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Do sheep grazing patterns affect ecosystem functioning in steppe grassland ecosystems in Inner Mongolia?

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ABSTRACT

Overgrazing has driven degradation and desertification of semi-arid grasslands in Northern China over recent decades. Selective grazing by sheep influences sward structure by inducing heterogeneous vegetation patterns comprising overgrazed hotspots and areas rejected by grazing sheep. In this study, we examined the effects of grazing intensity (ungrazed, light and heavy grazing in 2008 and 2010) and grazing system (a mixed system involving continuous grazing alternating annually with hay making vs. a continuous system involving continuous utilization of the same area for grazing) on plant biomass distribution and ecosystem functioning after 4 years and 6 years of controlled grazing in a semi-arid steppe of Inner Mongolia, China. The spatial biomass distribution was determined by sward height measurements converted to biomass and afterwards visualized in biomass distribution semivariograms. Within each of the different areas: grazed (i.e., areas frequently grazed by sheep), rejected (i.e., areas largely avoided by grazing sheep) and fenced (i.e., areas from which grazing had been excluded by fencing), plant species and soil parameters were sampled in order to analyze the mechanisms and effects of grazing patterns on ecosystem functioning. The results revealed a more homogeneous biomass distribution in the ungrazed and heavily grazed plots compared to lightly grazed plots, in which heterogeneous biomass distribution patterns included both overgrazed hotspots and rejected areas. The patch vegetation patterns were consistent between years only under light grazing intensity. However, patch vegetation patterns in the continuous system did not necessarily indicate negative effects on grassland ecosystem functioning. Within the 6 years of grazing experiment, it appears that patchy structure rather than homogeneous patterns showed higher biodiversity, significant variations in litter, soil water content and soil temperature and smaller effects on belowground biomass and carbon storage. Therefore, heterogeneous patchy vegetation patterns are likely to moderate grassland recovery and optimize ecosystem functioning by forming resource islands with sufficient water and nutrients in the short run.

1. Introduction

Overgrazing is a major driver of disfunction in grassland ecosystems (Milchunas and Lauenroth, 1993; Pakeman, 2004; Cingolani et al., 2005). It induces environmental and economic problems, such as degradation and reduced livestock production, especially for plant community under semi-arid and arid climatic conditions. Although the effects of overgrazing have been the subject of several studies (Diaz et al., 2001, 2007; Adler et al., 2005; Schonbach et al., 2012), few studies have investigated the influence of animal grazing behavior on plant growth, animal productivity and ecosystem functioning. Grazed areas can be divided into patches resulting from the grazing behavior of animals. These patches can be characterized into frequently-grazed areas with low or even no soil coverage and rejected areas dominated by mature plant

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species. This variable sward structure may change the microenvironment within a paddock (Burke et al., 1998; Aguiar and Sala, 1999). The patchy pattern in the plant community is considered to be the effect of selective grazing (Teague and Dowhower, 2003; Dumont et al., 2012). Forage quality attracts the livestock to stay in their preferred food patches (Dumont et al., 2012) and grazing animals have the ability to retain their memory of specific food plots (Dumont and Petit, 1998). According to previous studies, young plant materials have clearly better nutrient quality than mature plants (Schonbach et al., 2009). Although grazing-induced vegetation variations are well understood, little attention has been drawn to the effects of the behavior of grazing animals on the spatial distribution of vegetation and the consequent effects on plant communities. It is unclear how grazing patterns affect grassland ecosystem functioning. Moreover, there are few findings concerning the appropriate grazing intensity and grazing management for improving grassland productivity and maintaining steppe ecosystem sustainability in Inner Mongolia. Low stocking rate per unit area under continuous grazing is not a normative practice for protecting grassland, since overgrazed hotspots may also occur under light grazing pressure. In addition, the nutrient imbalance resulting from dung and urine patches of herbivores influence heterogeneity in biomass production and species composition (Macdiarmid and Watkin, 1971; Jaramillo and Detling, 1992; Shiyomi et al., 1998). Therefore, more detailed information about the spatial distribution of vegetation is important to understand the complex interaction of vegetation–animal-grazing patterns.

In this study, we examined the effects of grazing intensity and grazing system (continuous grazing alternating annually with hay making vs. continuous utilization of the same area for grazing) on spatial patch pattern, plant biomass distribution and ecosystem functioning in the fourth and sixth year after the start of a grazing experiment in the Xilin River Basin, Inner Mongolia, China (Schonbach et al., 2009). Plant species and soil parameters across three kinds of vegetation patches (grazed, rejected and fenced area) were evaluated to explore the mechanism and effects of grazing patterns on ecosystem functioning. We hypothesize that grazing intensity affects the pattern of grazing, and that patterns persist over time. The objectives of the study were (1) to determine the spatial biomass distribution under different grazing intensities and management systems; (2) to correlate the spatial vegetation patch pattern with plant and soil variables; and (3) to identify links between grazing patterns and ecosystem functioning in steppe grassland ecosystems.

2. Material and methods

2.1. Study area

The study site is located in a semi-arid, native grassland of the Xilin River catchment, Inner Mongolia Autonomous Region, P.R. China, near the Inner Mongolia Grassland Ecosystem Research Station (IMGERS 43°38′N, 116°42′E, located at about 1200 m a.s.l.). The investigated typical steppe ecosystem is dominated by the perennial rhizome grass *Leymus chinensis*, and the perennial bunchgrass *Stipa grandis* (Bai et al., 2004). The average temperature in the region is 0.9 °C. Mean annual precipitation is 329 mm (1982–2010), with the highest values in the summer from June to August. The variations of temperature and precipitation during our experimental years are shown in Fig. 1. The annual effect of precipitation was determined by using effective annual precipitation (previous-year September to current-year September) instead of using calendar annual (January to December) sums (Ren et al., 2012). The vegetation period lasts for approximately 150 days from April to September. The predominant soil types of this region are calcic chestnuts and calcic chernozemes, which cover acid volcanic parent rock. Soil texture is highly susceptible to wind erosion because it is dominated by fine-sand loess, mainly derived by deflation (Hoffmann et al., 2008).

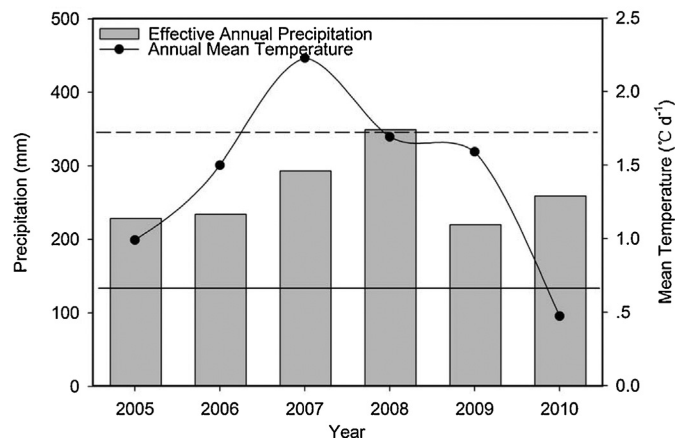

Fig. 1. Effective annual precipitation rates (previous-year September to current-year September) (left *y*-axis) and annual mean temperature (right *y*-axis) from 2005 to 2010. The horizontal dashed line denotes the 20-year (1983–2004) mean effective annual precipitation of 343 mm, and the horizontal solid line denotes the 20-year mean annual temperature of 0.7 °C (Ren et al., 2012).

