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Grazing effects on soil characteristics and vegetation of grassland in northern China

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Abstract

Large areas of grassland in the agro-pastoral region of northern China were converted into cropland for grain production, and the remaining grasslands are being overgrazed and seriously degraded. The objective of this study was to evaluate how reductions in grazing intensity affect the soil and vegetation characteristics in grasslands of northern China. Soil heterogeneity and vegetation characteristics were evaluated for ungrazed (UG), moderate grazing (MG), and heavy grazing (HG) sites. Grazing increased diversity, but heavy grazing decreased aboveground biomass and increased the non-grass component. Vegetation biomass was greatest at the UG site (220 $g\,m^{-2}$) followed by the MG (99 $g\,m^{-2}$) and HG (27 $g\,m^{-2}$) sites ($P < 0.05$). The non-grass proportion of total biomass increased with grazing intensity, which was 8, 16, and 48 % for UG, MG, and HG sites, respectively. Species richness at the MG and HG sites was significantly higher than at the UG site ($P < 0.05$) with 3.6, 5.5, and 5.7 for UG, MG, and HG sites, respectively. Over grazing homogenized soil characteristics at a 10 m scale. The ranges of spatial autocorrelation for soil organic C (SOC) and total N were both > 120 m at the HG site, which was considerably larger than that at the MG and UG sites with corresponding distances of 17.3 and 20.8 m for the MG site and 25.8 and 15.0 m for the UG site, respectively. Therefore, MG was recommended as the preferred management alternative for grasslands in northern China because of increased plant diversity without negative consequences related to decreased forage quality and forage quantity, and soil heterogeneity in northern China's grasslands.

1 Introduction

Arid and semi-arid ecosystems are highly heterogeneous in space and time because of considerable variation in biotic and abiotic factors related to vegetation and soil properties (Schlesinger et al., 1996; Peters et al., 2006; Garcia-Palacios et al., 2011). This heterogeneity is essential to provide multiple ecosystem functions and services such as biodiversity, habitats, and ecosystem stability (Tongway and Ludwig, 2003; Peters et al., 2006; Wang and Shao, 2013). Thus, maintaining spatial patterns of vegetation and soil heterogeneity should be primary goals for the sustainable management of grassland ecosystems (Pellant et al., 2000; Herrick et al., 2005).

Grazing intensity is a key management variable that influences the structure and composition of grassland ecosystems (Hickman et al., 2004; Bestelmeyer et al., 2009; Lin et al., 2010). In tallgrass prairie, grazing significantly increased species richness, diversity, and forb cover (Hickman et al., 2004; Koerner and Collins, 2013). In subalpine grassland in the eastern Pyrenees (Andorra), heavy grazing increased species richness and diversity, while decreased forage quality and production (Komac et al., 2014). Overgrazing has profound effects on important ecosystem characteristics, such as water erosion (Cerdà and Lavee, 1999), soil water content (SWC) (Lin et al., 2010), soil organic carbon (SOC) (Su et al., 2006; Costa et al., 2015), soil N (Augustine and Frank, 2001; Lin et al., 2010; Hirobe et al., 2013), plant species richness and diversity (Gibson, 1988; Hickman et al., 2004; Ren et al., 2012; Angassa, 2014), belowground bud bank (Qian et al., 2014), and ecosystem stability (Su et al., 2006; Ren et al., 2012). However, the effects of livestock grazing on soil heterogeneity have not been consistent with some studies showing that overgrazing increased soil heterogeneity (Schlesinger et al., 1990; Su et al., 2006), while other studies reporting that soil heterogeneity and vegetation diversity decreased from a patchy to a homogeneous distribution with increased grazing intensity (e.g., Zhao et al., 2011). Grazing increased spatial heterogeneity of vegetation and soil in the semi-arid shrublands of northern Patagonia in South America (Kröpfl et al., 2013). However, results of Lin et al. (2010) showed that neither SOC nor soil N responded to grazing intensity at a large scale (1–18 m) but that overgrazing increased vegetation fragmentation (< 2 m) in desert steppe of northern China. In a grazed ecosystem in Yellowstone National Park, grazing animals increased diversity of plant species at a fine scale (20 cm × 20 cm) and altered the distribution of soil N across a topographic gradient at large spatial scales (5–30 m) with soil N properties exhibiting increased variance among sampling points at increasing distances from 5

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to 30 m. Ungrazed grasslands exhibited no spatial structure in soil N distribution with no topographic correlation (Augustine and Frank, 2001). In China, overgrazing was hypothesized to spatially homogenize SOC and total N pools at 2 m scales (Wiesmeier et al., 2009; Lin et al., 2010). However, Su et al. (2006) hypothesized that the lack of spatial heterogeneity of soil properties (10 m scales) from overgrazing could not be reversed even when grazing was eliminated for four years. Therefore, the effects of grazing intensity on soil heterogeneity may be positive, negative, or negligible depending on the level of grazing intensity and scale of observation (Fuhlendorf and Smeins, 1999).

