn, find this article and download the supplementary data attachment.

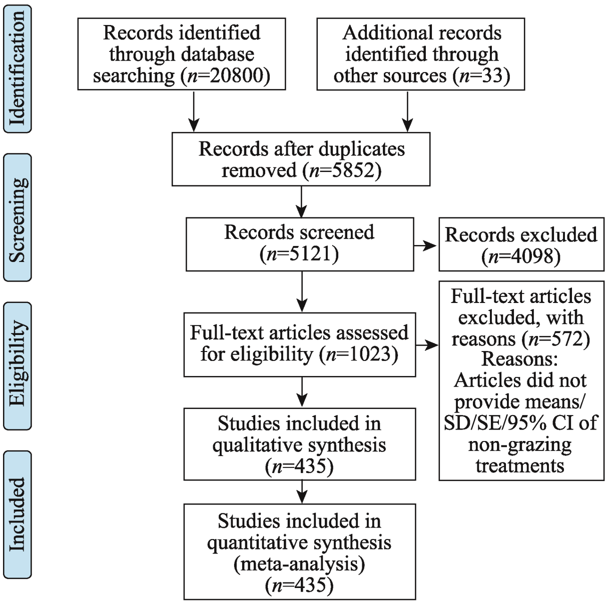

Fig. 1 The flow diagram for identifying the studies to include in the meta-analysis

estimation increases with an increase in the sample size, the effect values of small sample studies in a funnel plot would be distributed at the bottom of the graph, while the effect values of large sample studies in a funnel plot would be distributed in the middle or top of the graph.

We used GetData Graph Digitizer (http://getdata-graph-digitizer.com) to extract data from papers only providing standard deviations and sample numbers in graphical figures. Standard deviation (*SD*) was calculated as follows:

$$SD = SE\sqrt{n} \tag{1}$$

where *SE* is the standard error; and *n* is the sample number. Following the exclusion of duplicates in the various studies, 435 sets of vegetation community characteristic data and environmental data from 61 studies were included in our analysis.

2.2 Meta-analysis

Meta-analysis was conducted using METAWIN 2.1, STATA 12.0, and Origin 8.0 software. The natural log of the response ratio (ln *R*) represented the effect size (Hedges et al., 1999; Wang et al., 2011). The random-effect model was adopted for those cases. The effect-size ln *R* was calculated as follows (Cohen, 1988; Hayley and Jones, 2010).

$$\ln R = \ln\left(\bar{X}_t\right) - \ln\left(\bar{X}_c\right) \tag{2}$$

with a variance of:

$$v = \frac{S_t^2}{n_t \bar{X}_t^2} + \frac{S_c^2}{n_c \bar{X}_c^2} \tag{3}$$

where ln *R* is the effect size; $\bar{X}_t$ and $\bar{X}_c$ are the means of the treatment and control groups, respectively; n_t is the sample size of the treatment group; n_c is the sample size of the control group; S_t is the standard deviation of the treatment group; and S_c is the standard deviation of the control group.

We calculated the heterogeneity of effect size by subgroup analysis, and the between-group (Q_B) heterogeneity was calculated as follows:

$$Q_B = \sum_{i=1}^{m}\sum_{j=1}^{k_i} w_{ij}\left(\ln R_{i+} - \ln R_{+}\right)^2 \tag{4}$$

with degree of freedom $df = m-1$, *m* is the number of groups, k_i is the number of comparisons in the *i*th group, $w_{i,j}$ is the weighting factor of each group, ln R_{i+} is the individual weighted log effect size, ln R_+ is the weighted log effect size, If Q_B is larger than a critical value, then the independent variable has a significant influence on the response ratio (Hedges, 1984). Statistical significance was tested at the $P <$ 0.05 level.

Grazing effects were estimated as a *PC* (percentage change) relative to the control, and calculated using equation (5).

$$PC = \left(R_{+} - 1\right) \times 100\% \tag{5}$$

2.3 Classification of grazing indices

The study region extends from the Greater Hinggan Mountains in the east to the Juyan Sea in the west, covering semi-humid, semi-arid and arid regions with different climatic and soil hydro-meteorological conditions. With an average elevation of 1000–1200 m, the terrain shows a gradual downward trend from the southwest to the northeast. The average annual precipitation in the study area is about 100–400 mm, while the average annual temperature ranges from –5.0 to 7.0 ℃. By 2010, the grassland area of Inner Mongolia was about 86.67 million ha, accounting for 44.08% of the total grassland area in China, making it an important animal husbandry production base (Dai, 2016). Due to the variation in hydrothermal conditions and topography, the natural grassland vegetation in the study area consists of meadow steppes, typical steppes, and desert steppes.

In grazing experiments, grazing intensity refers to the number of grazing livestock per unit area of grassland, which directly affects the stability and sustainable development of the grassland ecosystem (GB/T 34754–2017). In this paper, we divided the grazing intensity into light grazing (0.15–0.93 sheep per ha per half year), moderate grazing (0.94–1.82 sheep per ha per half year) and heavy grazing (1.83–2.89 sheep per ha per half year). Grazing durations ranged widely from a half month up to several years, and the experiments with more years of grazing are inevitably affected by the cumulative grazing influence of previous years. To examine the effects of grazing on vegetation community characteristics not affected by the cumulative grazing years, we included an assessment of the grazing experiments with 1-year grazing duration or less, which were divided into short-term grazing (0–3 months), moderate-term grazing (3–6 months), and long-term grazing (6–12 months). The grassland types in the Inner Mongolian study sites were classified as meadow, typical, and desert steppes.

3 Results

3.1 Effects of grazing on grassland vegetation community characteristics

Figure 2 shows the percentage changes of VC, TB, AGB, UGB, PD, and SI in response to grazing in Inner Mongolia. AGB was affected by grazing with a reduction of 35.04% (95% CI: −47% to −27%), while VC was reduced by 27% (95% CI: −39% to −6%), TB was reduced by 45% (95% CI: −56% to −34%), UGB was reduced by 14% (95% CI: −23.5% to −4%), and PD was reduced by 15% (95% CI: −2.5% to −30%). Meanwhile, no significant effect was found on the SI. Between-group heterogeneity tests (Table 1) showed that the effect on VC was not significantly different among grazing intensities or grazing durations, but a significant difference was found among grassland types (Q_B = 25.3576, P = 0.009). The AGB showed significant differences among grazing intensities (Q_B = 68.0871, P = 0.001). The UGB exhibited significant differences among grassland types (Q_B = 18.8179, P = 0.005). The SI demonstrated significant differences among grazing durations (Q_B = 72.7619, P = 0.001).

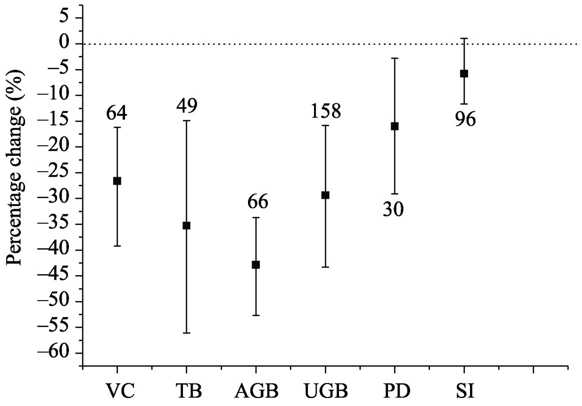

Fig. 2 Percentage changes of vegetation community characteristics in response to grazing in Inner Mongolia

Note: Vegetation coverage (VC), total biomass (TB), above-ground biomass (AGB), under-ground biomass (UGB), plant density (PD), and the SI were included in the meta-analysis. Error bars indicate 95% confidence intervals (CIs). A significant effect is indicated if the 95% CI does not overlap zero. The numbers above or below the error bars show the number of observations used in the analysis of each characteristic.