2.2. Experimental design

A 160 ha sized grazing experiment was established in 2005 and lasted for 6 years. The grazing experiment is described in detail by Schonbach et al. (2011). Until 2003 the area had been heavily used for sheep grazing, after which the grass swards were given a 2-year recovery before the experiment started. The original grazing experimental site covered a total area of 160 ha and was divided into 2-ha paddocks. For the present study, we selected 12 plots, covering a total of 24 ha. The plots were arranged in a split-plot design with two management systems (i.e., continuous grazing vs. mixed grazing system) and three levels of grazing intensity (GI) with two replicates as blocks differing by topographic position (one level block and one sloping block). The continuous grazing system was grazed in each year during the vegetation period (June–September). The mixed grazing system was managed by annual alternations between grazing and hay making. In the present study, the grazing system included ungrazed (GI-0), light (GI-2) and heavy (GI-5) grazing intensity. Stocking rates (i.e. 0, 3.0, and 7.5 sheep/ha) and herbage allowance were used to classify GI (Schonbach et al., 2011, it referred to another set of field experiment). Herbage allowance was calculated as the amount of available aboveground standing biomass for sheep grazing at any point in time during the grazing season (Sollenberger et al., 2005; Schonbach et al., 2011). For the present study, field sampling and measurements were carried out in the fourth (2008) and the sixth year (2010) of the grazing experiment. The fences were set in the beginning of the experiment in 2005. After spatial biomass distribution analysis in 2008, marks were made for all patches. We chose the fences according to the marks we made in 2008. According to the results of spatial biomass distribution, patch vegetation patterns were observed among grazing intensities in different grazing systems. Three types of patches (i.e., grazed (G), rejected (R) and fenced (F) areas) were chosen in both systems in 2008 and in 2010 (Fig. 2), with the fenced area set on part of the grazed area identified from the biomass distribution maps in 2008. Further plant and soil variables were tested under each patch in this system in order to analyze grazing pattern effects.

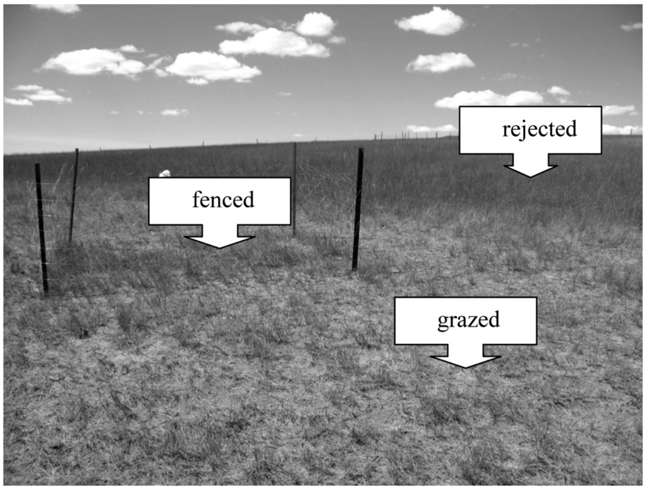

Fig. 2. Schematic figure of sampling design for fenced area (F), grazed area (G) and rejected area (R). The fenced area was set on part of the grazed area.

2.3. Spatial biomass distribution

Fig. 3 shows the layout of sampling plots in experimental area. The sampling plots are randomly distributed with true replicates. Spatial biomass distribution semivariograms in short range (<50 m) and long range (<200 m) were used to deduce grazing behavior. At the peak biomass period in mid-August of 2008 and 2010, the aboveground biomass was measured in continuous and mixed grazing system at three levels of GI (i.e., ungrazed (GI-0), lightly grazed (GI-2) and heavily grazed (GI-5)). To outline the spatial structure in small-scale regular orthogonal grids, 200 points were measured with a spacing of 20 cm within a 10 m × 10 m grid in each 2 ha-sized plot. The biomass was quantified five times by measuring height in each grid point with a 20 cm diameter rising plate meter (GRASTEC) (the diameter is 20 cm) and a mean value was calculated for that point. A calibration equation (1) was used to quantify the linear relationship between aboveground standing biomass (g DM/m^2) and sward height (H) (Schönbach et al., 2008; Hakl et al., 2012). The semivariograms show the heterogeneity of vegetation under different grazing intensity in two systems (Fig. 4). Each plot had its own characteristics depending on variations in soil, topography, shape, infrastructure (Auerswald et al., 2010), and presumably even rain (Auerswald et al., 2012). In order to extract the pattern properties that were caused by the grazing system (mixed vs. continuous) and grazing intensity (GI-0, GI-2, GI-5), all plots and years had the same grazing system and intensity were pooled (Voltz and Webster, 1990). Hence six experimental semivariograms (2 systems × 3 intensities) resulted where each was calculated from eight pooled measuring campaigns (4 plots × 2 years).

$$\mathrm{DM}\quad [\mathrm{g\ m^{-2}}] = 22.61 \times H - 5.15 \qquad (1)$$

2.4. Patch analysis

Based on biomass distribution results of grazing patch patterns under different grazing intensities in two grazing systems in 2008 and 2010, a detailed sampling was undertaken in the last experimental year 2010. A randomized block design was applied. In each of two blocks (flat and slope) with lightly grazing intensity three patches were chosen: grazed (G), rejected (R) and fenced (F) (Fig. 2). The fenced 2 ha plots which were set at the beginning of the grazing experiment in 2005, were arranged using exclosure cages and selected locating on grazed areas representing undisturbed aboveground biomass. The size of each sampling quadrat was about 2 m × 2 m. For all patches three or four replications were randomly arranged within each plot. The spacing among sampling quadrats was about 10 m. In the semivariograms, the short