Grasslands are used for livestock grazing extensively in the dry area of China, where grazing pressure may increase substantially in the future due to increasing demands for animal products (Han et al., 2008). The effects of grazing on spatial heterogeneity of grassland ecosystems as related to soil properties and vegetation have been inconsistent and need clarification. In this study, we hypothesized that a reduction in grazing intensity will alter soil spatial heterogeneity and vegetation characteristics in grasslands of northern China. The study aimed to quantify the effects of various grazing intensities on vegetation and soil spatial heterogeneity of SWC, SOC, N, and P at a 10 m scale in grasslands of Inner Mongolia.

2 Materials and methods

2.1 Study area

Our study site was a temperate grassland on the Mongolian Plateau, at the Guyuan Experimental Station of China Agricultural University in Hebei Province of northern China (41°4′ N, 115°46′ E; elevation 1380 m) (Fig. 1). This region has a semiarid continental monsoon climate, which in summer (June–August) is warm and relatively rainy. Autumn, winter, and spring seasons (September–May) are windy, cold and dry. Mean annual precipitation is about 400 mm but varies among years with strong seasonal vari-

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ability (Ma et al., 2014). The coefficient of variation for annual precipitation ranges from 25 to 50 %. The rainy season in 2012 began in late-June. Long term mean annual air temperature of the region is 1 °C, with a mean minimum temperature in January (−18.6 °C) and mean maximum of in July (17.6 °C). The mean frost-free growing season of the region is 85 to 95 days. Frequent droughts and lower temperature during the short growing season are usually the limiting factors for plant growth. The soil is a chestnut soil (Chinese classification) or a Calci Orthic Aridisol (USA classification). The soil has a sandy loam texture, and soil characteristics of the three grazed sites are presented in Table 1.

Vegetation of the study site is relatively homogeneous, dominated by *Leymus chinensis* (Trin.) Tzvelev and *Stipa krylovii* Roshev., companion with *Phragmites communis* Trin., *Cleistogenes chinensis* (Maxim.) Keng., *Carex duriuscula* (Maxim.) Keng., *Taraxacum mongolicum* Hand.-Mazz., *Artemisia frigida* Willd., and *Polygonum sibiricum* Laxm.

2.2 Experimental design

Three grazing sites (each with 1.5 ha) were used in this study, which located about 100 to 150 m apart within a 24 ha area (Zhu et al., 2015). The study region had been free grazed by beef cattle and sheep year round with estimates stocking rate of 2–3 sheep unit ha^{-1} for more than 50 years prior to 2009 and was fenced in 2009 (Zhu et al., 2015). In 2010, We set up three grazing intensities treatments: ungrazed (UG, 0 sheep ha^{-1}), moderate grazing (MG, 6.7 sheep ha^{-1} with 50 to 55 % biomass removal and equal to 1.43 sheep unit ha^{-1} year^{-1}), and heavy grazing (HG, 9.3 sheep ha^{-1} with 70 to 85 % biomass removal and equal to 2.33 sheep unit ha^{-1} year^{-1}). The HG site is typical of the historical grazing intensity in this area. The grazing period was about 3.5 months per year from 15 June to 30 September. The grazing gradient used in this study represented the range of grazing pressures that can be found in this region (Ma et al., 2014). At the MG and HG sites, there was a rubber trough with fresh water replaced each day and a plastic shed that sheltered the sheep. The sheep were free grazed at MG and HG sites during the grazing period.

2.3 Measurements

To evaluate the spatial patterns of soil and vegetation characteristics, we employed a modified sampling design of Su et al. (2006) and Lin et al. (2010). At each grazing site (150 m × 100 m), we established a sampling matrix consisting of 126 grids (10 m × 10 m). For soil sampling, 70 intersecting cross points were randomly marked (Fig. 2), and two soil samples at each transect point were taken to a depth of 10 cm using a soil auger (5 cm diameter) and bulked to obtain a composite sample. This allowed for an estimation of the effect of grazing intensity on soil characteristics at a 10 m scale. We removed all plant litter from the soil surface during soil sampling.

For vegetation sampling, 12 10 m^2 grids were randomly chosen, and each of the grids was divided into 25 2 m^2 subgrids (Fig. 2). One of the 2 m^2 subgrids was used to measure canopy height, and two 0.25 m^2 sub-subgrids were used to measure species richness and aboveground biomass. Soil and vegetation samples were collected in late July 2012. Species richness (S) was calculated for each grazing site as the mean number of species per site, whereas species diversity was calculated using the Shannon–Wiener diversity index (H′), which is determined by the following equation:

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

where s is the number of species, and p_i is the proportion of individuals belonging to the ith species for each quadrat.

The aboveground biomass was clipped and oven-dried at 65 °C for 2 days. Soil water content (SWC) was determined gravimetrically by oven-dried at 105 °C for 48 h. Soil samples were sort out debris and gravel, air-dried and passed through a 2 mm. Subsamples were finely ground to pass a 0.25 mm sieve and analyzed for SOC, total N, and total P. A Rapid C Analyzer (Elementer, Germany) was used to determine

SOC. Total N was determined by the Kjeldahl Method, and total P was determined by a spectrophotometer after NaOH digestion (ISSCAS, 1978).