Figure 3 shows the percentage changes of the vegetation community characteristics in response to differing grazing intensity, grazing duration, and grassland type. The responses of vegetation communities in different types of grassland were obviously different under various grazing intensities and durations. Differences were evident in the percentage changes in VC, AGB, and UGB among the corresponding groups. The TB of grasslands decreased by 20% (95% CI: –50% to 10%), while SI increased by 27% (95% CI: 5% to 35%) with short grazing duration.

Table 1 Between-group heterogeneity (Q_B) and probability (P) for grazing effects on VC, PD, TB, AGB, UGB, and SI among different grazing intensities, grassland types, and grazing durations.

Subgroup	Category	Q_B	P
Grazing intensity	VC	5.6528	0.338
	PD	0.4744	0.896
	TB	2.9992	0.085
	AGB	68.0871	0.001
	UGB	4.6779	0.344
	SI	5.9352	0.413
Grassland type	VC	25.3576	0.009
	PD	5.8753	0.275
	TB	5.1752	0.022
	AGB	12.3124	0.061
	UGB	18.8179	0.005
	SI	2.4998	0.723
Grazing duration	VC	0.9955	0.834
	PD	5.2990	0.148
	TB	2.8244	0.106
	AGB	9.7965	0.085
	UGB	7.4774	0.085
	SI	72.7619	0.001

3.2 Effect of grazing on VC

Figure 4 shows the percentage changes of VC in response to different grazing intensities and grazing durations. The effect on VC varied among the desert, typical, and meadow steppes (Q_B = 25.3576, P = 0.009). Light grazing decreased VC by 40% (95% CI: –59% to –17%) in the desert steppes, while it had no significant effect on other types of grassland; VC decreased by 32% (95% CI: –61% to –11%) in the desert steppes under moderate grazing intensity, while the moderate grazing had no significant effect on the VC of other types of grassland. The VC of grassland in Inner Mongolia was significantly decreased when grazing was heavy, with the greatest reduction occurring in the desert steppe (a reduction of 40%; 95% CI: −58% to −18%), followed by the typical and meadow steppes. VC was more sensitive to grazing intensity in the desert steppe.

VC of the desert steppe was reduced by 50% (95% CI: –111% to 5%) after short-term grazing. However, the 95% CI crossed the invalidation line due to the limited data collected for this group. VC of desert steppe and meadow steppe decreased by 65% (95% CI: –130% to –5%) and 15% (95% CI: –30% to 2%), respectively, after the moderate-term grazing, while VC of typical grassland had no obvious effect from the moderate-term grazing. After long-term grazing, the VC of desert steppe decreased by 23% (95% CI: –48% to 35%), while the meadow steppe showed no significant change. VC of meadow steppe declined after short-term grazing, but that was reversed to an increase after long-term grazing.

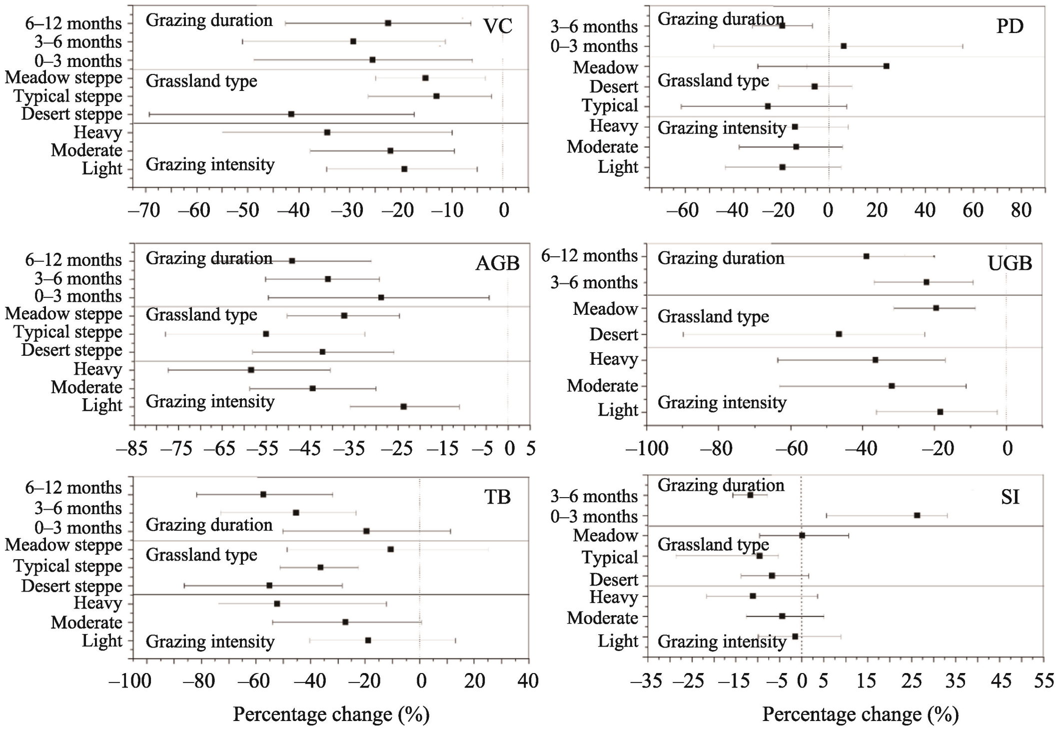

Fig. 3 Percentage changes of vegetation community characteristics due to differing grazing intensity, grazing duration, and grassland type.

Note: Values are means ± 95% CI.

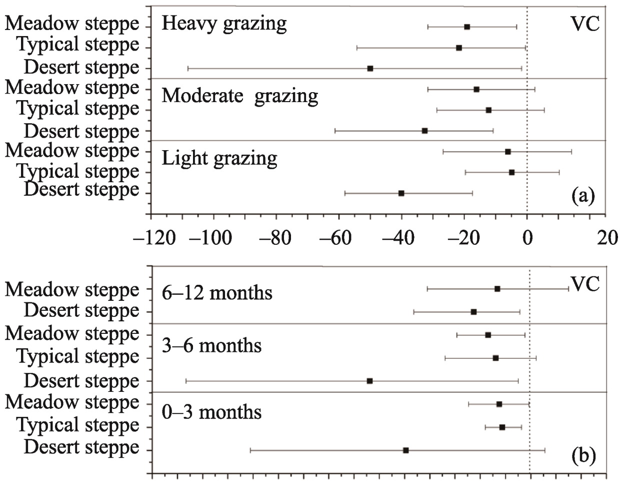

Fig. 4 Percentage changes of VC in response to different grazing intensities (a) and grazing durations (b)

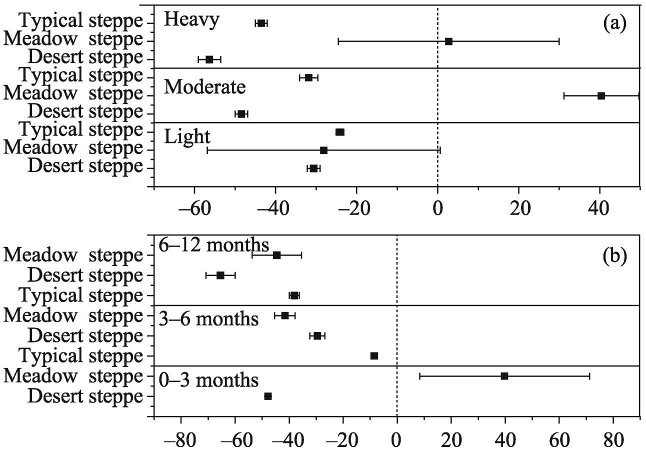

Fig. 5 Percentage changes of TB in response to different grazing intensities (a) and grazing durations (b)

3.3 Effect of grazing on TB

Figure 5 shows the percentage changes of TB in response to different grazing intensities and grazing durations. Light grazing reduced TB of the grasslands in Inner Mongolia gradually. TB of the desert and typical steppe decreased by 48% (95% CI: –50% to –49%) and 31% (95% CI: –35% to –32%), respectively, under moderate grazing intensities, while the TB of meadow steppe increased by 40% (95% CI: 25% to 50%). TB of the desert and typical steppe declined with the increase of grazing intensity, but TB of meadow steppe was not affected by the heavy grazing intensity. The biggest drop in TB was always in the desert steppe, followed by the typical and meadow steppe.