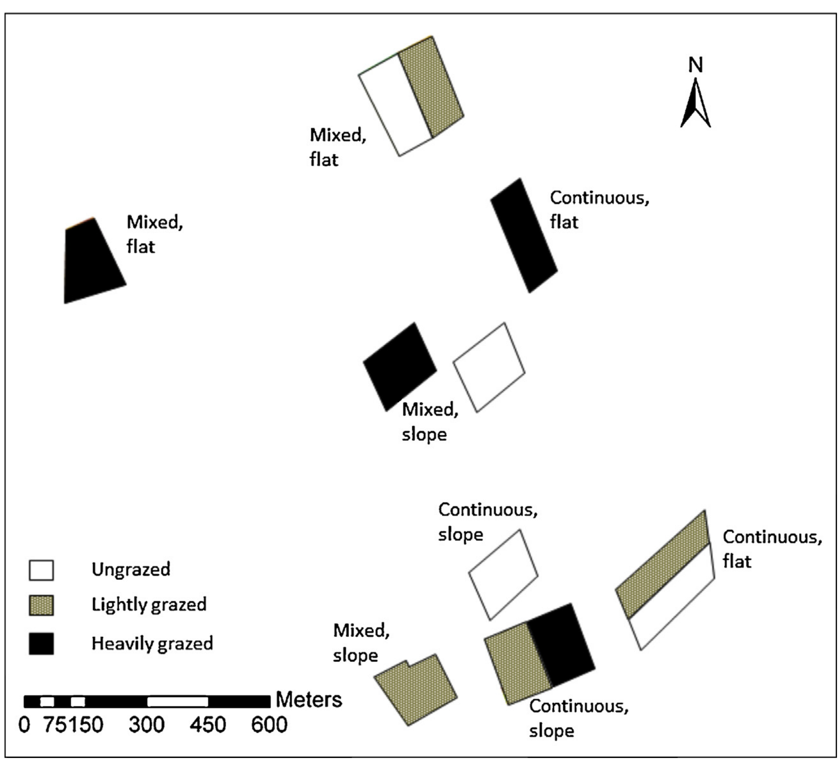

Fig. 3. The layout of sampling plots in experimental area. Mixed and continuous represent mixed grazing system and continuous grazing system. Flat and slope are two blocks which differ in topographic position.

range (<50 m) variation and the long range (<200 m) variation were shown. This characterized the patchiness of the grazed area. This may (especially for low grazing intensities) also include areas that are more or less completely avoided for grazing (e.g., narrow corners, plot border close to disturbances like frequently used roads). In consequence, a second process may shape those long-range semivariograms that may lead to nested semivariogram models (for theory of nested variogram models see Taylor and Burrough, 1986). Starting from the middle of June, the species sward height in each patch was measured every 2 weeks using a rising plate meter and transformed to aboveground biomass production as outlined in Eq. (1). Number of bunches and the mean and maximum height of the species were recorded. At peak biomass period in mid-August, soil coverage was estimated visually and the litter was combed out and weighed. Then the number of species in the patch was counted as richness and the total standing aboveground biomass was clipped to 1 cm height inside 0.5 m^2 rectangular transects (0.25 m × 2 m) and separated by species, and taken back to laboratory for dry matter determination after drying at 60 °C for 24 h. The necrotic biomass was also weighed. Nutritive value for each species was analyzed using the Near-Infrared-Spectroscopy (NIRS) technique. The species nutritive value included the following parameters: organic matter (OM), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), cellulase digestible organic matter (CDOM) and metabolizable energy (ME). Soil water content was analyzed every 2 weeks at six depths (0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm) from the middle of June to the middle of August. In mid-August, the root biomass in a 0.25 cm^2 transect drill was collected, dried and weighed in all six soil layers. Soil total C and N content was measured at 0–10, 10–20 and 20–40 cm depth in mid-August. Topsoil (1–5 cm) temperature was measured at sunny noon. The variograms between patch size and semivariance were used to analyze the degree of spatial autocorrelation of biomass distribution.

2.5. Statistical analysis

Geostatistical simulation with Arc GIS 9.2 software (ESRI, Redlands, USA) and geostatistical analysis with R 2.14.0 (Vienna, Austria) were applied to detect grazing patterns across three grazing intensities and between two different grazing systems. The experimental semivariograms were calculated with geostatistic (Pebesma and Gräler, 2015) in the R environment. Variograms are distance-type structure functions, which were used to determine the degree of spatial variability. Spatial autocorrelation is the technical term for the fact that spatial data from near locations are more likely to be similar than data from distant locations (O'Sullivan and Unwin, 2010). The variogram is calculated as in Eq. (2). The geostatistical analysis and the variograms employed height data from the 10 m × 10 m grid sampled in 2008 and 2010. The variograms between patch size and semivariance were used to analyze the degree of spatial autocorrelation of biomass distribution. Autocorrelation is calculated using (semi)variance $\gamma(h)$, which is calculated as half the average of squared differences between measurements at points separated by the distance interval h:

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

where $N(h)$ is the number of observation pairs separated by the lag distance h and $z(x_i + h)$ is the observed value at a location at distance h from x_i.

An ANOVA with mixed models was used to analyze the data. 'Grazing intensity', 'patch' and their interactions were used as fixed effects, 'block' and 'block × grazing intensity' were used as random effects (SAS Version 9.1, SAS Institute Inc., Cary, NC, USA). Multiple comparisons of means were applied by using Tukey's test. The level of significance was $P < 0.05$.

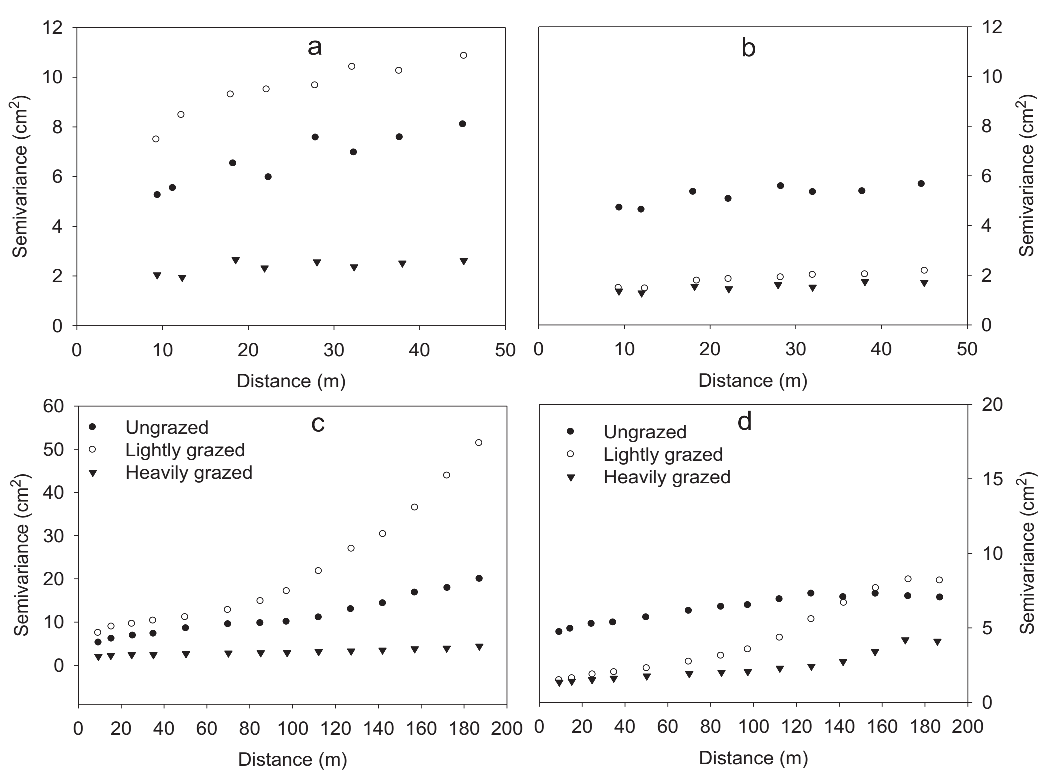

Fig. 4. Semivariances derived from vegetation heights (cm) along with short (<50 m) and long range (<200 m) under different grazing intensities in continuous systems (a and c) and mixed systems (b and d).

