Effects of grazing and precipitation on herbage production, herbage nutritive value and performance of sheep in continental steppe

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Abstract

The present study highlights the effects of sheep grazing and precipitation on herbage and animal performance in a grazed steppe of Inner Mongolia. Experimental data were collected during grazing periods of four consecutive years (2005–2008), and effects were analysed across a gradient of seven grazing intensities. Variation in annual precipitation, reflected by the effect of ‘year’, was the major factor affecting herbage; i.e., the production and nutritive value of herbage increased with increasing precipitation. Herbage parameters were also affected by grazing intensity, as herbage production (HP) and herbage nutritive yields decreased, while herbage nutritive values increased with increasing grazing intensity. The grazing-induced decrease in herbage nutritive yields suggests that decreases in HP offset the positive effect of grazing on the nutritive value. Liveweight gain (LWG) was predominantly affected by grazing intensity, as LWG per sheep and per ha decreased and increased, respectively, with increasing grazing intensity. However, responses varied among years: LWG per sheep was maximized by light grazing in the drought year and by moderate grazing the wet year. Our results showed that herbage shortage at high grazing intensities reduces LWG per sheep and thus diminishes responses in LWG per ha. Nevertheless, the highest grazing intensity provides highest animal production per ha in the short term; however, this is not sustainable in the mid- and long term because decreasing HP induces degradation processes. Based on our results, a reduction in grazing intensity that still provides 78% of the maximum LWG per ha meets the requirements of a sustainable grazing management.

Keywords: grazing experiment, grazing intensity, grazing management, herbage quality, Mongolia, net primary production

Introduction

The Inner Mongolian grassland is part of the Eurasian steppe ecosystem and is widely used for livestock grazing, mainly by goats and sheep. Increasing demand for grazing land has resulted in both a reduction in the size of the grassland and the need for it to support more livestock. Since the 1960s, the increasing grazing pressure has led to a substantial reduction in soil cover, and this has initiated degradation processes throughout much of the Inner Mongolian grassland (Wang and Ripley, 1997). Today, most of this steppe ecosystem is overgrazed and shows severe signs of degradation (Ren et al., 2008). Grassland degradation not only affects ecosystem multifunctionality but also imperils the production goals of farmers. For example, overgrazing typically reduces herbage production (HP) (Patton et al., 2007; Schönbach et al., 2009, 2011) and alters species composition (Wang, 2004; Liang et al., 2009), which may constrain performance of grazing livestock. Furthermore, grazing affects herbage nutritive value, either directly through defoliation (Schönbach et al., 2009) or indirectly through changes in species composition (Zhang et al., 2004; Cao et al., 2011). While improved herbage nutritive value has been considered to be a short-term grazing response (Schönbach et al., 2009), possible changes in species composition, such as a shift from high- to poor-quality herbage species, may also follow long-term overgrazing (Christensen et al., 2003;
Zhang et al., 2004). Therefore, grassland ecosystem functioning, as well as livestock production goals, is likely to be impaired by long-term overgrazing. Overgrazing in this region is quite common because the current regional grazing practice is geared to a maximization of animal gains per ha that provide high economic output in the short term. It has been concluded that current regional management practices of Inner Mongolian sheep farmers do not meet the goals of sustainable grassland-based livestock production, as considered from either an ecological or an economic perspective (Ren et al., 2008; Schönbach et al., 2011). The current strategy of farmers to continuously stock the same grassland area year by year with high grazing intensities in combination with relatively low and variable rainfall increases grasslands’ susceptibility to degradation. This impairs the stability and functioning of the grassland ecosystem as well as the stability and productivity of the livestock production system. However, there are few long-term investigations on the herbage-to-animal relationship for this particular agro-ecosystem, and further research is required to develop and provide approaches for sustainable grassland-based sheep farming.

In this study, we aim to identify the effects of grazing intensity and precipitation on the production, nutritive value and nutritive yield of herbage, as well as on the liveweight gain (LWG) per sheep and per ha. In this context, we aim to determine the degree to which the grassland is impeded or promoted in its productivity and quality by different grazing intensities and rainfall conditions. The interaction between herbage, and sheep begs the questions: (i) how does LWG respond to increasing grazing intensity and (ii) does the expected grazing-induced increase in the herbage nutritive value compensate for the expected decrease in HP? Therefore, a controlled grazing experiment with sheep was conducted to analyse grazing effects along a gradient of grazing intensities, from ungrazed to very heavily grazed, over four consecutive years (2005–2008). Our research may result in a recommendation of an optimum or sustainable grazing intensity that avoids overgrazing and grassland degradation.