TB of desert steppe decreased by 44% (95% CI: –45% to –43%), while it increased by 40% (95% CI: 8% to 71%) after the moderate-term grazing in the meadow steppe. TB of the three types of grasslands decreased significantly after moderate-term grazing, and the ranking of the decreasing amplitude was: meadow steppe > desert steppe > typical steppe. With the increasing of the grazing duration, TB of the grasslands in Inner Mongolia further declined. Therefore, it can be seen that the desert steppe is more sensitive to the grazing duration.

3.4 Effect of grazing on AGB

Figure 6 shows the percentage changes of AGB in response to differing grazing durations and grassland types. AGB decreased with increasing grazing intensity (Q_B = 68.0871, P = 0.001). Heavy grazing caused a significant negative effect on AGB, with lesser effects being found for moderate and light grazing intensities. However, the decreases in AGB caused by light and moderate grazing intensities were similar to short-term grazing (approximately 20%). AGB for the desert steppe under light and moderate grazing intensities declined by 15% (95% CI: −33% to −4%) and 50% (95% CI: −80% to −24%), respectively.

3.5 Effect of grazing on SI

The SI is a diversity index that indicates the adaptation of species to the environment following competition. Figure 7 shows the percentage changes in the SI caused by differing grazing durations (a) and intensities (b). The SI was more profoundly affected by grazing intensity (Q_B = 5.9352, P = 0.413) than by the grazing duration (Q_B = 72.7619, P = 0.001). Compared with typical and meadow steppe, the SI for the desert steppe was more sensitive to grazing intensity, decreasing by 8% (95 CI: −17% to −1%), 11% (95 CI: −20% to −3%), and 19% (95 CI: −24% to −9%) under light, moderate, and heavy grazing, respectively. The SI for the meadow steppe was not affected by either light or heavy grazing, but showed a 10% (95 CI: −21% to −4%) reduction under moderate grazing.

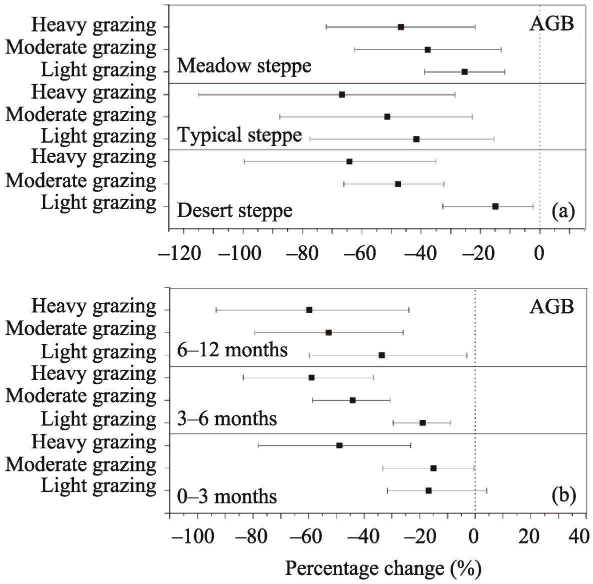

Fig. 6 Percentage changes of AGB in response to differing grazing durations (a) and grassland types (b)

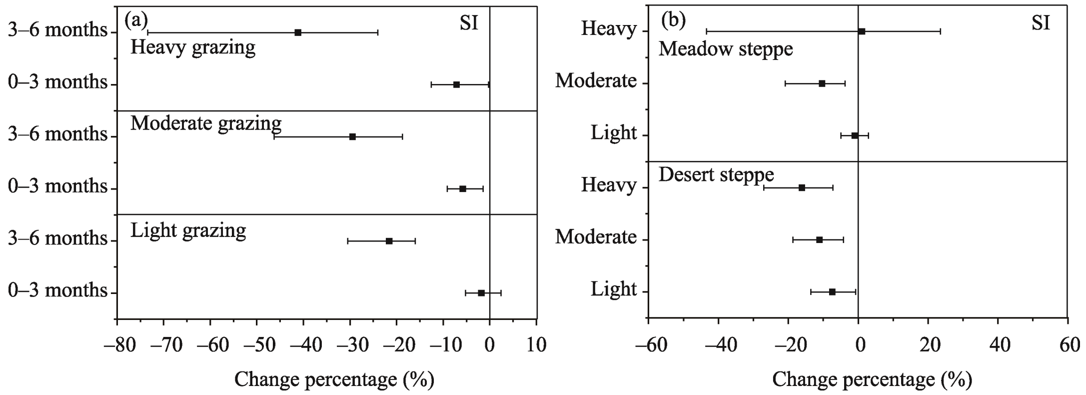

Fig. 7 Percentage changes in the SI caused by differing grazing durations (a) and grassland types (b)

After short-term grazing, the SI of Inner Mongolia did not show a significant change under the light grazing intensity, but it was reduced by 7% (95% CI: −10% to −3%) and 9% (95% CI: −15% to –1%) under the moderate and heavy grazing intensities, respectively. The SI of grassland decreased with the increasing of the grazing intensity after moderate-term grazing, as it declined by 21% (95% CI: −31% to −15%), 30% (95% CI: −47% to −19%), and 42% (95% CI: −73% to −25%) under light, moderate, and heavy grazing intensities, respectively.

4 Discussion

4.1 Effects of grazing on grassland productivity

Our study revealed that grazing can reduce the grassland productivity of Inner Mongolia. We compared the effects of grazing on productivity at global scales (Milchunas and Lauenroth, 1993) and national scales (Yan et al., 2013) to Inner Mongolia (Table 2). AGB was reduced by 43% in Inner Mongolia, approximately double the reduction on a global scale. Grazing resulted in UGB reduction in Inner Mongolia, but an incremental increase on the global scale.

TB was reduced by 38% in Inner Mongolia, while there is no obvious effect of grazing when examined on the global scale (Table 2). This difference can be attributed to the more palatable species to livestock which occur in Inner Mongolia, as this leads to heavy grazing as a common form of land-use. Furthermore, the rapid expansion of the grazing area largely reduced the soil nutrients and vegetation degradation (Bai et al., 2015; Du et al., 2020).

Table 2 Percentage changes in grazing effects globally, in China, and in Inner Mongolia

Spatial scale	Global (%)	China (%)	Inner Mongolia (%)
	Milchunas and Lauenroth, 1993	Yan et al., 2013	This study
TB	No significant effect	−58.34	−45.12
AGB	−23	−42.77	−35.04
UGB	20	−23.13	−13.85

Compared to results at the national scales, the decrement of the grassland biomass was only slight in Inner Mongolia. The effect of grazing on the grassland biomass is mainly regulated by the variations in the community composition in each grassland type. The meadow and typical steppe, which account for 79% of the total steppe area in Inner Mongolia (Dong et al., 2020), involved plentiful biodiversity including species with higher grazing tolerance, such as *Stipa baicalensis*, *Chinensis*, *Stipagrandis, Cleistogenes polyphylla, Carex piriformis,* and *Spodinpogon sibiricus,* et al. Moreover, owing to the broader study area in Yan et al (2013), the smaller number of experiments in the Inner Mongolian steppe was covered in the meta-analysis, which also largely contributed to the difference.