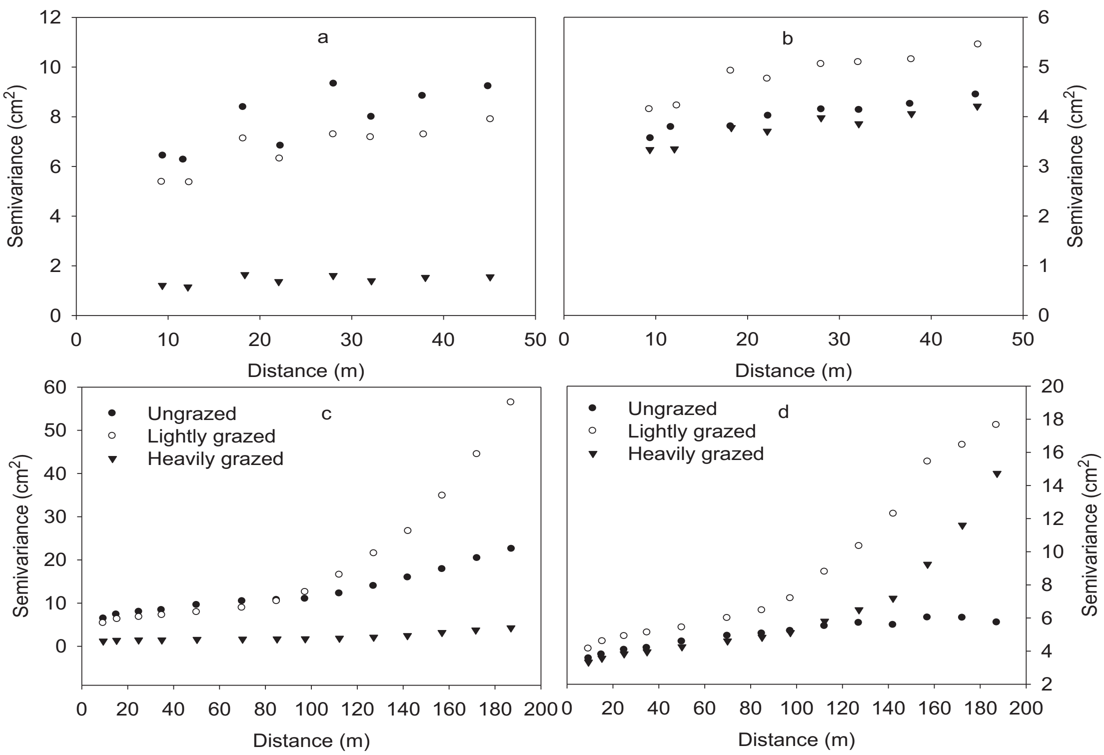

Fig. 5. Semiviariances derived from vegetation heights (cm) along with short (<50 m) and long range (<200 m) under different grazing intensities in 2008 (a and c) and 2010 (b and d).

3. Results

3.1. Biomass distribution semivariograms

In Fig. 4 spatial biomass distribution semivariograms along grazing intensities are shown within two systems. Each semivariance (data point) resulted from 800 to 8000 pairs and can be regarded robust. In short range (<50 m) semivariogram (Figs. 4 and 5a, b). In both grazing systems, the semivariance of ungrazed plots was rather similar (because the system cannot have an influence without grazing). The nugget (small scale heterogeneity beyond resolution of measurement locations) was large (around 4–5) and contributed most to the total semivariance. Only a little linear model was superimposed on the nugget variation (slightly more in the plots, which were assigned to the continuous system). This indicated that variation caused by soil, topography, etc. that may create a gradient was rather unimportant. With heavy grazing intensity, the semivariance was greatly reduced (to about 1/3 of GI-0) because the intensive grazing caused a very short canopy in which height differences also can only be small. Both grazing systems behaved practically identical, indicating that the influences of the previous season (in which the management of both systems was different) were not important under heavy grazing. Practically all variations could be attributed to the nugget, which was superimposed by a small linear gradient.

With light grazing (GI-2), the picture changed pronouncedly. In the mixed system the grass had been cut in the previous year and thus the entire area was rather homogeneous regarding height and age of the vegetation cover at the onset of grazing. This caused the grazed areas (on this scale) to be grazed homogeneously by the sheep and in consequence, semivariance was similar to the heavily grazed plots. For the continuous system, the area started already heterogeneously with stubble of varying height left over from the previous year(s), which then caused spots that were avoided for grazing in the following year(s) in close neighborhood to heavily grazed areas. This caused a spherical model to be superimposed on the nugget. The range of the spherical model was about 20 m, which quantifies the maximum size of the heavily/lightly grazed areas. Patch grazing pattern was more clearly displayed in the continuous system than in the mixed system. In the long range (<200 m) semivariogram (Figs. 4 and 5c, d), for ungrazed plot GI-0, the semivariograms for larger distances essentially remained similar to those of short distances. Again most of the variation was caused by the nugget and the mixed and the continuous system were rather similar. Only the plots assigned to the continuous system exhibited a small long-range trend that may result from differences in soil or rain. The patch pattern caused by plot properties that are not influences by grazing system or grazing intensity remained rather small and should not blur the grazing effects. For heavy grazing plot GI-5, the semivariograms for larger distances essentially remained similar to those of short distances. The semivariance was much smaller than for GI-0 and mainly caused by the nugget. Only for the mixed system there was a small increase for large distances which, due to its small effect, was difficult to assign to either site properties or grazing.