Materials and methods

Study area

The study area is located approximately 1200 m a.s.l. in the Xilin River catchment, Inner Mongolia, Autonomous Region, China (43°38’N, 116°42’E). Mean annual (1982–2008) precipitation of 335 mm and mean temperature of 0°C characterize the continental and semi-arid climate in this grassland area. About 80% of annual precipitation coincides with highest temperatures in summer (May–August). The growing season lasts for approximately 150 d from April/May to September/October, with the grazing season typically being slightly shorter because early-season grazing (before mid-May) is prohibited in order to protect the grassland. Perennial C3 grasses, such as the rhizomatous species Leymus chinensis Trin. Tzvel. and the bunchgrass Stipa grandis P. Smirn., contributed more than 50% to the herbage dry-matter (DM) yield (Schönbach et al., 2011). Soils are classified as Calcic Chernozems (WRB, 2006), and texture is dominated by windborne debris, mainly fine-sand loess, which is highly susceptible to wind erosion. The experimental area had been used for sheep grazing at a moderately high level of utilization until 2003, and thereafter swards recovered for 2 years before the experiment started in June 2005.

Experimental design

A randomized complete block design was selected to analyse the effects of sheep grazing on HP, herbage nutritive value and herbage nutritive yield, as well as on animal LWG. Experimental grazing periods were geared to the common local grazing season and lasted from June to September for 98, 90, 93 and 94 d in 2005, 2006, 2007 and 2008 respectively. Grazing effects were analysed along a gradient of seven grazing intensities: ungrazed, GI0; very lightly grazed, GI1; lightly grazed, GI2; light-moderately grazed, GI3; moderately grazed, GI4; heavily grazed, GI5; and very heavily grazed, GI6. Grazing intensity was defined by herbage allowance, a herbage-to-animal relationship inversely related to grazing pressure and expressed as kg dry matter (DM) of herbage mass kg–1 liveweight (LW) of sheep at any one point in time during the respective grazing period (Sollenberger et al., 2005). Dedication of herbage allowances and stocking rates to grazing-intensity classes is shown in Table 1. In order to realize the herbage-allowance target ranges (Table 1), herbage on offer was controlled biweekly by estimating herbage mass with a calibrated-height plate meter (Grasstec, Charleville, Ireland) and, if required, sheep numbers were adjusted monthly by using the put-and-take stocking method (Allen et al., 2011).

In total, 14 plots were subjected to the seven treatments, replicated in flat areas and on slopes to account for any difference that might exist between those landscapes. Treatment plots were 2 ha except those of GI1, which were 4 ha in order to accommodate at least six sheep.

Herbage sampling

Before grazing started, three representative sampling areas were chosen on each plot to reflect the sward composition, and within each sampling area, a temporary
movable grazing exclosure cage (2 × 3 m) was set up prior to grazing in June. Successive herbage samples were taken at the beginning of June, July, August and September. Samples were first taken in June directly before exclosure cages were set up and grazing started. All subsequent samples (July, August and September) were taken inside and outside each exclosure cage. Subsequent to each sampling, exclosures were moved to previously grazed locations to account for the herbage growth. Previous-year litter and standing dead herbage was combed out before clipping the standing herbage mass to 1-cm stubble height inside rectangular sampling frames (0.25 × 2 m). The collected fresh material was oven-dried at 60°C for 24 h, weighed and pooled by plot. The herbage mass was sampled inside and outside each exclosure cage to calculate the annual HP by using the difference method:

$$\text{HP} = W_1 + (W_{2u} - W_1) + (W_{3u} + W_{2g}) + (W_{4u} + W_{3g})$$

(1)

where HP is the annual herbage production and $W_i$ is the weight of herbage DM at sample time $t_i$ (i = 1, 2, 3, 4: beginning of June, July, August, September respectively). $W_1$ represents the first sampling prior to initial grazing in each season. Indices u and g for ungrazed and grazed, respectively, represent samples taken inside and outside the exclosure cages. Peak herbage mass represented the GI0 treatment.

For herbage quality analysis, the herbage samples were ground to 1 mm by a Cyclotec 1093 Sample Mill (Tecator AB, Hoegeanaes, Sweden). Herbage nutritive value was determined from samples taken outside the exclosure cages, and data presented are weighted annual averages. The nutritive value of herbage samples comprised concentrations of organic matter (OM), crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), acid detergent lignin (ADL), cellulose digestible organic matter (CDOM) and metabolizable energy (ME). Herbage samples were analysed by using the near-infrared spectroscopy (NIRS) technique. Samples were scanned twice using a NIR-System 5000 monochromator (Perstrop Analytical Inc., Silver Spring, MD, USA) over a wavelength range from 1100 to 2500 in 2-nm intervals. The software NIRS 2 Infrasoft International (ISI, Port Mathilda, PA, USA) was used to scan, process, calibrate and statistically analyse spectra files. Calibration (2005: n = 138, 2006: n = 44, 2007: n = 31, 2008: n = 25) and validation (2005: n = 25, 2006: n = 10, 2007: n = 15, 2008: n = 15) subsets were chosen for chemical laboratory analysis. OM was derived by the difference between dry sample and the residue (ash) after ignition at 550°C. Herbage nitrogen (N) concentration was determined by C/N analysis based on the DUMAS combustion method (Vario Max CN; Elementar Analysesysteme, Hanau, Germany), and thereafter, CP concentrations were calculated (6.25 × N). NDF, ADF and ADL were analysed sequentially according to Van Soest et al. (1991) using semi-automatic ANKOM technology. NDF and ADF were expressed including residual ash, while ADL was