The grasslands in Inner Mongolia are distributed in arid and semi-arid areas, where the competition for water dominates the inter-species relationships. The precipitation in Inner Mongolia is lower than in other temperate steppes (Mónica et al., 1996; Ni, 2004; Su et al., 2017). The low and unevenly distributed precipitation during the summer can have negative effects on the AGB, even if the precipitation increases in the subsequent period (Fang et al., 2005). The grazing by livestock reduces the individual species and AGB in the low precipitation condition, increasing surface exposure. As a result, soil evaporation is enhanced, and then the plant species are inhibited from growing due to water stress. The AGB of meadow steppe with perennial hybrid grass is positively correlated with the growing season precipitation, while the AGB of the desert steppe is significantly negatively correlated with the amount of precipitation (Sala et al., 1988).

Figure 8 shows the relationships between observed factors and the mean annual temperature of the experimental year. The response ratios of UGB (Fig. 8c) and TB (Fig. 8b) showed linear relationships with the mean annual temperature of the experimental year. The ln R of UGB and TB decreased with the increasing temperature. However, no significant relationship was found between AGB (Fig. 8d), TB (Fig. 8b), and precipitation. Furthermore, grassland productivity is widely limited by various nutrients, such as N, P, K, and micronutrients (Jobbágy et al., 2002; Dangal et al., 2016).

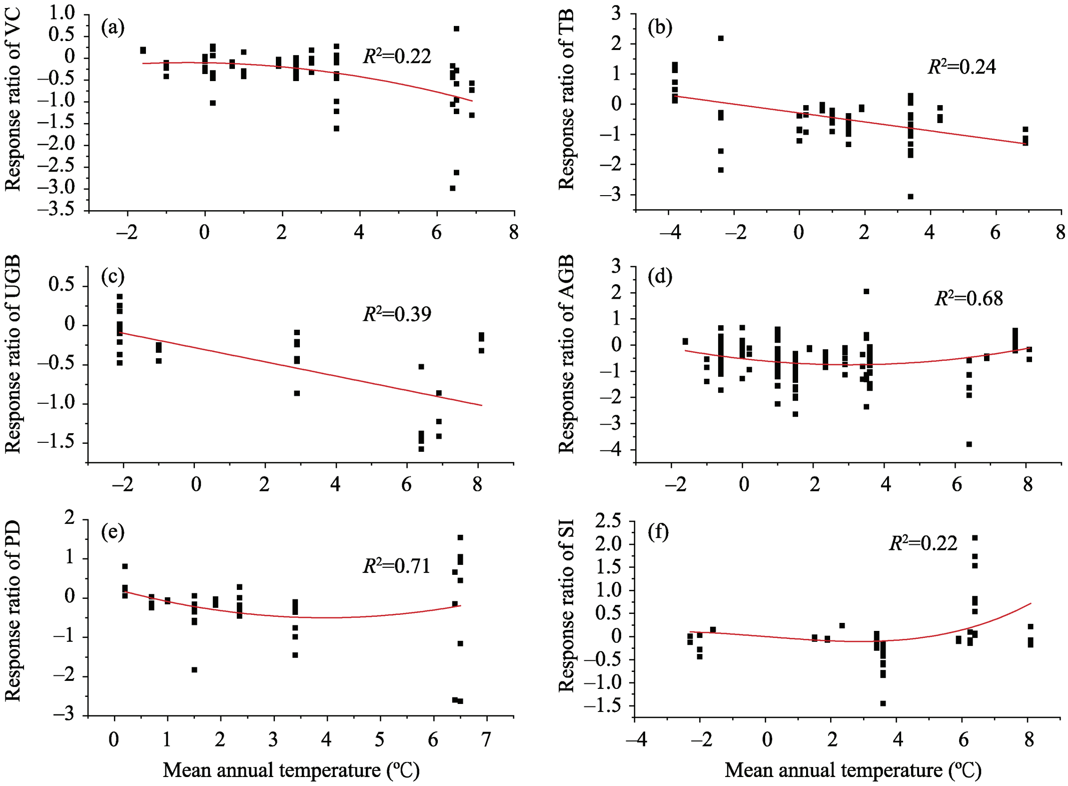

Fig. 8 Response ratios of VC (a), TB (b), UGB (c), AGB (d), PD (e), and SI (f) relative to mean annual temperature of experimental year.

It is worth noting that the TB of the meadow steppe increased by 40% under moderate grazing intensity and moderate-term grazing, because the vegetation biomass exhibited compensatory growth (Burke et al., 1997; Ferraro and Martín, 2002; Bai et al., 2012; Fay et al., 2015). Previous studies have reported that compensatory growth occurs only under a suitable grazing intensity (Xue et al., 2010) or in the croplands where strong cultivation management measures are applied (Münkemüller and Johst, 2006). Furthermore, the seasonal distribution of temperature determines the beginning and length of the vegetation growing season. Increased precipitation and temperature may exert positive effects on the biomass production of meadow steppes (Xiao, 1996).

4.2 Effects of grazing on SI

The SI declined obviously with an increasing grazing intensity and duration, except under the light and short-term grazing. Moderate grazing reduced SI of the meadow and desert steppe. This is different from the intermediate disturbance hypothesis (IDH) (McManus et al., 1972), which assumes that species diversity reaches peak levels at intermediate disturbance (Wang et al., 2003), because grazing jeopardizes the regenerative ability of edible herbage (Milchunas et al., 1988). Moreover, grazing reduces the soil organic matter, which leads to the depletion of soil nutrients, and thus reduces the competitiveness of plants (Mazumder, 1998).

The water-related factors are the main driving variables of species diversity in the thermal and temperate zones (Connell, 1979; Watt and Gibson, 1988; Wang et al., 1998). With increasing precipitation, the negative effects of grazing on SI first decreased and then increased (Fig. 9f). Previous studies verified IDH through a large number of experiments and found that the IDH appeared in different grazing stages of different grassland types. For example, it was generally confirmed at the stage of light to moderate grazing intensity in humid meadows, and the stage of moderate to heavy grazing intensity in the dry grassland (Nautiyal et al., 2004; Kreft and Jetz, 2007).