2.4 Statistical analysis

Mean, standard deviation (SD), and coefficient of variation (CV) were calculated from all data. All data was tested for normality distribution before analysis using Kolmogorov–Smirnov Test, kurtosis, and skewness. All statistical analyses were conducted with SAS 9.2.

The spatial patterns of SWC, SOC, total N, total P, C : N ratio, C : P ratio, and N : P ratio were analyzed geostatistically using semivariograms. All the field data were calculated semivariance using GS^+ (Gamma Design Software, 2005) and the fitting of models to semivariograms were determined according to the best fit of the experimental semivariogram. The semivariance (Y(h)) for each specific lag distance (h) was calculated using the following formula:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)], \quad (2)$$

where $N(h)$ is the number of pairs separated by distance h, $Z(x_i)$ is the measured sample value at spatial location x_i, and $z(x_i + h)$ is the value of the measured variable at spatial location $x_i + h$ (Isaaks and Srivastava, 1989; Rossi et al., 1992). A variogram function is determined by three parameters: the nugget effect, the range and the sill. The nugget effect (C_0) is either the variance within sampling unit or represents a spatial dependence at a scale smaller than the minimum distance examined. The range is the scale of spatial autocorrelation and is estimated by the maximum distance at which pairs of separating sampling points. The sill ($C + C_0$) is the maximum semivariance of all sampling points. The proportion of structural variance (C, difference between sill and nugget) to the estimated total sample variation (sill, $C + C_0$) was used to evaluate the magnitude of spatial dependence. For the measured data with a spatial patterned

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distribution, the semivariance is relatively small at short lag distances which indicate neighboring samples are more similar and autocorrelated, whereas the semivariance is relatively large when the paired sample becomes less similar.

3 Results

3.1 Ground cover characteristics

Aboveground biomass was 220 $g\,m^{-2}$ at the UG site, which was significantly greater than that at the MG site (99 $g\,m^{-2}$) and HG site (27 $g\,m^{-2}$) ($P < 0.05$) (Fig. 3). Standing dead or litter was not observed at the HG site, and only a relatively small amount of standing dead or litter was present at the MG site. Green biomass was 115 $g\,m^{-2}$ at the UG site, which was also significantly greater than that at the MG and HG site (Fig. 4a). Grass was the dominant biomass component at all three sites, comprising 91, 84, and 52 % of live biomass at the UG, MG, and HG sites, respectively (Fig. 4b). Non-grass biomass comprised 8, 16, and 48 % of live biomass at the UG, MG, and HG sites, respectively (Fig. 4c).

Species richness at the 0.25 m^2 scale was not significantly different ($P < 0.05$) between the MG site (5.5) and HG site (5.7), which were significantly greater than the UG site (3.6) (Fig. 5a). The α diversity indices for the UG, MG, and HG sites were significantly different ($P < 0.05$) with values of 0.43, 0.80, and 1.18, respectively (Fig. 5b).

3.2 Soil physical and chemical properties

The highest mean values for SWC, SOC, total N, total P, and N : P ratio were observed at the MG site compared to the HG or UG sites (Table 2). Highest CV values were observed for SOC, C : P ratio, and N : P ratio compared to the other soil characteristics. Mean total P was similar for the three sites. The CV values for SOC and C : N ratio were higher for the MG and HG sites than UG site, indicating that grazed soils had a higher degree of variability for SOC and C : N ratio.

3.3 Semivariance analysis of soil properties

Semivariograms were constructed for each soil characteristic during evaluating the spatial variation of soil properties. The normality results using frequency distribution and Kolmogorv–Smirov tests showed that most variables were normally distributed with the exception of C : P ratio and N : P ratio at the UG site and C : N ratio at the MG site. After log-transformation of data that were not normally distributed, all data sets for soil characteristics were normally distributed.

Best-fit model parameters for the semivariograms were calculated based on the smallest residual sum of square (RSS) (Table 3). Semivariagrams for soil properties were fitted to spherical, exponential, or Gussian models. Semivariances for soil properties were generally lower at the UG site than the MG and HG sites (Fig. 6). A relatively large nugget value means that the random portion of spatial variability was large or had small spacing distances. The nugget value for SWC was larger at the MG site than UG and HG sites (Table 3). Sill values represented the estimated total sample variation and were generally higher for the MG and HG sites than UG site, indicating less spatial variability for soil characteristics at the MG and HG sites compared to UG site. All soil characteristics evaluated in our study showed a moderate or strong spatial dependence with the proportion of spatial structure [C/(C+C0)] ranging from 0.51 to 1.00. The proportion of sample variance explained by small-scale patchiness $[C/(C+C_0)]$ was especially high at the UG site for SWC, total N, and total P, suggesting that the UG site had a higher degree of fine-grained variability for these soil characteristics compared to the MG and HG sites. For SOC, variability was higher for the MG and HG sites compared to the UG site. The range of autocorrelation (A_0) for total N was 15.0 and 20.8 m for the UG and MG sites, respectively, and for SOC was 25.8 and 17.3 m for the UG and MG sites, respectively, which was less than that for the HG site in both cases (> 120 m). These results suggested that spatial variability for these soil characteristics was greater at the UG and MG sites than HG site.