The semivariograms for light grazing plot GI-2 differed largely from the other two cases. For both systems, a pronounced increase in semivariance started at a distance of about 100 m. This indicated that with low grazing pressure only the central part of the plots was intensively grazed while the areas in corners or close to the fence were avoided by grazing and thus developed contrasting vegetations heights. This contrast caused by areas avoided for grazing was much more pronounced in the continuous system, where the contrast will build up over years. Especially the dry and rigid stems from the previous year will lead to high vegetation heights when measured as compressed height that also reflects rigidity of the vegetation cover. In the mixed system that had been cut in the previous year, these carry-over effects could not evolve and especially no old and dry stems were present. In consequence, the semivariance for a lag of 180 m was only 8 cm^2 (corresponding to a

Table 1
The area conditions under light grazing intensity in the continuous system in 2008 and 2010.

Year	Richness	ANPP (g DM)	CP (% DM)	Ave height (cm)	Max height (cm)	Sampling size (m^2)	G patch (%)	UG patch (%)
2008	11a	249.8a	11.11a	10.5a	25a	2 × 2	37.5a	10.8a
2010	9a	203.8b	10.51a	9.2b	20b	2 × 2	37.9a	11.9a

The abbreviations are: ANPP (aboveground net primary productivity), CP (crude protein), Ave height (average height), G (grazed), UG (ungrazed).
Means with different letters within each row are significantly different ($P < 0.001$).

standard deviation of about 3 cm) for the mixed system while it was 51 cm^2 (corresponding to a standard deviation of about 7 cm) for the continuous system. Nevertheless, both values were far above the respective values for heavy grazing plot GI-5. In the continuous system and GI-2 the increase in semivariane for distances larger than 100 m was especially pronounced in 2008 (Fig. 5c, d). In 2010 the thick snow cover during the winter 2009/2010 had flattened the old stems and thus reduced the carry-over effects similar to the conditions as in the mixed system. This lead to a semivariance for a lag of 180 m of only 24 cm^2 (corresponding to a standard deviation of about 5 cm) in 2010, which was already close to the values found for the mixed system, while in 2008 the semivariance was even 78 cm^2 (corresponding to a standard deviation of about 9 cm) for this distance. The grazed and ungrazed patches were repeated observed in the same location in different years (distribution map not shown). Table 1 shows that in these 2 years, grassland productivity, forage nutrient value (e.g. crude protein) and plant species height (average and maxima) were all higher in the wet year (2008) than in dry year (2010). However, species richness, sampling quadrat, the percentage of grazed and ungrazed patches did not show differences (Table 1).

3.2. *Response of plant and soil traits in the continuous grazing system in 2010*

In the experimental year 2010, the effects of grazing intensity, patch type and their interactions on plant species and soil traits were tested (Table 2). The species aboveground biomass, root biomass, soil total carbon content from 0 to 40 cm, soil temperature at 5 cm depth, soil water content and richness were affected by grazing intensity ($P < 0.05$), with a negative relationship between grazing intensity and plant and soil parameters, except soil temperature. Species total aboveground biomass, necrotic biomass, litter biomass, root biomass, richness, and the biomass of the dominant species (*L. chinensis*, *S. grandis*, *Cleistogenes squarrosa*) and their crude protein (CP) content and neutral detergent fiber (NDF) content, as well as the percentage of exposed bare soil, soil temperature from 1 to 5 cm, and soil water content were all strongly affected by patch type ($P < 0.001$) in the pattern. The rank order of species CP content was fenced > grazed > rejected grazing patch. Plant root biomass, soil total nitrogen and total carbon content from 0 to 40 cm depth were not affected by patch type. There was no interaction effect of grazing intensity and patch type on all the above mentioned parameters (Table 2).

Table 3
The mean (±S.E.) ($n = 10$) temperature (T) of topsoil (0–1 cm and 0–5 cm) in two patch types.

PATCH	Soil T (°C) 1 cm	Soil T (°C) 5 cm
G	35.4 ± 0.41^A	30.8 ± 0.44^A
R	30.3 ± 0.41^B	25.1 ± 0.44^B

Means with different superscript letters within each row are significantly different ($P < 0.001$).
Grazed area (G), rejected area (R).

The soil temperature at 1 cm and 5 cm depth was significantly lower by more than 5 degrees in rejected areas compared to grazed areas (Table 3). Species aboveground biomass, richness and the biomass of dominant species (*L. chinensis* and *S. grandis*) had their highest values in the rejected area and lowest values in the grazed area (Fig. 6), while there was an opposite relationship between patch type and bare soil ratio. In rejected areas, the bare soil was less than 2%, but in grazed areas, around 60% was bare soil. The biomass of *C. squarrosa* in the fenced areas was higher than in the rejected areas. The biomass of necrotic materials followed the order: rejected area > grazed area > fenced area. Litter biomass and soil water content were both higher in the rejected areas than in the other two areas. The litter biomass in the rejected area was tenfold

Table 2
F-values statistics for the effect of grazing intensity (GI) and patch (p) type on plant species and soil parameters.

GI	AB (g DM/m^2)	Necrotic (g DM/m^2)	Litter (g DM/m^2)	*L.ch* (g DM/m^2)	*S.gr* (g DM/m^2)	*C.sq* (g DM/m^2)	RB (g DM/m^2)	CP_{Ley} (% DM)	CP_{Sti} (% DM)	NDF_{Ley} (% DM)	NDF_{Sti} (% DM)
GI	4.1^{*}	1.9 ns	1.6 ns	1.1 ns	1.9 ns	1.8 ns	3.2^{*}	0.8 ns	2.2 ns	0.1 ns	0.9 ns
PATCH	43.7^{***}	299.3^{***}	122.7^{***}	12.7^{***}	10.4^{***}	12.8^{***}	2.5 ns	92.5^{***}	59.0^{***}	33.7^{***}	42.9^{***}
GI × PATCH	1.3 ns	0.8 ns	1.9 ns	0.5 ns	0.9 ns	0.8 ns	1.8 ns	0.7 ns	2.1 ns	0.4 ns	1.4 ns
GI	Ntot (%) 0–10 cm	Ntot (%) 10–20 cm	Ntot (%) 20–40 cm	Ctot (%) 0–10 cm	Ctot (%) 10–20 cm	Ctot (%) 20–40 cm	Bare soil (%)	Soil T (°C) 1 cm	Soil T (°C) 5 cm	SWC (%) 0–100 cm	Richness
GI	5.4^{**}	6.0^{**}	0.8 ns	4.6^{**}	3.5^{*}	6.0^{**}	2.8 ns	0.7 ns	3.8^{*}	3.1^{*}	3.3^{*}
PATCH	1.1 ns	0.1 ns	0.2 ns	1.6 ns	0.1 ns	0.0 ns	109.2^{***}	79.7^{***}	84.9^{***}	8.4^{***}	22.7^{***}
GI × PATCH	0.1 ns	0.4 ns	0.3 ns	0.1 ns	0.2 ns	0.1 ns	0.8 ns	0.7 ns	0.4 ns	0.1 ns	1.4 ns

The abbreviations are: DM (dry matter), AB (aboveground biomass), RB (root biomass), *L.ch* (*Leymus chinensis*), *S.gr* (*Stipa grandis*), *C.sq* (*Cleistogenes squarrosa*), CP (crude protein), NDF (neutral detergent fiber), Ntot (nitrogen total), Ctot (carbon total), T (temperature), SWC (soil water content).
Root biomass was sampled in six layers (0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm). Only biomass in the first layer (0–10 cm) is shown here, as the other layers had no significant responses.
SWC was sampled in six layers (0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm), and all layers showed the same response, so the table shows the average value across layers.
* $0.01 < P < 0.05$.
** $0.001 < P < 0.01$.
*** $P < 0.001$.
ns indicates not significant, $P > 0.05$.