4.3 The relationship between productivity and species diversity

The relationship between productivity and species diversity is crucial for explaining the attributes of vegetation community characteristics (Field et al., 2005), and it is generally believed that higher biodiversity can maintain higher productivity. Our results confirmed that the grassland productivity decreased with the reduction of species diversity because the reduction in the number of species decreased the supply sources of productivity (Fig. 10) (Oesterheld et al.,

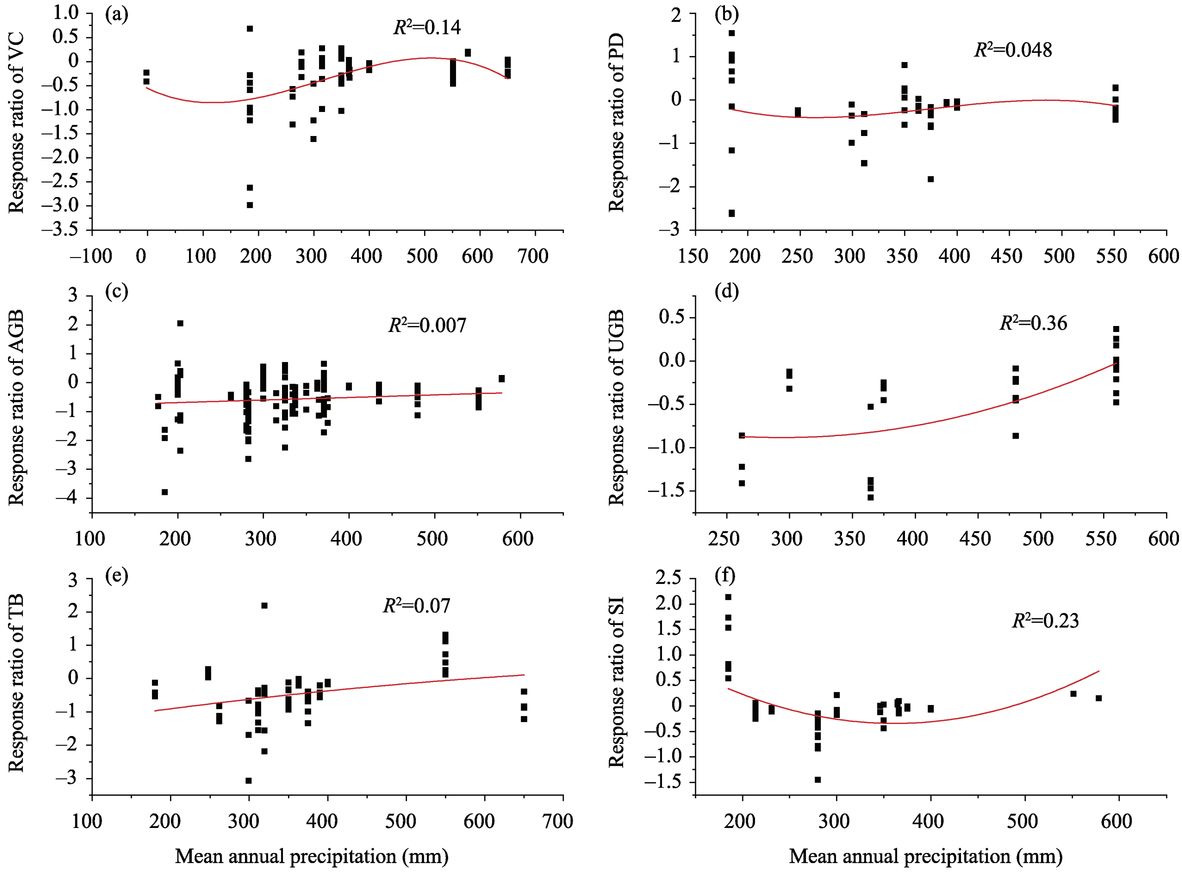

Fig. 9 Response ratios of VC (a), PD (b), AGB (c), UGB (d), TB (e), and SI (f) relative to mean annual precipitation of the experimental year.

1999; Bai et al., 2001; Guang et al., 2002). The analysis of the structural equation model showed that the grassland vegetation community characteristics were affected not only by grazing intensity and duration, but also the observed community characteristics were closely related to each other. The SI was negatively linearly correlated with VC and PD. The heavy grazing intensity and duration had direct negative effects on VC, PD, AGB, and SI, while they had indirect negative effects on TB (Fig. 11).

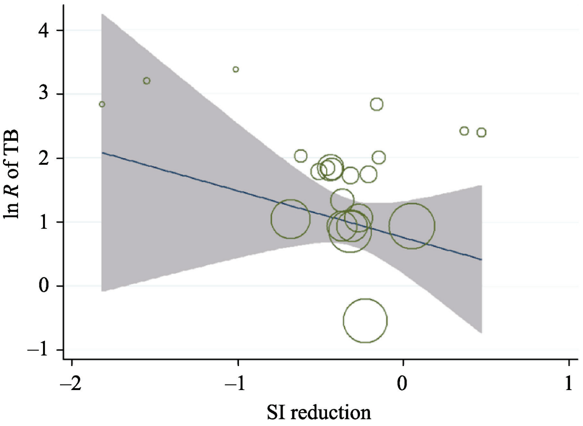

Fig. 10 Bubble plots of the meta-regression results between the responses of TB to the SI reduction

Note: The size of each bubble is the relative weight of the effect size (response ratio, ln *R*) in the meta-regression. Larger bubbles indicate study outcomes that contributed a greater overall weight in the meta-regressions.

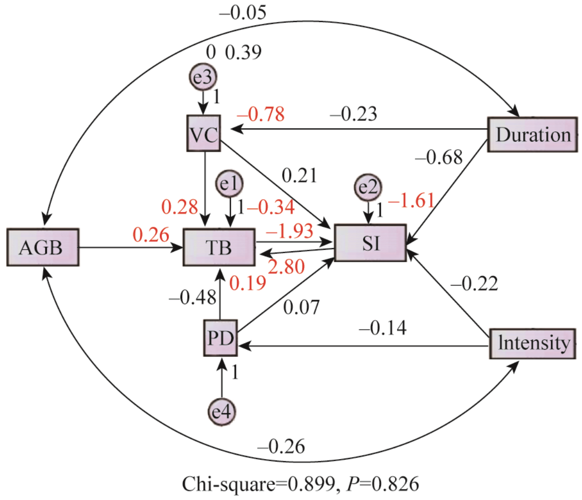

Fig. 11 Structure equation modeling examining the direct and indirect effects on vegetation community characteristics of grasslands in Inner Mongolia (n = 159)

Note: Double-headed arrows represent covariance between related variables. Single-headed arrows indicate the hypothesized direction of causation. The numbers in red adjacent to arrows are standardized path coefficients.

Several studies have analyzed the relationships between productivity and species diversity from different spatial scales and ecosystem types since 1990, and six relationship types, including positive correlation (Zhu et al., 2020), humped-back correlation (Shea et al., 2004), negative correlation (Wang et al., 2001), unitary correlation (Guo and Berry, 1998), no correlation (Al-mufti et al., 1977) and "U" relationships (Guo and Berry, 1998), were found between them (Scheiner and Willig, 2005; Jain et al., 2007). The relationship between species diversity and productivity is known to be driven by multiple factors, such as the climate (Kondoh, 2001), soil (Gillman and Wright, 2006), and density (Waide et al., 1999), and each factor changes with the spatial scale (Mittelbach et al., 2001). On the other hand, due to differences in environmental conditions, species composition, and habitats, differences in grassland productivity are often out of synchronization with changes in the factors that affect species diversity. Therefore, productivity may be a poor predictor of plant diversity (Peter et al., 2011). It is difficult to explain plant function without taking into account of all these elements (Hadgu et al., 2009). Furthermore, some details such as sampling area, location of sampling sites, sampling number, and methods of measuring productivity would also affect the relationship between productivity and species diversity.

4.4 The need for appropriate grazing intensity criteria

The standard for the divisions of the grazing intensity affects the accuracy of the meta-analysis by integrating the groups. In addition, an inappropriate division of grazing intensity may lead to grassland degradation under the guidance of a correct grazing policy (Wolfe et al., 2004). Reconsidering the grazing intensity criteria is necessary for defining the relationship between grazing and the grassland degradation degree. Grazing modifies the vegetation community characteristics by changing species composition (Šimova et al., 2013) and alters grassland productivity by changing VC, vegetation height, and biomass (Adler et al., 2011). Proposed indicators of grassland deterioration include vegetation composition, VC, litter, biomass, SI, and soil nutrients (Guang et al., 2002). Some studies inferred the grazing intensity from the distance to drinking water (Wang et al., 2020) or herder huts (Marcos and Willig, 2004). Other studies classified the grazing intensity according to the feces density (Rodríguez et al., 2003), species composition (Xia et al., 2005), or the proportion of herbivore mammals (Peter, 2012). A uniform standard for the grazing intensity classification has not been established yet. Currently, quantifying the number of herbivore mammals per unit area and unit time is the generally used criterion for classifying grazing intensity, but it cannot reflect the corresponding effect. The moderate grazing intensity in one ecosystem may be defined as heavy grazing intensity in another ecosystem. Therefore, the use of grazing intensity should be redefined based on different grassland types according to plant composition, herbage yield, soil coarse fraction, amount of soil litter, and soil erosion rate (Haynes et al., 2013).