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4 Discussion

4.1 Aboveground cover characteristics

Livestock overgrazing in the dry steppe exerts a strong influence on ecosystem dynamics by decreasing vegetative biomass, and changing species composition and soil properties (Rietkerk et al., 2000; Augustine and Frank, 2001; Kondo et al., 2011). Grazing affects plant diversity in many ecosystems (Milchunas and Lauenroth, 1993; Hoshino et al., 2009) and generally increases plant diversity through reductions in competition (Collins et al., 1998) and creation of environmental heterogeneity at different spatial scales (McNaughton, 1983; Sommer, 2000). Grazing and exclosure studies conducted by Oba et al. (2001) in arid grasslands of northern Kenya indicated that maximum plant-species richness occurred at an intermediate level of biomass production. However, the link between plant-species richness and biomass in their study was not direct and was hypothesized to be influenced by factors such as soil water content, soil type, time of year, type of management, etc.

Our study demonstrated that vegetation characteristics changed significantly with grazing (Figs. 3–5). These effects of grazing were probably caused by decreased total biomass (live, standing dead, and litter) (Su et al., 2006; Lin et al., 2010; Komac et al., 2014), changes in species composition (Augustine and Frank, 2001; Hickman et al., 2004; Koerner and Collins, 2013), and decreased input of organic matter (Zhao et al., 2005; Su et al., 2006; Lin et al., 2010). Similar results were observed in the tallgrass prairie of the USA (Hickman et al., 2004; Koerner and Collins, 2013), a semi-arid grassland in the Mediterranean Region (Komac et al., 2014), and Euro-Asian steppes (Zhao et al., 2005; Lin et al., 2010).

After sheep grazing was excluded for four years at the UG site and grazing intensity was reduced at the MG site, vegetation recovered to some extent at these sites. Moreover, vegetation characteristics differed significantly from those at the HG site where heavily grazing was continuous for another four years. The results showed that vegetation composition and biomass characteristics could be improved even in a period

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of four years. However, Ren et al. (2012) also working in the steppes of Inner Mongolia showed that plant species composition and diversity varied among years, were primarily determined by precipitation and temperature, and were little affected by grazing intensity. In our study, grazing increased species richness and diversity, especially at the HG site. The proportion of grass in total biomass decreased with increasing grazing intensities, whereas the non-grass proportion showed the opposite trend. The probable reason may be that heavy grazing removed a large proportion of the aboveground biomass (especially grass biomass), which correspondingly decreased plant cover and opened niches for non-grass species. This agrees with the results of Augustine and Frank (2001) who found that greater plant diversity (20 cm × 20 cm) was observed in small patches in grazed grassland in Yellowstone National Park in the USA. Results concerning the effect of grazing on vegetation variation and spatial heterogeneity patterns sometimes differ depending on how plant diversity is defined and the particular methods used (Adler et al., 2001). The effect of grazing on plant diversity also may be related to the measurement scale, as indicated by Augustine and Frank (2001) who found that grazed grassland exhibited greater plant diversity at small scales (20 cm × 20 cm) compared to large scales (4 m × 4 m). In our study, vegetation variation was measured at a 50 cm^2 scale, a relatively small scale.

4.2 Soil spatial properties as affected by grazing

In the present study, we determined the magnitude of soil heterogeneity under three grazing intensities at a 10 m scale. Our results showed that the ranges of spatial autocorrelation for SOC and total N were smaller at the UG and MG sites than HG site. These results indicated that soil characteristics were relatively uniform across the HG site compared to the UG and MG sites at the examined scale. Grazing had a strong influence on the spatial patterns of soil characteristics and was the main reason for reduced spatial dependency in grasslands of Turkey (Ozgoz et al., 2013), which may have resulted in soil and vegetation characteristics being relatively homogeneous at grazed sites and heterogeneous at ungrazed sites in China (Zhao et al., 2011). Hirobe

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et al. (2013) also reported that grazing in Mongolian grasslands homogenized the spatial patterns of net N mineralization and net nitrification, which were not related to their original spatial patterns and were largely determined by differences in vegetation structure. This was probably due to heavy grazing reducing the input rate of organic matter, decreasing plant cover, trampling damage to plant tissue, increasing soil bulk density, and decreasing soil water infiltration. However, Su et al. (2006) found greater spatial variability in soil characteristics on sites rested for five years after heavy grazing, which is inconsistent with our findings. A possible reason for this discrepancy may be that Su et al. (2006) conducted their study in sand dune vegetation compared to steppe vegetation in our study, where the distribution of soil properties and vegetation was not uniform across different types of sand dunes.