### Table 1

Average herbage allowance in kg dry matter (DM) kg⁻¹ liveweight (LW) and stocking rates in numbers of sheep ha⁻¹ grazing season⁻¹ assigned to herbage-allowance target ranges (TR) and grazing-intensity classification. Data represent seasonal means (±se).

<table>
<thead>
<tr>
<th>Grazing-intensity classification*</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbage-allowance TR (kg DM kg⁻¹ LW)</td>
<td>–</td>
<td>&gt;12</td>
<td>6–12</td>
<td>4–5–6</td>
<td>3–4–5</td>
<td>1–5–3</td>
<td>&lt;1–5</td>
</tr>
<tr>
<td><strong>2005</strong> Stocking rate (sheep ha⁻¹ grazing season⁻¹)</td>
<td>0 ± 0</td>
<td>1±5</td>
<td>3±0</td>
<td>4±5</td>
<td>6±0</td>
<td>7±5</td>
<td>9±0</td>
</tr>
<tr>
<td>Herbage allowance (kg DM kg⁻¹ LW)</td>
<td>–</td>
<td>23±7</td>
<td>7±2</td>
<td>9±0</td>
<td>3±4</td>
<td>5±4</td>
<td>1±6</td>
</tr>
<tr>
<td><strong>2006</strong> Stocking rate (sheep ha⁻¹ grazing season⁻¹)</td>
<td>0 ± 0</td>
<td>1±5</td>
<td>3±0</td>
<td>4±5</td>
<td>6±0</td>
<td>7±5</td>
<td>9±0</td>
</tr>
<tr>
<td>Herbage allowance (kg DM kg⁻¹ LW)</td>
<td>–</td>
<td>20±6</td>
<td>5±4</td>
<td>8±0</td>
<td>1±8</td>
<td>2±8</td>
<td>2±7</td>
</tr>
<tr>
<td><strong>2007</strong> Stocking rate (sheep ha⁻¹ grazing season⁻¹)</td>
<td>0 ± 0</td>
<td>3±0</td>
<td>7±1</td>
<td>2±8</td>
<td>3±6</td>
<td>7±4</td>
<td>9±0</td>
</tr>
<tr>
<td>Herbage allowance (kg DM kg⁻¹ LW)</td>
<td>–</td>
<td>15±3</td>
<td>4±6</td>
<td>4±8</td>
<td>0±2</td>
<td>4±1</td>
<td>0±6</td>
</tr>
<tr>
<td><strong>2008</strong> Stocking rate (sheep ha⁻¹ grazing season⁻¹)</td>
<td>0 ± 0</td>
<td>2±8</td>
<td>5±6</td>
<td>3±1</td>
<td>6±9</td>
<td>0±9</td>
<td>8±4</td>
</tr>
<tr>
<td>Herbage allowance (kg DM kg⁻¹ LW)</td>
<td>–</td>
<td>20±5</td>
<td>6±2</td>
<td>11±8</td>
<td>3±4</td>
<td>5±5</td>
<td>1±1</td>
</tr>
</tbody>
</table>

*Grazing intensity: 0, ungrazed; 1, very light; 2, light; 3, light-moderate; 4, moderate; 5, heavy; 6, very heavy.
†Grazing season lasted 98, 90, 93 and 94 d in 2005, 2006, 2007 and 2008 respectively.
expressed on ash-free basis. In vitro CDOM and ME concentrations were measured by determining the pepsin cellulase solubility of OM (De Boever et al., 1986). According to equations derived by Weissbach et al. (1999) for grass and grass products, crude ash (CA) and non-soluble enzymatic substance (EULOS) were used to calculate herbage CDOM in % of OM (2), CA, CP and EULOS were used for the calculation of herbage ME concentration in MJ kg$^{-1}$ DM (3):

$$\text{CDOM} = \frac{100 \cdot (940 - CA - 0.02EULOS - 0.000221EULOS^2)}{1000 - CA} \quad (2)$$

$$\text{ME} = 13.98 - 0.0147CA - 0.0102EULOS - 0.00000254EULOS^2 + 0.00234CP \quad (3)$$

Herbage nutritive yields were calculated by multiplying annual HP with the concentration of the respective herbage nutritional parameter.