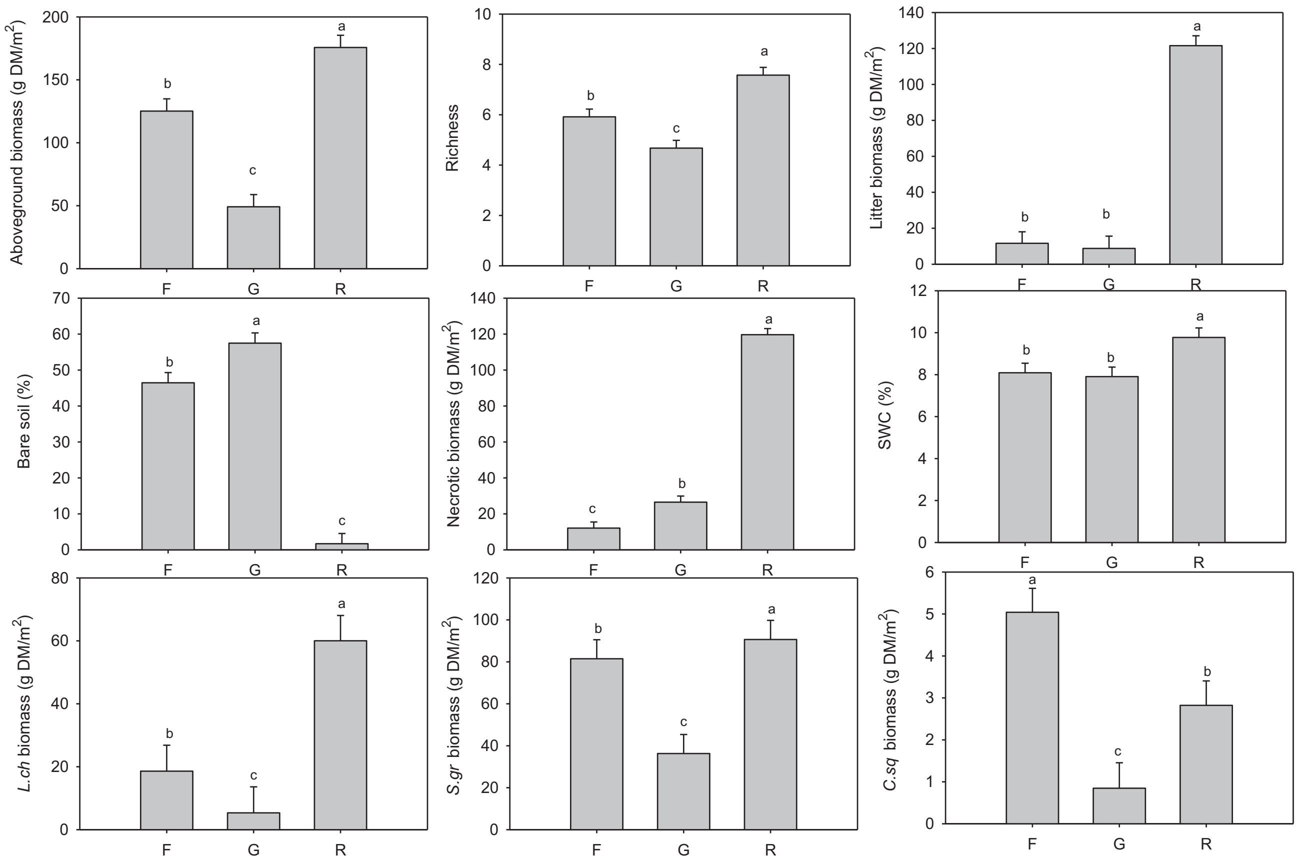

Fig. 6. Effect of three patch types in the continuous grazing system on plant species and soil traits in 2010. Fenced area (F), grazed area (G), rejected area (R), SWC (soil water content). *L.ch* (*Leymus chinensis*), *S.gr* (*Stipa grandis*), *C.sq* (*Cleistogenes squarrosa*). Vertical bars indicate standard errors of the mean ($n = 96$). Different letters represent significant differences among treatments (Tukey's test, $P < 0.05$).

higher than in the grazed and fenced area. There were no significant differences in litter biomass and in soil water content between fenced areas and grazed areas. The necrotic materials included partial green leaves or stems, and thus this measure is not exactly the same as litter biomass.

Patch structure had significant effects on species nutritional value (Fig. 7). The dominant species, *L. chinensis* and *S. grandis*, showed the highest CP content and the lowest NDF content in the fenced area. The fenced area was located in the grazed area, so the species composition was the same, and the species nutritional value in the fenced area was also the same as that in the grazed area. Thus the grazed areas provided preferable feeding materials compared to the rejected areas. Following the livestock's track, the lowest nutritional value was observed in the rejected area, which fits with knowledge of livestock selective eating behavior.

4. Discussion

4.1. Effects of grazing intensity and patch types on spatial biomass distribution

A heterogeneous spatial pattern of vegetation biomass was observed in lightly grazed plots in the continuous system. In the heavily grazed and ungrazed plots, as well as in the mixed system, the biomass of vegetation tended to have a homogeneous spatial distribution. Wiesmeier et al. discussed several processes to account for the homogeneous distribution of biomass and soil in ungrazed and heavily grazed grasslands. Firstly, the ungrazed plots recovered from grazing pressure since 2003 and showed ensured vegetation restoration and homogenization. By contrast, in the heavily grazed plots, because of the heavy feeding burden from livestock, vegetation tended to have no patches and showed a very even distribution of low biomass. As reported by Wiesmeier et al. (2009), overgrazing leads to a homogenization of soil organic matter, bulk density and heterogeneous vegetation, and some vegetation patches were removed. Barnes et al. (2008) also suggested that grazing distribution can be more even under intensive rather than extensive management.