Soil physical characteristics have been shown to be the main factors controlling spatial patterns of soil water and soil nutrients (Zhao et al., 2011). Soil compaction following heavy grazing can lead to a homogenous spatial distribution of soil characteristics and increase the vulnerability of soil water and soil loss, and consequently reduce water availability for plants and rangeland production (Zhao et al., 2011). With increasing grazing intensity, heterogeneity of soil and plant characteristics changed from a patchy to a homogeneous distribution (Zhao et al., 2011). This was also confirmed in our study where heavy grazing decreased variation in soil properties at the 10 m scale, strongly modified soil property patterns, and changed species composition. In our study, four years after grazing intensity was altered from heavy grazing to moderate grazing at the MG site, spatial variability of soil properties increased at the MG site compared to the HG site. Livestock grazing resulted in changes to litter input, which may have influenced SOC (Zhao et al., 2005; Su et al., 2006; Lin et al., 2010; Komac et al., 2014). Although Lin et al. (2010) thought those factors resulted in a more homogenous grazing distribution, they were not strong enough to alter the pre-existing spatial patterns of vegetation and soil fertility in their desert steppe. They found that neither SOC nor total N responded to grazing intensity at a coarse scale (1–18 m), while soil water content and SOC decreased with increasing grazing intensity at a fine scale

(< 2 m) (Lin et al., 2010). Our findings from the typical steppe confirmed that livestock grazing can change the spatial patterns of soil properties at a 10 m^2 scale and make them more homogenous. The heterogeneity of SOC patches decreased with increasing grazing pressure, which was agreement with the long-term (> 25 years) responses of SOC spatial patterns to grazing in a semi-arid steppe in Inner Mongolia (Wiesmeier et al., 2009). This was also confirmed with the findings of Augustine and Frank (2001) who found that semivariance was positively correlated with distance between sampling points in grazed grassland at Yellowstone National Park, indicating that homogenous patches occurred at a scale > 30 m for soil N.

The responses of spatial patterns to grazing depend on the scale at which they are measured (Augustine and Frank, 2001; Lin et al., 2010; Zhao et al., 2011). At small scales (10–200 cm), removal of grazers increased patchiness in soil N, while grazed grassland exhibited extremely fine-grained (< 10 cm) variability (Augustine and Frank, 2001). At larger spatial scales extending across a topographic gradient, soil N properties exhibited no spatial structure in ungrazed grassland, while homogenous patches for soil N occurred at a scale of 30 m in grazed grassland (Augustine and Frank, 2001). Lin et al. (2010) found that in some fragile areas, grazing could lead to a high degree of spatial heterogeneity in soil characteristics which resulted in land degradation/desertification. These studies indicated that additional documentation is needed to clarify how the interactive effects of grazing and physical environment affect ecosystem heterogeneity at different spatial scales.

5 Conclusions

This study contributes to the understanding of the ecological effects of grazing on the soil and vegetation characteristics of steppe grasslands in northern China. We found that reducing livestock grazing intensity increased the heterogeneity of soil characteristics at a 10 m scale. As expected, grazing markedly reduced vegetation biomass under heavy and moderate grazing. In addition, grazing increased the non-grass component of the vegetation, and species richness and diversity increased. Little heterogeneity was observed for soil characteristics at scales > 10 m under heavy grazing. For this agro-pastoral area of northern China, livestock grazing should be reduced to restore heterogeneity of soil properties and aboveground biomass. One alternative is to feed sheep in feedlots during the non-growing season, which may help in restoring heterogeneity of soil and vegetation characteristics.

Author contributions. Yuping Rong and Zhongmei Wang designed the experiments, Zhongmei Wang carried them out. Zhongmei Wang, Douglas A. Johnson and Yuping Rong interpreted the results and prepared the manuscript.

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Table 1. Soil characteristics for ungrazed (UG), moderate grazing (MG), and heavy grazing (HG) sites (mean ± standard error).

Grazed site	Soil pH	SBD[a] $g\,cm^{-3}$	SOC[b] $g\,kg^{-1}$	STC[c] $g\,kg^{-1}$	TN[d] $g\,kg^{-1}$
UG	9.15 ± 0.12^{e}	1.34 ± 0.03^{e}	12.28 ± 1.96^{g}	21.86 ± 1.97^{f}	1.55 ± 0.07^{f}
MG	9.21 ± 0.20^{e}	1.35 ± 0.04^{e}	18.75 ± 2.28^{ef}	31.00 ± 0.41^{e}	2.43 ± 0.13^{e}
HG	9.03 ± 0.19^{e}	1.41 ± 0.05^{e}	13.46 ± 0.20^{fg}	27.94 ± 0.95^{e}	2.22 ± 0.20^{e}

Means within a column with different letters are significantly different at $P < 0.05$.
[a] SBD = Soil bulk density; [b] SOC = Soil organic carbon; [c] STC = Soil total carbon; [d] TN =,Soil total nitrogen.
[e,f,g] display the significant differences for the soil characteristics between treatments.

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Table 2. Statistical characteristics of soil properties at sites exposed to different grazing intensities (UG = ungrazed, MG = moderate grazing, and HG = heavy grazing).