**Animals**

The grazing animals were 15-month-old non-lactating and non-pregnant female sheep of the local fat-tailed breed. All animals had free access to water and mineral lick stones and were subjected to anthelmintic treatment at the beginning of June and once again at the end of July. The average LW of sheep was 31, 34, 32 and 36 kg at the beginning of the grazing season in 2005, 2006, 2007 and 2008 respectively. Six sheep of each plot with similar initial liveweight, defined as ‘core’ sheep, were chosen at the first weighing. The core sheep were kept continuously on the same respective treatment plot throughout the grazing season and were used for the analysis of LWG. Stand-by sheep used for the put-and-take stocking were kept on moderately grazed grassland nearby and were additionally allocated to the plots on demand. Initial liveweight of sheep was determined after a 10-d adaptation period. Weighing of sheep was made on two consecutive days, and the actual animal LW was calculated as an average of these two measurements. Seasonal LWG per sheep (LWG$_{\text{sheep}}$) in g sheep$^{-1}$ d$^{-1}$ (4) and seasonal LWG per ha (LWG$_{\text{ha}}$) in g ha$^{-1}$ d$^{-1}$ (5) were calculated as follows:

$$\text{LWG}_{\text{sheep}} = \frac{LW_{E} - LW_{B}}{d} \quad (4)$$

$$\text{LWG}_{\text{ha}} = \text{LWG}_{\text{sheep}} \times \text{SR} \quad (5)$$

where LW$_{E}$ is the mean liveweight of sheep in each treatment (g sheep$^{-1}$) at the beginning (B) and end (E) of the grazing season, $d$ the number of grazing days and SR the stocking rate (sheep ha$^{-1}$ grazing season$^{-1}$).

**Statistical methods**

A randomized complete block design with two field replicates was applied to analyse the effects of grazing intensity on end-of-season herbage mass, HP, herbage nutritive value, herbage nutritive yield and on animal LWG per sheep and per ha. Data were analysed by ANOVA using the Mixed Model in SAS version 9.1 (SAS Institute Inc., Cary, NC, USA) with an autoregressive covariance structure. ‘Grazing intensity’, ‘block’, ‘year’ and their interactions were considered fixed effects with ‘year’ treated as a repeated effect and ‘grazing intensity × block’ as the subject effect. Multiple comparisons of means were made by Tukey’s test (Steel and Torrie, 1980). Statistical significance was tested at 0.05 level of probability. Simple linear regression analysis in SAS was used to determine herbage-to-precipitation, herbage-to-grazing-intensity and animal-to-grazing-intensity relationships. In order to increase the accuracy of regression analysis, $y$-values were assigned to their actual stocking rate instead of using grazing-intensity classification.

**Results**

**Precipitation**

Mean annual precipitation was 158, 312, 319 and 369 mm in 2005, 2006, 2007 and 2008 respectively. During the experimental period (2005–2008), the variation in annual precipitation was 32%, which noticeably exceeded the long-term variability of 22%. In comparison with the annual long-term average of 335 mm, the experimental period was characterized by drought conditions in 2005, average conditions in 2006 and 2007 and wet conditions in 2008. Growing-season precipitation from April to September was 140, 275, 189 and 316 mm in 2005, 2006, 2007 and 2008, respectively, suggesting that 89, 88, 60 and 86% of the annual precipitation occurred during this time.

**Herbage mass and herbage production**

The effect of ‘year’ accounted for most of the variation in end-of-season herbage mass ($P < 0.001$) and in HP ($P < 0.001$) (Table 2). There was an obvious increase in the mass and production of herbage in years of higher precipitation. Averaged over all grazing intensities, end-of-season herbage mass amounted to 731, 600, 897 and 1403 kg DM ha$^{-1}$ and HP was 1343, 1455, 1709 and 2123 kg DM ha$^{-1}$ corresponding to precipitation rates of 158, 312, 319 and 369 mm in 2005, 2006, 2007 and 2008 respectively. Regression analysis supported the ANOVA results and revealed a positive linear relation-
The effect of ‘grazing intensity’ was well reflected by changes in herbage parameters (Table 2). The end-of-season herbage mass decreased from 1659 kg DM ha\(^{-1}\) at GI0 to 139 kg DM ha\(^{-1}\) at GI6. Thus, herbage removal by sheep was 0, 26, 62, 55, 80 and 92% at GI1, GI2, GI3, GI4, GI5 and GI6 respectively. Herbage production tended to decrease with increasing grazing intensity (\(P = 0.091\)) from 1953 kg DM ha\(^{-1}\) at GI0 to 1057 kg DM ha\(^{-1}\) at GI6. This effect of grazing intensity was supported by the negative linear relationship between HP and grazing intensity (Figure 2).