4.5 The influences of climate change on the grassland vegetation community characteristics under different grazing intensities and durations

According to the Fifth IPCC Climate Assessment Report, the rate of the national average annual temperature rise is about 0.21–0.25 ℃ (10 yr)$^{-1}$ in the recent 50–60 years, which is higher than the global average over the past 100 years (1909–2011) (IPCC, 2013). Sarah et al. (2015) suggested that vegetation community characteristics and ecosystem processes are strongly affected by the climate change. The increasing temperature will bring forward the spring phenological period and prolong the growing period of grasslands, resulting in a significant increase in AGB, thus improving the grassland productivity (Silva, 2020). However, more frequent meteorological disasters caused by extreme climate, such as extremely high temperatures and droughts in summer, could decrease the grassland biomass and species diversity. The grassland will deteriorate severely assuming a long-term exposure of grasslands to extreme climate (Ali, 2020). The trend of climate warming and drying across Inner Mongolia, as well as the occupation of surface water by grazing, have reduced surface water and hinder the growth of vegetation (Zhao, 2019).

4.6 Uncertainties

To determine the effects of grazing on vegetation community characteristics not affected by the cumulative grazing years, we analyzed the effects just within grazing durations of one year or less. But the lack of experimental data for more than one year's grazing duration in our study results in certain limitations over the long term. In addition, since many unpublished and grey literature studies with statistically non-significant results are inaccessible and could not be compiled into the database, some limitations of this study remain to some extent. We evaluated the publication bias by funnel plots (Gonnet et al., 2003) (Fig. 12). Most of the samples in this study were distributed at the top of the funnel plot and clustered toward the center, indicating there were a few issues with publication biases in this study. Besides, the different variables that represent the vegetation growth in various studies, such as vegetation height, the Simpson Index, annual net primary production, and other ecosystem trait indexes (Li et al., 2008), need to be considered fully in further studies. Therefore, the meta-analysis related to the effects of grazing on grassland requires further study and exploration.

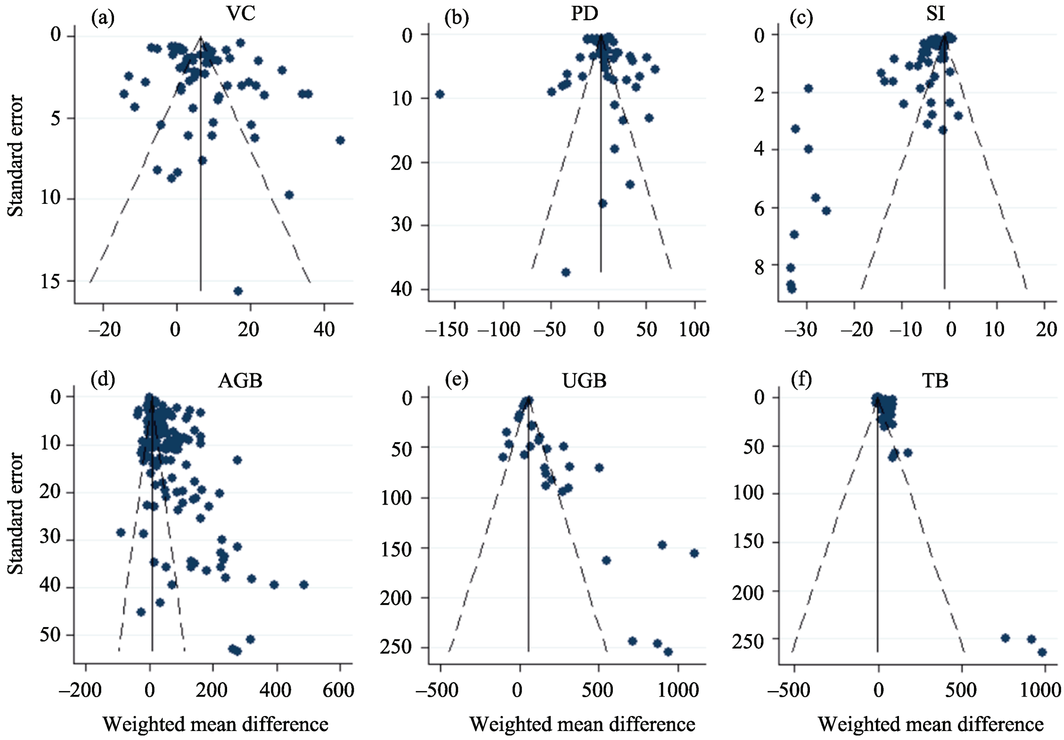

Fig. 12 Funnel plots of VC (a), PD (b), SI (c), AGB (d), UGB (e), and TGB (f) used for assessing publication bias in this study.

5 Conclusions

The Inner Mongolia grassland ecosystem exhibits a pronounced response to grazing. Unlike the intermediate disturbance hypothesis (IDH), SI of the desert and meadow steppe showed a negative linear relationship with the grazing intensity in Inner Mongolia. The meadow steppe in Inner Mongolia had a typical compensatory growth phenomenon with suitable grazing intensity and duration. The negative effects of grazing on steppe biomass in Inner Mongolia were higher than that on the global scale, while less pronounced than that in China.

References

Adler P B, Seabloom E W, Borer E T, et al. 2011. Productivity is a poor predictor of plant species richness. *Science*, 333(6050): 1750–1753.

Al-Mufti M M, Sydes C L, Furness S B, et al. 1977. A quantitative analysis of shoot phenology and dominance in herbaceous vegetation. *Journal of Ecology*, 65(3): 759–791.

Bai Y F, Li L H, Huang J H, et al. 2001. The influence of plant diversity and functional composition on ecosystem stability of four *Stipa* communities in the Inner Mongolia Plateau. *Acta Botanica Sinica*, 43(3): 280–287.

Bai Y F, Wu J G, Clark C M, et al. 2012. Grazing alters ecosystem functioning and C: N: P stoichiometry of grasslands along a regional precipitation gradient. *Journal of Applied Ecology*, 49(6): 1204–1215.

Bai W M, Fang Y, Zhou M, et al. 2015. Heavily intensified grazing reduces root production in an Inner Mongolia temperate steppe. *Agriculture, Ecosystems & Environment*, 200: 143–150.

Boval M, Dixon R M. 2012.The importance of grasslands for animal production and other functions: A review on management and methodological progress in the tropics. *Animal*, 6(5): 748–762.

Burke I C, Lauenroth W K, Parton W J. 1997. Regional and temporal variation in net primary production and nitrogen mineralization in grasslands. *Ecology*, 78(5): 1130–1340.

Cohen J. 1988. Statistical power analysis for the behavioral sciences. London, UK: Routledge.

Connell J H. 1979. Intermediate-disturbance hypothesis. *Science*, 204(4399): 1344–1345.