However, in the lightly grazed plots in the continuous system, patch grazing pattern contributed to a heterogeneous spatial distribution of vegetation biomass. This finding, confirmed by many previous studies, resulted from the selective feeding behavior of herbivores and their habitual behavior (Teague and Dowhower, 2003; Dumont et al., 2012). Under light grazing intensity, forage availability is sufficient for livestock to graze selectively, and herbivores such as sheep may be able to remember the sites from where they previously had benefited more, returning to these areas regularly (Dumont and Petit, 1998; Dumont et al., 2002). According to optimal foraging theory, herbivores have efficient strategies to obtain preferred resources (Ritchie, 1998; Dumont et al., 2002). As in our study sheep were able to identify patches with high nutritional value. The grass in the grazed patches regrew and therefore offered younger and more digestible materials than in the other areas, and thus the sheep returned to the area they had previously grazed. Our results also showed that the forage in fenced areas, which were located within grazed areas and can be taken to represent the herbage ingested by sheep, has higher nutritional value than that in the rejected areas, where grass was getting older and more unpalatable. Forage with high crude protein and low fiber content produces better digestibility and more energy for sheep

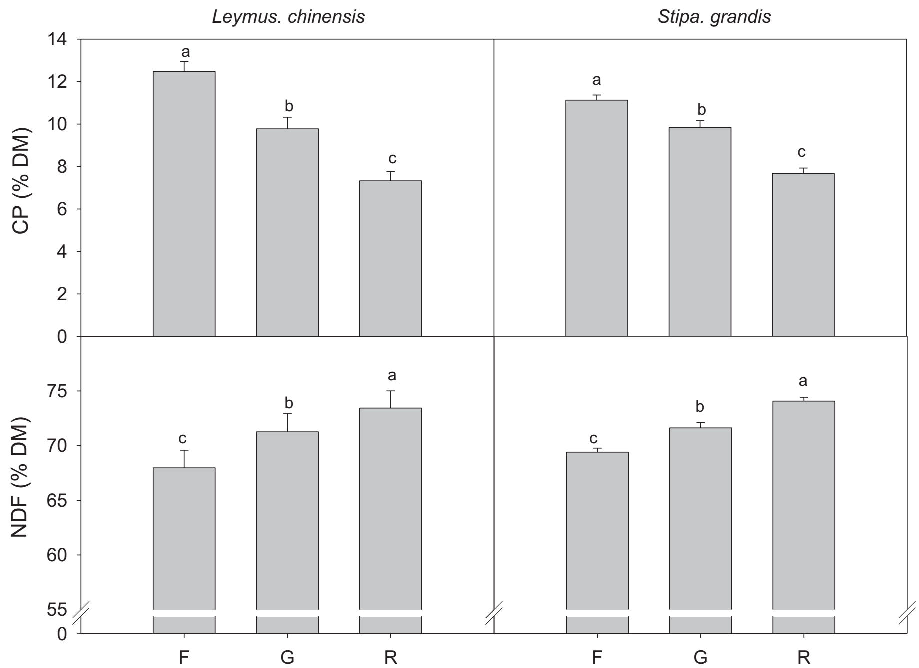

Fig. 7. Effects of three patch types on nutritional value of *Leymus chinensis* and *Stipa grandis*. Fenced area (F), grazed area (G), rejected area (R), CP (crude protein), NDF (neutral detergent fiber). Vertical bars indicate standard errors of the mean ($n = 96$). Different letters represent significant differences among treatments (Tukey's test, $P < 0.05$).

(Schonbach et al., 2009, 2012). Therefore the responses of herbivores to the particular nutrient qualities of the forage resources may be the major reason for the formation of patchy grazing patterns. The selective grazing of herbivore may depend on the nutrient quality of herbage, rather than a species-determined selection process, which depends on the feed on offer. With enough herbage offered under light grazing intensity, herbivores may graze more high nutrient forage. With repeated grazing, the preferred patches become more apparent due to regrowth of young plant species material. In addition, sheep exhibited a preference for previously grazed plants and areas, not only related to their nutritional status, but also to habitual behavior, as evidenced by the presence of trails related to presence of water and shade, and also for plants they have grazed before (O'Connor, 1992). Their preference for certain species is partly due to previous experience and what they have learned (Villalba et al., 2015). In our study, the individual sheep in the grazing flocks in 2008 and 2010 were completely different, which may indicate that sheep has a strong ability to identify good forage quality patches, rather than indicating that sheep retained a memory for previously grazed sites.

A contrary point of view might consider that the patchy structure owing to sheep behavior may lead to dysfunctional territorial differentiation, and finally affect the niche differentiation of the whole grassland ecosystem. Our results showed that aboveground biomass, necrotic biomass, litter biomass, dominant individual species biomass and species richness and soil water content decreased in grazed areas, whereas bare soil coverage increased (Fig. 6). This is similar to other authors who showed strongly negative effects from heavy grazing pressure, as indicated by high soil temperature, low productivity and soil coverage, and a tendency toward degradation (Zhao et al., 2007; Hoffmann et al., 2008; Zuo et al., 2008; Schonbach et al., 2011). Also in our study soil surface temperatures were lower in rejected areas than in grazed areas. This may because the vegetation above dry soil in grazed areas has less coverage (Jia et al., 2006). Higher surface temperatures and radiation probably favor the microbial degradation of soil organic carbon. However, our results confirmed that there was no significant difference in soil carbon storage among patches. And the geostatistical spherical model was about 20 m, which quantifies the maximum size of the heavily/lightly grazed areas. Therefore, the grazed patches are still likely not affected strongly enough to cause soil erosion and further degradation. Taking all negative environmental effects of patches into account, it indicates that light grazing does not necessarily imply an optimum intensity for sustainable grassland utilization since degraded areas and soil erosion could develop. Although some studies have explored the role of moderate stocking rates in maintaining grassland ecosystem balance (Schonbach et al., 2009; Wiesmeier et al., 2009), our result suggests that herbivore behavior and plant–herbivore interactions have to be taken into consideration.

On the other hand, previous studies have also shown the effects of vegetation patches on soil organic materials and biomass density by the formation of resource islands with the accumulation of water and nutrients under ungrazed sites (Garner and Steinberger, 1989; Bhark and Small, 2003). However, the heterogeneous vegetation due to patch grazing may lead to divergent species composition dynamics. Species richness in the rejected areas was higher than in the fenced areas, and much higher than in the grazed areas. Patchy grazing patterns may create feasible conditions for restoring biodiversity in fertile grasslands, where 'parent' areas exist for seed production of species to be transported by vectors into formerly intensively grazed areas. The rejected grazing areas may include more grazing-resistant species, whereas the high species richness in the fenced exclosure within the grazed area indicates the rich seed bank under the grazed area, since grazing in the whole experimental site has lasted for 6 years. These grazed areas may store more potential species that are not resistant to grazing but that have an opportunity to recover from grazing. Thus, in our 6 years study, when degraded grassland begins to recover after overgrazing, a patchy grazing pattern may help in rapid grassland recovery and optimizing ecosystem functioning by forming water and nutrient resource islands. Some other studies have also concluded that the productivity of patchy grassland is better than that of non-patchy grassland (Dumont et al., 2002; Wiesmeier et al., 2009). Precipitation run-off from bare soil patches to vegetation patches enhances primary production in vegetation patches (Ludwig et al., 1999). Run-off areas allow the run-on sites to receive a higher level of rainfall input, and thus achieve greater plant production and sustain vegetation. Thus, heterogeneous vegetation patterns play essential roles in resource (water) limited grasslands. Although our study focused on grassland ecosystem, the resource islands with the accumulation of water and nutrients were formed in the same mechanism as reported in the study by Ludwig et al. (1999). That study was at different scales (field scale 120 m × 150 m or plant scale 2 m × 2 m) from our study (10 m × 10 m), and suggests that grazing patch patterns may help ensure the sustainability and productivity of grasslands at different scales.