Variables	Treatment	Mean (min.–max.)	CV %	Skewness	Kurtosis
SWC	UG	19.2 (13.7–27.0)	15.6	0.25	–0.36
(%)	MG	24.1 (12.6–31.4)	14.6	–0.87	1.63
	HG	16.9 (7.0–26.1)	24.5	0.10	–0.62
SOC	UG	12.2 (5.7–22.8)	33.4	0.52	–0.54
($g\,kg^{-1}$)	MG	18.2 (6.0–31.7)	35.6	0.13	–0.76
	HG	15.9 (5.1–34.8)	44.8	0.86	0.27
Total N	UG	1.6 (0.7–2.6)	28.4	0.50	0.19
($g\,kg^{-1}$)	MG	2.5 (0.9–3.9)	24.5	–0.30	0.04
	HG	2.2 (1.0–3.7)	28.6	0.45	–0.17
Total P	UG	0.36 (0.09–0.53)	25.0	–0.89	0.89
($g\,kg^{-1}$)	MG	0.38 (0.18–0.54)	18.4	–0.55	0.68
	HG	0.35 (0.22–0.50)	17.1	0.24	–0.01
C : N ratio	UG	8.0 (5.0–11.4)	22.4	0.40	–0.94
	MG	7.6 (2.4–12.4)	29.0	1.39	6.81
	HG	6.9 (3.6–12.0)	23.8	0.44	0.47
C : P ratio	UG	36.6 (17.6–101.8)	47.0	2.11	4.47
	MG	49.0 (13.4–131.1)	40.0	1.45	4.18
	HG	44.2 (12.4–82.8)	37.1	0.24	–0.66
N : P ratio	UG	4.6 (2.6–15.6)	45.7	3.31	12.61
	MG	6.4 (3.2–12.0)	24.9	0.84	1.96
	HG	6.2 (2.9–9.8)	22.9	–0.23	–0.25

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Table 3. Summary of semivarogram model parameters for ungrazed (UG), moderate grazing (MG), and heavy grazing (HG) sites.

Property	Site	Model	RSS[a]	r^2	Nugget [b] (C_0)	Sill[c] (C_0+C)	Range[d] (A_0)(m)	$C/(C_0+C)$[e]
SWC (%)	UG	Spherical	13.4	0.00	0.3	9.1	12.7	0.97
	MG	Gaussian	6.3	0.94	9.2	39.4	> 120	0.77
	HG	Spherical	7.9	0.94	2.6	19.0	54.8	0.86
SOC ($g\,kg^{-1}$)	UG	Exponential	32.8	0.19	2.3	17.3	25.8	0.87
	MG	Spherical	567.0	0.02	0.1	41.0	17.3	0.99
	HG	Gaussian	554	0.93	11.2	223.0	> 120	0.95
Total N ($g\,kg^{-1}$)	UG	Spherical	0.003	0.01	0.0	0.2	15.0	0.98
	MG	Gaussian	0.05	0.15	0.0	0.4	20.8	0.90
	HG	Gaussian	0.06	0.85	0.2	2.4	> 120	0.93
Total P ($g\,kg^{-1}$)	UG	Gaussian	3.67×10^{-5}	0.67	0.0	0.1	> 120	0.91
	MG	Gaussian	5.84×10^{-6}	0.66	0.0	0.0	91.1	0.51
	HG	Gaussian	7.0×10^{-7}	0.91	0.0	0.0	> 120	0.80
C : N ratio	UG	Exponential	1.18	0.29	0.4	3.3	28.8	0.87
	MG	Spherical	2.98	0.04	0.0	2.9	18.7	1.00
	HG	Exponential	0.82	0.87	1.7	5.1	> 120	0.67
C : P ratio	UG	Gaussian	> 1000	0.74	–	–	> 120	0.75
	MG	Spherical	0.02	0.00	0.0	0.2	16.3	1.00
	HG	Gaussian	> 1000	0.89	39.0	788.9	> 120	0.95
N : P ratio	UG	Gaussian	2.30	0.71	0.1	1.0	> 120	0.93
	MG	Spherical	4.87	0.01	0.0	2.3	16.0	1.00
	HG	Gaussian	3.49	0.79	0.7	6.5	> 120	0.89

[a] RSS = residual sum of squares.
[b] Nugget (C_0) = spatial dependence at a scale smaller than the minimum distance examined.
[c] Sill (C_0+C) = estimated total sample variation.
[d] Range = range of spatial dependency or autocorrelation.
[e] $C/(C_0+C)$ = magnitude of spatial dependence.