Dangal S R S, Tian H Q, Lu C Q, et al. 2016. Synergistic effects of climate change and grazing on net primary production of Mongolian grasslands. *Ecosphere*, 7(5): e01274. DOI: 10.1002/ecs2.1274.

de Mazancourt, Loreau M, Abbadie L. 1998. Grazing optimization and nutrient cycling: When do herbivores enhance plant production? *Ecology*, 79(7): 2242–2252.

Dong Y Q, Sun Z J, An S Z, et al. 2020. Community structure and carbon and nitrogen storage of sagebrush desert under grazing exclusion in Northwest China. *Journal of Arid Land*, 12(2): 239–251.

Dong S K, Gao H W, Xu G C, et al. 2007. Farmer and professional attitudes to the large-scale ban on livestock grazing of grasslands in China. *Environmental Conservation*, 34(3): 246–254.

Dowling P M, Kemp D R, Ball P D, et al. 2005. Effect of continuous and time-control grazing on grassland components in south-eastern Australia. *Australian Journal of Experimental Agriculture*, 45(4): 369–382.

Du S, Shen J P, Sun Y F, et al. 2020. Grazing does not increase soil antibiotic resistome in two types of grasslands in Inner Mongolia, China. *Applied Soil Ecology*, 155: 103644. DOI: 10.1016/j.apsoil.2020.103644.

Fang J Y, Piao S L, Zhou L M, et al. 2005. Precipitation patterns alter growth of temperate vegetation. *Geophysical Research Letters*, 32(21): L21411. DOI: 10.1029/2005GL024231.

Fay P A, Prober S M, Harpole W S, et al. 2015. Grassland productivity limited by multiple nutrients. *Nature Plants*, 1(7): 15080. DOI: 10.1038 /nplants.2015.80.

Fedrigo J K, Ataide P F, Filho J A, et al. 2017. Temporary grazing exclusion promotes rapid recovery of species richness and productivity in a long-term overgrazed Campos grassland. *Restoration Ecology*, 26(4): 677–685.

Ferraro D O, Martín O. 2002. Effect of defoliation on grass growth: A quantitative review. *Oikos*, 98(1): 125–133.

Field R, O'Brien E M, Lavers C P. 2005. Global models for predicting woody plant richness from climate: Development and evaluation. *Ecology*, 86(9): 2263–2277.

Focht T, Pillar V D. 2003. Spatial patterns and relations with site factors in a Campos grassland under grazing. *Brazilian Journal of Biology*, 63(3): 423–436.

Gan L, Peng X, Peth S, et al. 2012. Effects of grazing intensity on soil thermal properties and heat flux under *Leymus chinensis* and *Stipa grandis* vegetation in Inner Mongolia, China. *Soil & Tillage Research*, 118: 147–158.

Gillman L N, Wright S D. 2006. The influence of productivity on the species richness of plants: A critical assessment. *Ecology*, 87(5): 1234–1243.

Gillson L, Hoffman M T. 2007. Ecology: Rangeland ecology in a changing world. *Science*, 315(5808): 53–54.

Gonnet J M, Guevara J C, Estevez O R. 2003. Perennial grass abundance along a grazing gradient in Mendoza, Argentina. *Journal of Range Management*, 56(4): 364–369.

GB/T 34754–2017. 2017. Grade of grazing intensity on rangeland for the household ranch. Beijing, China: China Academic Journal Electronic Publishing House. (in Chinese)

Guo Q F, Berry W L. 1998. Species richness and biomass: Dissection of the hump-shaped relationships. *Ecology*, 79(7): 2555–2559.

Hanke W, Böhner J, Dreber N, et al. 2014. The impact of livestock grazing on plant diversity: An analysis across dryland ecosystems and scales in southern Africa. *Ecological Applications*, 24(5): 1188–1203.

Hayley E, Jones J. 2010. Introduction to meta-analysis. *Paediatric and Perinatal Epidemiology*, 24: 131–139.

Hadgu K M, Rossing W A H, Kooistra L, et al. 2009. Spatial variation in species diversity, soil degradation and productivity in agricultural landscapes in the highlands of Tigray, northern Ethiopia. *Food Security*, 1(1): 83–97.

Haynes M A, Fang Z D, Waller D M. 2013. Grazing impacts on the diversity and composition of alpine rangelands in Northwest Yunnan. *Journal of Plant Ecology*, 6(2): 122–130.

Hedges L V, Gurevitch J, Curtis P S. 1999. The meta-analysis of response ratios in experimental ecology. *Ecology*, 80(4): 1150–1156.

Hedges L V. 1984. Advances in statistical methods for meta-analysis. *New Directions for Program Evaluation*, (24): 25–42.

IPCC. 2013. Working Group I Contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The Physical Science Basis: Summary for Policy makers. Cambridge, UK: Cambridge University Press.

Jobbágy E G, Sala O E, Paruelo J M. 2002. Patterns and controls of primary production in the Patagonian steppe: A remote sensing approach. *Ecology*, 83(2): 307–319.

Jain S, Collins L S, Hayek L A C. 2007. Relationship of benthic foraminiferal diversity to paleoproductivity in the Neogene Caribbean. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 255(3–4): 223–245.

Kondoh M. 2001. Unifying the relationships of species richness to productivity and disturbance. *Proceedings of the Royal Society B*: *Biological*

Sciences, 268(1464): 269–271.

Kreft H, Jetz W. 2007. Global patterns and determinants of vascular plant diversity. *Proceedings of the National Academy of Sciences of the USA*, 104(14): 5925–5930.

Li Y H, Wang W, Liu Z L, et al. 2008. Grazing gradient versus restoration succession of *Leymus chinensis* (Trin.) Tzvel. Grassland in Inner Mongolia. *Restoration Ecology*, 16(4): 572–583.

Marcos G P, Willig M R. 2004. Landscape responses of bats to habitat fragmentation in Atlantic forest of Paraguay. *Journal of Mammalogy*, 85(4): 688–697.

Mavridis D, Salanti G. 2014. How to assess publication bias: Funnel plot, trim-and-fill method and selection models. *Evidence-based Mental Health*, 17(1): 30. DOI: 10.1136/eb-2013-101699.

Mazumder P A. 1998. Reversal of grazing impact on plant species richness in nutrient-poor vs. nutrient-rich ecosystems. *Ecology*, 79(8): 2581–2592.

McIntyre S, Nicholls A O, Graff P, et al. 2019. Experimental reintroduction of three grassland forbs to assess climate-adjusted provenancing, grazing protection and weed control. *Australian Journal of Botany*, 66(8): 628–639.

Mcmanus W R, Reid J T, Donaldson L E. 1972. Studies of compensatory growth in sheep. *Journal of Agricultural Science*, 79(1): 1–12.

Mcnaughton S J. 1976. Serengeti migratory wildebeest: Facilitation of energy flow by grazing. *Science*, 191(4222): 92–94.

Milchunas D G, Sala O E, Lauenroth W K. 1988. A generalized model of the effects of grazing by large herbivores on grassland community structure. *The American Naturalist*, 132(1): 87–106.

Milchunas D G, Vandever M W, Ball L O, et al. 2011. Allelopathic cover crop prior to seeding is more important than subsequent grazing/mowing in grassland establishment. *Rangeland Ecology & Management*, 64(3): 291–300.

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.

Mittelbach G G, Steiner C F, Scheiner S M, et al. 2001. What is the observed relationship between species richness and productivity? *Ecology*, 82(9): 2381–2396.

Münkemüller T, Johst K. 2006. Compensatory versus over-compensatory density regulation: Implications for metapopulation persistence in dynamic landscapes. *Ecological Modelling*, 197(1–2): 171–178.

Nautiyal M C, Nautiyal B P, Prakash V. 2004. Effect of grazing and climatic changes on alpine vegetation of tungnath, Garhwal Himalaya, India. *Environmentalist*, 24(2): 125–134.