4.2. Effects of year on spatial biomass distribution

The persistent patchy grazing pattern between years under light grazing intensity is in agreement with our hypothesis that vegetation patches persist over years. In 2010, the thick snow cover during the winter from the previous year had reduced the carry-over effects by flattening the old stems. Therefore the semivariance for a lag of 180 m in 2010 was much smaller than in 2008 for this distance. With respect to the cumulative effect from a series of dry years on the data collected in 2008, the directional trends in the biomass for different species were tested (Ren et al., 2012). Owing to the weak correlation between species biomass and annual precipitation, the trends of species biomass over time may not be attributed to the continued effects of persistent drought. Even though precipitation increased from the experimental year 2005 to an average level in 2008, species biomass still did not show significant increase with higher precipitation. No matter whether in a wet year or in a dry year, the percentages of grazed and rejected grazing areas were relative consistent, and patch proportion, species composition and diversity did not extend or reduce. This indicates that patchy grazing changes vegetation structure and microenvironment but may not damage grassland by causing soil erosion or further degradation in short time span. As reported, even small grass tussocks can act as a microenvironment and accumulate water, seeds, litter and other organic materials beneath their canopy (Hook et al., 1991). The lasting patch grazing pattern within years is likely to maintain the functioning of a semi-arid grassland ecosystem in the short term.

4.3. Effects of management system on spatial biomass distribution

When comparing grazing patterns under light grazing intensity in the mixed grazing system and the continuous grazing system, the more pronounced patchy pattern in the latter system suggests that continuous light grazing is responsible for a significant progressive differentiation of grazed and rejected patches, which may affect the homogeneous structure of the community and the natural balance of ecosystem functioning. By contrast, in the mixed grazing system, the annual interval from grazing allows time for vegetation regeneration. After cutting for hay making, the entire area was rather homogeneous regarding height and age of the vegetation cover at the onset of grazing. Sheep are unlikely to distinguish grazed and ungrazed areas, because the sheep have no reason to select between young grass areas of even quality. Researchers have found that burning grazed grassland will also make it difficult for sheep to return to previously grazed patches. It used to be customary for researchers in southern Africa to regularly burn their grazing-research areas to reduce the persistence of grazed patches, mirroring the practice of pastoralists in the region. Cutting pasture for hay has the same effect. Therefore, the plant community could retain relatively stable vegetation coverage and biodiversity. For the continuous grazing system, the area started already heterogeneously with stubble of varying height left over from the previous year(s), which then caused spots that were avoided for grazing in the following year(s) in close neighborhood to intensively grazed areas. The study by Schonbach et al. (2011) suggested that under light grazing intensity the continuous grazing system showed similar aboveground biomass, litter and soil coverage to the mixed grazing system. Thus, because of the patchy grazing pattern in the continuous light grazing system, this system is more likely to form maintainable ecosystem functioning in terms of higher biodiversity and high productivity patches under rejected grazing hotspots. When both of these systems rest from grazing for a time, the continuous light grazing grassland has a stronger potential to recover faster, since the higher productivity and higher biodiversity patches in rejected grazing areas may tend to extend wider and grow faster. Therefore, the continuous grazing system seems to be more suitable for sustainable grassland management under light grazing intensities, while the mixed grazing system may be a more appropriate strategy under heavy grazing intensity. From a long term perspective, the mixed grazing system may indicate maximum sustainability with high economic and social benefit while not compromising indicators of ecological sustainability.

4.4. Scale of observation

According to our results, continuous grazing with light grazing intensity resulted in a distinct heterogeneous distribution of plant species and soil parameters in a semi-arid grassland in China. Norton (1998) reported very uneven livestock distribution in large paddocks under a continuous grazing system. In our study, after 6 years grazing, around 38% of the whole lightly grazed region was grazed patches. The low value of vegetation cover on a small spatial scale (2 m × 2 m sampling patch within a 10 m × 10 m area) may be not intense enough to cause considerable deterioration processes in the short run. This enables us to discuss appropriate indicators for steppe degradation and desertification and thus to regulate steppe ecosystem function. Some other studies at a field scale (120 m × 150 m) or a plant scale (2 m × 2 m) also assumed a homogeneous availability of vegetation and associated soil properties, which could induce disfunction of the grassland ecosystem (Ludwig and Tongway, 1995; Wiesmeier et al., 2009). Therefore, irrespective of the scale of observation, the spatial patchy distribution of vegetation is a consistent indicator that can be used in evaluating the effect of grazing intensity and management system on the grazing grassland. Because of the heterogeneity observed by our study, the spatial patterns of vegetation height at a small scale (10 m × 10 m) are likely to be an appropriate indicator for identifying strategies to improve grassland management.

5. Conclusions

Both grazing intensity and management system are key factors affecting the spatial distribution of grassland vegetation. Because of patch grazing, vegetation showed a heterogeneous distribution pattern under light grazing intensity in the continuous system. Selective grazing of sheep, which resulted in differences in herbage nutrient quality, enhanced the distinction between grazed and non-grazed patches. The patchy pattern remained stable over 3 grazing years (from 2008 to 2010) and the patches did not tend to increase in size. Under semi-arid climate conditions in Inner Mongolia, the heterogeneous vegetation structure of grazed and rejected grazed patches help in accelerating grassland recovery after over-grazing in the short term by making use of formed water and nutrient resource islands. Compared with a continuous grazing system, the mixed grazing system, with annual alternation between grazing and hay-making, is better able to maintain grassland productivity and biodiversity under heavy grazing intensity, but not necessarily under light grazing intensity. Under light grazing intensity, the continuous grazing system allows a more heterogeneous distribution of vegetation structure, which contribute to sustainable grazing management than in the mixed grazing system. For sustainable grassland development, a suitable scale of observation should be taken into consideration. The grazing pattern of sheep at different scales could affect ecosystem functioning in steppe grassland. Owing to the heterogeneous distribution, the spatial patterns of vegetation height at a small scale can be used as an indicator to guide semi-arid grassland management.

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