Herbage nutritive value

The factors ‘year’ and ‘grazing intensity’ strongly affected the herbage nutritive value (Table 2). The among-year variation in the nutritive concentrations of the herbage on offer corresponded well with the annual precipitation rates, i.e., CP concentrations were lowest and highest in 2005 (158 mm) and 2008 (369 mm) respectively (Figure 1). During the drought year of 2005, herbage CDOM concentrations were lowest, while NDF concentrations were highest (Figure 1). The nutritive value of herbage on offer improved with grazing intensity (Table 2), i.e., concentrations of fibre fractions NDF, ADF and ADL decreased, while

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**Table 2** Effects of grazing intensity on end-of-season herbage mass (HM), herbage production (HP), crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), acid detergent lignin (ADL), cellulase digestible organic matter (CDOM), metabolizable energy (ME) and liveweight gain (LWG) per sheep and per ha.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Grazing intensity*</th>
<th>P-values of variables†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YB G I Y</td>
<td>B G I Y</td>
</tr>
<tr>
<td>df</td>
<td>0 1 2 3 4 5 6</td>
<td>s.e.</td>
</tr>
<tr>
<td>HM (kg DM ha(^{-1}))</td>
<td>1659a 1786a 1223ab 628ab 325b 139b</td>
<td>&lt;0.001 0.012 0.009 0.005 0.001 0.019 0.030 0.009</td>
</tr>
<tr>
<td>HP (kg DM ha(^{-1}))</td>
<td>1954a 2106a 1886a 1469a 1332a 1057a</td>
<td>&lt;0.001 &lt;0.001 &lt;0.001 &lt;0.001 &lt;0.001 &lt;0.001</td>
</tr>
<tr>
<td>CP (g kg(^{-1}) DM)</td>
<td>104c 98c 112c</td>
<td>&lt;0.001 &lt;0.001 &lt;0.001</td>
</tr>
<tr>
<td>NDF (g kg(^{-1}) DM)</td>
<td>689ab 698a 696a</td>
<td>&lt;0.001 &lt;0.001 &lt;0.001</td>
</tr>
<tr>
<td>ADF (g kg(^{-1}) DM)</td>
<td>334abc 345a 335abc</td>
<td>&lt;0.001 &lt;0.001 &lt;0.001</td>
</tr>
<tr>
<td>ADL (g kg(^{-1}) DM)</td>
<td>48a 47a 46a</td>
<td>&lt;0.001 &lt;0.001 &lt;0.001</td>
</tr>
<tr>
<td>CDOM (g kg(^{-1}) DM)</td>
<td>607c 602c 607c</td>
<td>&lt;0.001 &lt;0.001 &lt;0.001</td>
</tr>
<tr>
<td>ME (MJ kg(^{-1}) DM)</td>
<td>8.4b 8.2b 8.4b</td>
<td>&lt;0.001 &lt;0.001 &lt;0.001</td>
</tr>
<tr>
<td>LWG (g sheep(^{-1}) d(^{-1}))</td>
<td>171d 285d 460c</td>
<td>&lt;0.001 &lt;0.001 &lt;0.001</td>
</tr>
<tr>
<td>LWG (g ha(^{-1}) d(^{-1}))</td>
<td>–</td>
<td>&lt;0.001 &lt;0.001 &lt;0.001</td>
</tr>
</tbody>
</table>

Within rows, means followed by the same small letters are not significantly different (\(P < 0.05\)).

*Classes 0, 1, 2, 3, 4 and 5 reflect grazing intensities of ungrazed, very light, light, light-moderate, moderate, heavy and very heavy respectively.

†Y, year; B, block; GI, grazing intensity.

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**Figure 1** Relationships between (a) annual precipitation (mm) and herbage production (HP, kg DM ha\(^{-1}\)) and between annual precipitation and herbage nutritive value parameters (g kg\(^{-1}\)), as (b) crude protein (CP), (c) cellulase digestible organic matter (CDOM) and (d) neutral detergent fibre (NDF).
concentrations of CP, ME and CDOM increased with increasing grazing intensity. These effects are also illustrated in Figure 3, showing linear relationships between grazing intensity and CP, CDOM, ME, ADF and ADL and a quadratic relationship between grazing intensity and NDF. The nutritive yields were also analysed by regression analysis with CP, CDOM and ME yields showing inverse patterns compared to the respective nutritive concentrations (Figure 3a–c).

Animal liveweight gain

The treatment effect of ‘year’ strongly affected animal LWG (Table 2). In 2005, 2006, 2007 and 2008, the respective seasonal LWG averaged 74, 80, 87 and 86 g sheep\(^{-1}\) d\(^{-1}\) and 351, 387, 496, 479 g ha\(^{-1}\) d\(^{-1}\), revealing a minimum animal performance and productivity in the drought year 2005. However, the effect of ‘grazing intensity’ was most important in determining LWG per

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**Figure 2** Relationship between grazing intensity (i.e. stocking rate in sheep ha\(^{-1}\) grazing season\(^{-1}\)) and herbage production (kg DM ha\(^{-1}\)). See Table 1 for grazing-intensity classification.