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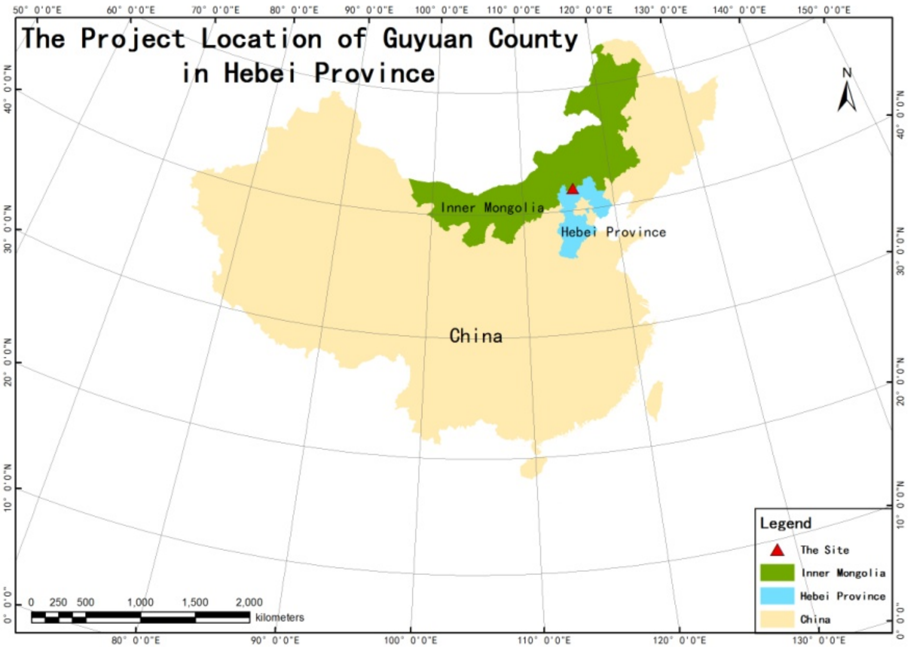

Figure 1. Project location in Guyuan County, Hebei Province in northern China.

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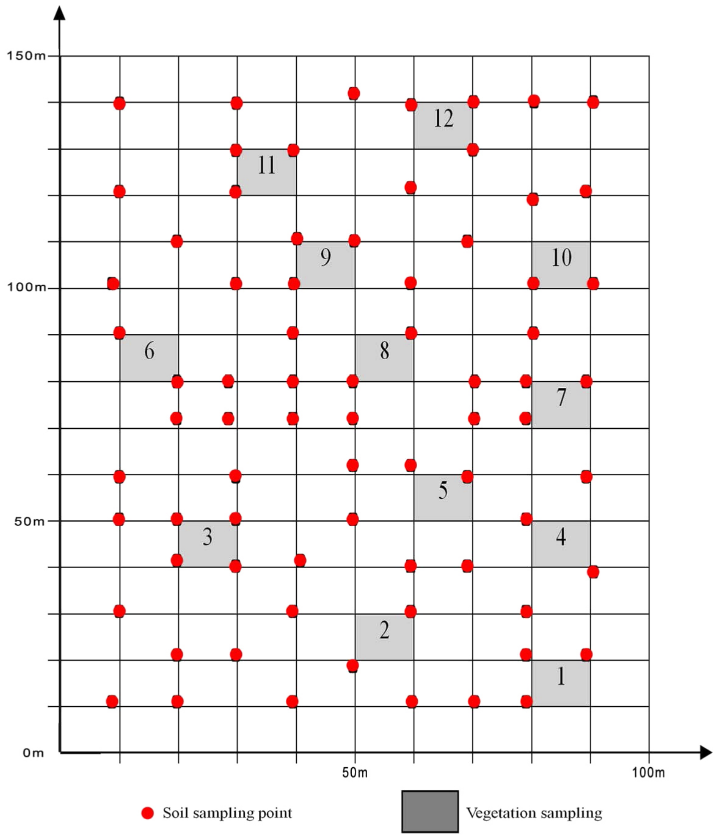

Figure 2. Soil and vegetation sampling points at one of the study sites.

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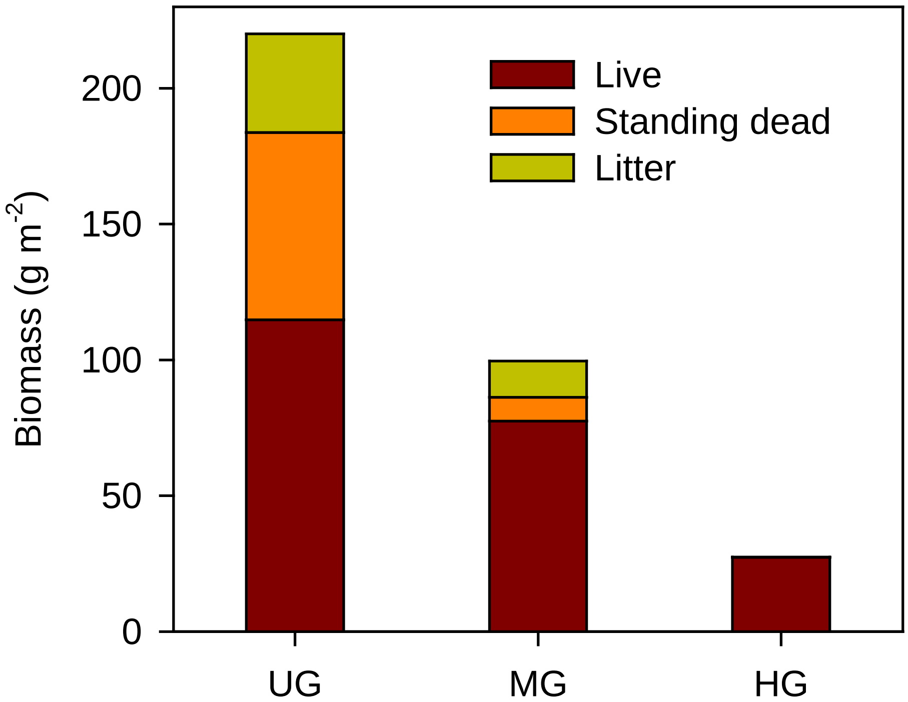

Figure 3. Aboveground biomass at sites exposed to three grazing intensities (UG = ungrazed, MG = moderate grazing, HG = heavy grazing).