Oesterheld M, Loreti J, Semmartin M, et al. 1999. Grazing, fire, and climate effects on primary productivity of grasslands and savannas. In: Walker L. (ed.). Ecosystems of disturbed ground. Oxford, UK: Elsevier Science.

Patton B D, Dong X J, Nyren P E, et al. 2007. Effects of grazing intensity, precipitation, and temperature on forage production. *Rangeland Ecology & Management*, 60(6): 656–665.

Peter G, Funk F A, Loydi A, et al. 2012. Variation in specific composition and cover in grassland exposed to various grazing pressures in the Monte Rionegrino. *Phyton*, 81(2): 233–237. (in Spanish)

Peter B, Eric W S, Elizabeth T B, et al. 2011. Productivity is a poor predictor of plant species richness. *Science*, 333(6050): 1750–1753.

Ren H Y, Schönbach P, Wan H W, et al. 2012. Effects of grazing intensity and environmental factors on species composition and diversity in typical steppe of Inner Mongolia, China. *Plos One*, 7(12): e52180. DOI: 10.1371/journal.pone.0052180.

Rodríguez C, Leoni E, Lezama F, et al. 2003. Temporal trends in species composition and plant traits in natural grasslands of Uruguay. *Journal of Vegetation Science*, 14(3): 433–440.

Xue R, Zheng S X, Bai Y F. 2010. Impacts of grazing intensity and management regimes on aboveground primary productivity and compensatory growth of grassland ecosystems in Inner Mongolia. *Biodiversity Science*, 18(3): 300–311.

Sala O E, Parton W J, Joyce L A, et al. 1988. Primary production of the central grassland region of the United States. *Ecology*, 69(1): 40–45.

Scheiner S M, Willig M R. 2005. Developing unified theories in ecology as exemplified with diversity gradients. *The American Naturalist*, 166(4): 458–469.

Šimova I, Li Y M, Storch D. 2013. Relationship between species richness and productivity in plants: The role of sampling effect, heterogeneity, and species pool. *Journal of Ecology*, 101(1): 161–170.

Scurlock J M O, Hall D O. 1998. The global carbon sink: A grassland perspective. *Global Change Biology*, 4(2): 229–233.

Shea K, Roxburgh S H, Rauschert E S J. 2004. Moving from pattern to process: Coexistence mechanisms under intermediate disturbance regimes. *Ecology Letter*s, 7(6): 491–508.

Silletti A, Knapp A. 2002. Long-term responses of the grassland co-dominants Andropogon gerardii and *Sorghastrum nutans* to changes in climate and management. *Plant Ecology*, 163(1): 15–22.

Silva V, Catry F X, Fernandes P M, et al. 2019. Effects of grazing on plant composition, conservation status and ecosystem services of Natura 2000 shrub-grassland habitat types. *Biodiversity and Conservation*, 28(5): 1205–1224.

Simons N K, Weisser W W. 2017. Agricultural intensification without biodiversity loss is possible in grassland landscapes. *Nature Ecology & Evolution*, 1(8): 1136–1145.

Su R N, Cheng J H, Chen D M, et al. 2017. Effects of grazing on spatiotemporal variations in community structure and ecosystem function on the grasslands of Inner Mongolia, China. *Scientific Reports*, 7(1): 40. DOI: 10.1038/s41598-017-00105-y.

Waide R B, Willig M R, Steiner C F, et al. 1999. The relationship between productivity and species richness. *Annual Review of Ecology and Systematics*, 30(1): 257–300.

Wang S P, Li Y H, Wang Y F, et al. 2001. Effects of different stocking rates on plant diversity of *Artemisia frigida* in Inner Mongolia steppe. *Journal of Botany*, 43: 89–96.

Wang S P, Wang Y F, Chen Z Z. 2003. Effect of climate change and grazing on populations of *Cleistogenes squarrosa* in Inner Mongolia steppe. *Acta Phytoecologica Sinica*, 27(3): 337–343.

Wang S P, Wang Y F, Li Y, et al. 1998. The influence of different stocking rates on herbage regrowth and aboveground net primary production. *Acta Agrestia Sinica*, 8(1): 15–20.

Wang S P, Wilkes A, Zhang Z C, et al. 2011. Management and land-use change effects on soil carbon in northern China's grasslands: A synthesis. *Agriculture, Ecosystems & Environment*, 142(3–4): 329–340.

Wang L, Luan L M, Hou F J, et al. 2020. Nexus of grazing management with plant and soil properties in northern China grasslands. *Scientific Data*, 7(1): 39. DOI: 10.6084/m9.figshare.11663340.

Wang X, McConkey B G, VandenBygaart A J, et al. 2016. Grazing improves C and N cycling in the Northern Great Plains: A meta-analysis.

Scientific Reports, 6: 33190. DOI: 10.1038/srep33190.

Wang Y S, Shiyomi M, Tsuiki M, et al. 2002. Spatial heterogeneity of vegetation under different grazing intensities in the Northwest Heilongjiang Steppe of China. *Agriculture*, *Ecosystems & Environment*, 90(3): 217–229.

Watt T A, Gibson C W D. 1988. The effects of sheep grazing on seedling establishment and survival in grassland. *Vegetatio*, 78(1–2): 91–98.

Yan L, Zhou G S, Zhang F. 2013. Effects of different grazing intensities on grassland production in China: A meta-analysis. *Plos One*, 8(12): e81466. DOI: 10.1371/journal.pone.0081466.

Yang L H. 2015. Developing a multicollaborative governance system: A meta-analysis for the Inner Mongolia grassland region. New York, USA: Palgrave Macmillan US.

Zhang Y F, Liang W T, Liao Z L, et al. 2019. Effects of climate change on lake area and vegetation cover over the past 55 years in Northeast Inner Mongolia grassland, China. *Theoretical and Applied Climatology*, 138(1–2): 13–25.

Zhu Y J, Delgado-Baquerizo M, Shan D, et al. 2020. Diversity-productivity relationships vary in response to increasing land-use intensity. *Plant and Soil*, 450(1–2): 1–10.

放牧对内蒙古草原植被群落特征的影响

郭彩贇[1,2]，赵东升[1]，郑 度[1]，朱 瑜[1,2]

1. 中国科学院地理科学与资源研究所，中国科学院陆地表层格局与模拟重点实验室，北京 100101；
2. 中国科学院大学，北京 100049

摘 要：近年来，畜牧业的持续增长导致了内蒙古草原生态系统的严重退化。以往的放牧实验表明，放牧对全球植被类型存在着广泛的影响，但目前仍然缺乏研究来识别区域特定植被群落对放牧的响应。本文对内蒙古不同类型草地在不同放牧强度和放牧时长下的植被盖度 (VC)、植被密度 (PD)、总生物量 (TB)、地上生物量 (AGB)、地下生物量 (UGB)和 Shannon-Weaver 指数 (SI) 进行了 Meta 分析。结果表明，放牧显著降低了 VC、TB、AGB、UGB 和 PD 值。放牧对内蒙古草原生物量产生的负面影响高于全球而低于全国平均水平。在中等放牧强度和时长条件下，内蒙古草甸草原 TB 值补偿性生长增加了 40%。荒漠草原和草甸草原的 SI 与放牧强度呈负相关。放牧期间 AGB、PD 和 SI 的变化百分比与试验年的平均气温呈二次方关系。随着试验年年平均降水量的增加，放牧对 UGB 和 SI 的负面影响先减小后增大，放牧对 VC 的负面影响呈三次方关系。

关键词：放牧强度；放牧时间；植被群落特征；Meta 分析；内蒙古