**Figure 3** Relationships between grazing intensity (i.e. stocking rate in sheep ha\(^{-1}\) grazing season\(^{-1}\)) and herbage nutritive values (left y-axis, g kg\(^{-1}\)) and herbage nutritive yields (right y-axis, kg ha\(^{-1}\)): (a) crude protein (CP), (b) cellulase digestible organic matter (CDOM), (c) metabolizable energy (ME), (d) neutral detergent fibre (NDF), (e) acid detergent fibre (ADF) and (f) acid detergent lignin (ADL). Solid lines describe concentrations (•), and long-dashed regression lines describe yields (○) of herbage nutritional parameters. Standard errors reflect the variation among years (n = 4). See Table 1 for grazing-intensity classification. (Herbage nutritive value: CP: y = 5.3X + 93.1, R\(^2\) = 0.5, P < 0.001; CDOM: y = 3.8X + 600, R\(^2\) = 0.3, P < 0.01; ME: y = 0.6X + 82.6, R\(^2\) = 0.2, P < 0.01; NDF: y = -0.8X\(^2\) + 6.3X + 688, R\(^2\) = 0.2, P < 0.05; ADF: y = -2.3X + 343, R\(^2\) = 0.3, P < 0.01; ADL: y = -0.8X + 483, R\(^2\) = 0.5, P < 0.001. Herbage nutritive yields: CP: y = -2.8X + 200, R\(^2\) = 0.1; P < 0.1; CDOM: y = -50.6X + 1252, R\(^2\) = 0.3, P < 0.001; ME: y = -6.9X + 173, R\(^2\) = 0.3, P < 0.001; NDF: y = -64.5X + 1463, R\(^2\) = 0.3, P < 0.001; ADF: -34.2X + 720, R\(^2\) = 0.3, P < 0.001; ADL: y = -5.3X + 101, R\(^2\) = 0.4, P < 0.001).
sheep and per ha \((P < 0.001)\). The daily LWG per sheep was highest for GI2 and GI3. This significantly exceeded the LWG of GI4, GI5 and GI6, with the latter being the lowest performing treatment (Table 2), whereas the LWG per ha increased with grazing intensity and showed its maximum at GI6. However, year × grazing intensity interaction affected LWG per sheep \((P < 0.001)\) and tended to affect LWG per ha \((P = 0.092)\) (Table 2). Therefore, among-year differences in LWG per sheep were significant only between 2005 and 2008 at GI3 (Figure 4). Furthermore, LWG per sheep responded differently to grazing intensity among years, as GI2 performed best in 2005 and 2006, whereas GI3 was best in 2008. In all years, GI6 was the least-performing grazing-intensity treatment (Figure 4). The interactive effect of year × grazing intensity was supported by the results of the regression analysis (Figure 5), as maximum LWG per sheep was associated with a seasonal stocking rate of 1.8 sheep ha\(^{-1}\) in 2005 (which equates to a grazing intensity of GI1–GI2), and with 0.1 sheep ha\(^{-1}\) in 2006 (which equates to a grazing intensity below GI1), but without being significantly correlated in 2007 or 2008. However, averaged over all years, maximum individual LWG was achieved with 3.0 sheep ha\(^{-1}\) grazing season\(^{-1}\) (LWG in g sheep\(^{-1}\) d\(^{-1}\) = 0.6X\(^2\) + 3.8X + 84.5; \(R^2 = 0.3, P < 0.001\)), which is equivalent to GI2. Regression analysis also showed among-year differences in the relationship between LWG per ha and grazing intensity. Grazing-induced decreases in individual LWG resulted in diminishing responses in LWG per ha, as described by significant quadratic correlations (Figure 6). Therefore, maximum LWG per ha was achieved at 7.6, 9.1 and 15.6 sheep ha\(^{-1}\) grazing season\(^{-1}\) in 2005, 2006 and 2008, respectively, which equates with grazing intensities of GI5, GI6 and above GI6. However, in 2007, LWG per ha linearly increased with increasing grazing intensity (Figure 6). Averaged over all years, peak LWG per ha was achieved at 13 sheep ha\(^{-1}\) grazing season\(^{-1}\) (LWG in g ha\(^{-1}\) d\(^{-1}\) = -4.3X\(^2\) + 109.6X – 25.8; \(R^2 = 0.8, P < 0.001\)).
Discussion