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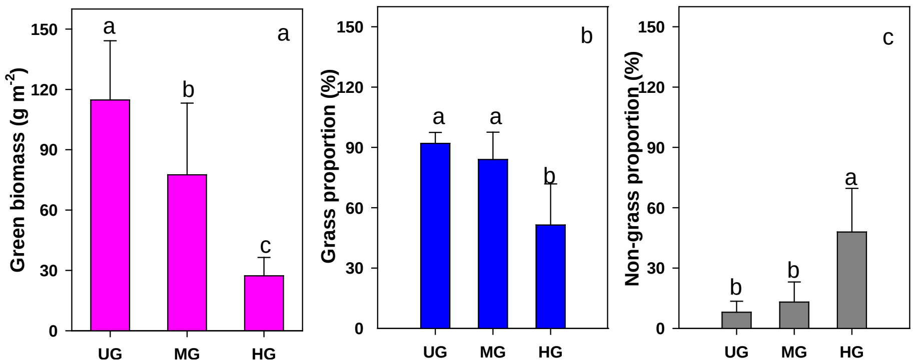

Figure 4. Green biomass **(a)**, grass composition proportion **(b)**, and non-grass composition proportion **(c)** at sites exposed to three grazing intensities (UG = ungrazed, MG = moderate grazing, HG = heavy grazing). Bars represent ± one standard deviation.

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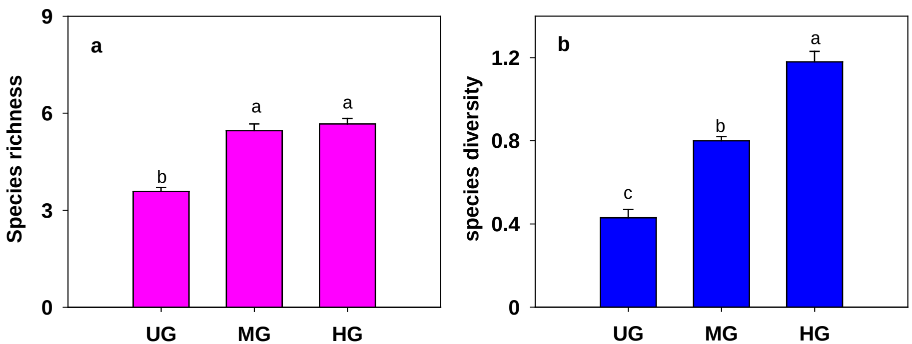

Figure 5. Species richness **(a)** and alpha diversity **(b)** at 0.25 m^2 scale for sites exposed to three grazing intensities (UG = ungrazed, MG = moderate grazing, HG = heavy grazing). Bars represent ± one standard deviation.

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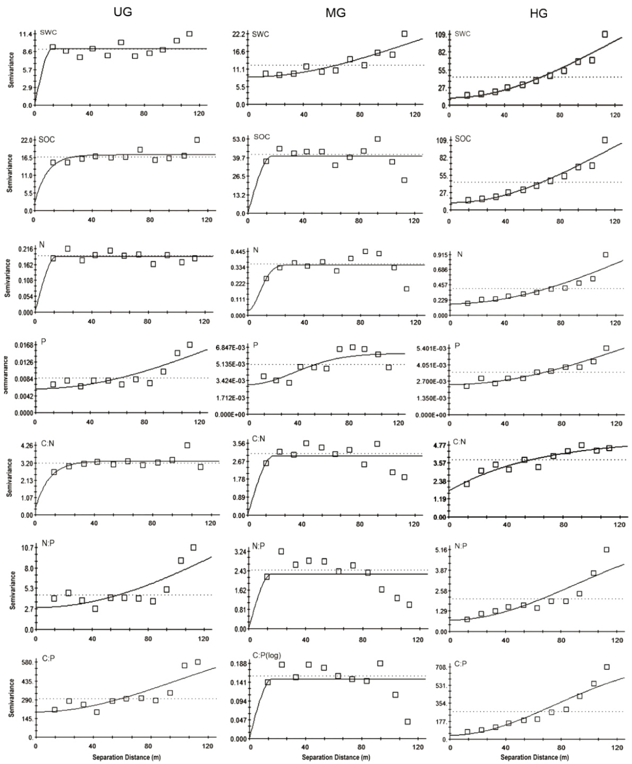

Figure 6. Semivarograms for soil water content (SWC), soil organic C (SOC), soil total N, total P, C : N ratio, N : P ratio, and C : P ratio for sites exposed to three grazing intensities: ungrazed (UG, first column), moderate grazing (MG, second column), and heavy grazing (HG, third column).

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