Herbage mass and herbage production

Our results suggest that interannual variability in precipitation explained most of the among-year differences in herbage mass and HP, i.e., the mass and production of herbage increased linearly with increasing annual precipitation. Owing to the high variability in precipitation, HP significantly varies among and within years. This poses serious difficulties for predicting the stocking rate in any single year and is thus a major reason for improper grazing intensity. In addition, our results show that the mass and production of herbage is strongly influenced by the intensity of grazing. The end-of-season herbage mass, a useful indicator to test whether the gradient of grazing intensity adequately reflects the grazing pressure, indicated that target ranges of grazing-intensity classification were well achieved (Table 1). Grazing intensity not only affected the mass but also the production of herbage. Owing to the negative linear relationship, as shown in Figure 2, HP decreased with grazing intensity, by 45% from ungrazed (GI0) to very heavily grazed (GI6). This seems to be a common herbage response in this steppe ecosystem, at least in the short term, because plants cannot overcompensate for the grazing- and trampling-induced sward damage (Schönbach et al., 2007; Schönbach et al., 2009, 2011). However, there is an ongoing debate about whether grazing at certain intensity levels holds the potential to increase the primary productivity of grasslands (Noy-Meir, 1993; Patton et al., 2007) or whether grazing generally decreases them. For example, Patton et al. (2007) presented results from a large-scale, 16-year grazing experiment in the prairie of south-central North Dakota, USA, and concluded that light-to-moderate and heavy cattle grazing, respectively, increases and decreases HP. The conclusion those authors have drawn from their study is not necessarily in contradiction to our findings; rather, there are several factors that may influence experimental results, and thus, studies conducted in different grassland ecosystems and under different conditions are not necessarily comparable. Herbage-to-animal relationship is very complex and is strongly influenced by several factors, such as the duration and intensity of grazing, environmental conditions (climate, soil), species composition, HP, herbage nutritive value or the grazing livestock. Therefore, several reasons may possibly explain the varying results, such as grazing livestock used for the experiment (cattle vs. sheep), experimental duration (16 years vs. 4 years), grazing-intensity gradient, experimental location (prairie vs. steppe) or methods used to estimate HP.

Herbage nutritive value

Most of the among-year variation in the herbage nutritive value could be explained by high interannual variability in precipitation. Therefore, annual precipitation rates not only determine the production but also the nutritive value of herbage. The results suggest that increasing amounts of annual precipitation lead to increases in herbage nutritive value (Figure 1). In semiarid grasslands, the plant-available water is closely linked to precipitation, and thus, increased precipitation leads to increased availability of nitrogen to plants because of accelerated mineralization. However, not only the availability of nitrogen but also the capacity of plants to assimilate nitrogen increases with greater moisture levels. Increasing nitrogen assimilation rates with increasing moisture are reported to be causally determined by several mechanisms, such as enzyme activities of nitrogen anabolism, net photosynthetic rate or stomatal conductance (Xu and Zhou, 2006).

The analysed herbage contained more fibre in the drought year of 2005 than in the following years. Moderate water stress is reported to delay plant maturation and causes herbage nutritive values to be maintained at higher levels (Buxton, 1996), but the 2005 drought caused severe water stress resulting in rapid plant maturation (Schönbach et al., 2009). Thus, the severe water stress resulted in fibrous and less digestible herbage in the 2005 growing season, whereas higher precipitation rates improved herbage nutritive values in all post-drought years, presumably as a result of delayed maturation. Owing to low HP in 2005, less necrotic material accumulated, and therefore, the post-drought year of 2006 offered relatively high nutritive values owing to the low proportion of necrotic plant material in the herbage.

The positive effect of increasing grazing intensity on herbage nutritive value is consistent with the findings of previous studies (Milchunas et al., 1995; Pontes et al., 2007; Schönbach et al., 2009) and is explained by several reasons. First of all, permanent intensive grazing decreases the residence time (survival rate) of tissue/leaves in the sward (Parsons et al., 1991) and thus less or even no plant material reached later phenological stages and less organic matter returns (Schönbach et al., 2009). In consequence, the mean age of tissue is lower than under more lenient grazing and thus younger (regrown) plant material contains higher nitrogen but less fibre. According to Volencec et al. (1996), large proportions of herbage nitrogen in grazed grass species are derived from nitrogen reserves mobilized from stem bases or roots to developing shoots and leaves. Grazing-induced reduction in herbage mass may also lead to an improved nitrogen supply of
remaining leaves owing to the higher relative nitrogen uptake (Noy-Meir, 1993). Further positive effects of grazing on herbage CP concentrations are discussed in the literature, including the deposition of animal dung and urine (Kurz et al., 2006). Mineralization rates are typically accelerated when herbivore excreta rather than senescent plant material are deposited on the soil surface, thereby increasing the availability of mineral nitrogen to plants. However, total nitrogen uptakes were negatively affected by grazing, as indicated by inverse trends in grazing responses of CP yields and CP concentrations (Figure 3a), because decreasing HP offsets the positive effect of grazing on CP concentrations. Therefore, HP rather than nutritive values determines nutritive yields.

Decelerated maturation of intensively grazed plants also resulted in less fibrous and ligneous herbage material. Owing to the strong negative relationship between ADL and CDOM (Schönbach et al., 2009), in vitro digestibility of herbage increased with grazing intensity, by 5% from GI0 to GI6. Nevertheless, the decrease in HP resulted in decreasing yields of digestible organic matter with intensified grazing (Figure 3b), because unlimited herbage on offer enables sheep to graze more selectively, not only to select for more palatable species but also to preferentially select for certain plant parts, like the uppermost layer of grass leaves, which contain higher concentrations of CP and less fibre than stems (Smart et al., 2001). The relationship between LWG and herbage allowance showed that this is true only up to a certain level of herbage availability, as animal LWG was impeded both at low levels and at an excessive level of herbage allowance (Animut et al., 2006; Lin et al., 2011). The extension of grazing time leads to an increase in energy expenditure for grazing and walking activities and thus to a reduction in the amount of energy available for growth (Lin et al., 2011), which explains the lower individual LWG of sheep at GI4, GI5 and GI6 compared with GI1, GI2 and GI3 (Table 2, Figure 4). Increases in herbage availability may increase the feed intake (Sun et al., 2008) because unlimited herbage on offer enables sheep to graze more selectively, not only to select for more palatable species but also to preferentially select for certain plant parts, like the uppermost layer of grass leaves, which contain higher concentrations of CP and less fibre than stems (Smart et al., 2001). The relationship between LWG and herbage allowance showed that this is true only up to a certain level of herbage availability, as animal LWG was impeded both at low levels and at an excessive level of herbage allowance (Figure 7). Liveweight gain begins to decrease beyond 15 kg DM kg\(^{-1}\) liveweight, suggesting diminishing effects from the relatively low herbage nutritive value of the very light grazing intensity.

All in all, our results showed that the optimum LWG per sheep was achieved at light to very light grazing intensity, i.e., a herbage-allowance range of 10–20 kg DM kg\(^{-1}\) liveweight (Figure 7), whereas the

**Figure 7** Relationship between herbage allowance [g dry matter (DM) kg\(^{-1}\) liveweight (LW)] and liveweight gain (LWG) of sheep (g sheep\(^{-1}\) d\(^{-1}\)). See Table 1 for herbage-allowance classification.
maximum productivity in terms of animal gain per ha, and thus the highest economic output, was achieved at high or very high grazing intensity owing to increases in stocking rate. Nevertheless, herbage shortage at very high grazing intensity constrained LWG per ha. This diminishing effect was more pronounced in dry years than in wet years.

The grazing intensity plays a major role in determining the profitability and productivity of a livestock grazing system. For example, high grazing intensity generates maximum LWG per ha and therefore may be highly profitable in the short term. However, intensive grazing in the present study as characterized by G15 and G16 can reduce end-of-season herbage mass by more than 80% (Table 2). Such grazing-induced reduction in herbage mass not only alters species composition (see Discussion section on herbage nutritive value) but also reduces soil cover by more than 60%, which can result in wind and water erosion that induce steppe degradation processes (Schönbach et al., 2011). Therefore, grazing-intensity levels of G15 and G16 may provide the highest LWG per ha in the short term but endanger productivity and profitability of the grassland-based livestock system in the long term (Christensen et al., 2003; Kemp and Michalk, 2007). Our results suggest that sustainable grazing should not exceed the moderate grazing intensity of G14 with an average stocking rate of 6.2 sheep ha$^{-1}$ grazing season$^{-1}$. Such intensity still avoids significant reductions in HP and provides 78% of the maximum LWG per ha (Table 2). This corresponds to findings from Kemp and Michalk (2007), who discussed optimum levels of grassland utilization with respect to both production goals and environmental requirements. Therefore, optimum grazing intensity ensuring sustainable grassland and livestock management requires reduced stocking rates at which 75% of the maximum productivity in animal gain per ha could be achieved.

Conclusions

Precipitation was the factor that predominantly determined HP and herbage nutritive value. Herbage parameters were also affected by grazing, as HP decreased and herbage nutritive values increased with increasing grazing intensity. Grazing responses of herbage nutritive yields suggest that improved herbage nutritive values could not compensate for the grazing-induced decrease in HP. Both the amount of precipitation and the intensity of grazing significantly influenced the availability of herbage for grazing sheep and were therefore crucial in determining animal LWG. Our results showed that a shortage of herbage at high grazing intensities resulted in reduced LWG per individual sheep but not per ha. Thus, the highest grazing intensity of those compared here provides the highest animal production per ha in the short term, and this confirms the current grazing practice of local sheep farmers. However, sustainable grassland and grazing management aim to preserve the multifunctionality of grasslands and to satisfy livestock production goals in the long term. Based on our results, a moderate grazing intensity that provides 78% of the maximum LWG per ha meets the requirements of a sustainable grazing management. Nevertheless, the adaptation of a more suitable grazing management system, like alternating grazing and hay making, may increase the production and nutritive value of herbage and thus contribute to a sustainable grassland use in Inner Mongolia.

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References


