Short-term management and stocking rate effects of grazing sheep on herbage quality and productivity of Inner Mongolia steppe

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Abstract.   Degradation and decreasing productivity increasingly demand sustainable grazing management practices within Inner Mongolian steppe ecosystems. This study focuses on grazing-induced degradation processes over a wide range of stocking rates and aims to identify short-term sensitive indicators and alternative management practices. Short-term effects of 2 grazing management systems (Mixed System and Traditional System) and 7 stocking rates (SR0, SR1.5, SR3, SR4.5, SR6, SR7.5, and SR9 for 0, 1.5, 3, 4.5, 6, 7.5, and 9 sheep/ha, respectively) on yielding performance and herbage quality were measured on experimental plots in which moveable exclosures were used on areas chronically grazed by sheep. The experiment was conducted in a typical steppe ecosystem in Inner Mongolia, P. R. China. Results are presented for 2005 and 2006.

Sampling time was the main factor affecting yield and quality. Stocking rate also showed considerable effects on yield. Herbage mass decreased linearly from SR0 to SR9, by 85% and 82% in 2005 and 2006, respectively. Herbage accumulation was also affected by stocking rate, and was highest at SR1.5 and clearly reduced at SR9. Grazing effects on relative growth rate indicated grazing tolerance of plants in the short-term, since up to high stocking rates, relative growth rates remained stable. Precipitation also determined plant responses to increasing levels of grazing. The year of higher rainfall generated higher grazing tolerance of plants and higher herbage growth than the drought year. Despite considerable reduction of herbage mass, consistent short-term responses of herbage quality to grazing in 2005 and 2006 were reflected only in terms of crude protein and acid detergent lignin. Herbage crude protein content was highest at SR7.5 and SR9, while lignin was lowest at SR7.5 and SR9. Neither productivity nor herbage quality was affected by the management system, suggesting that both systems may be applicable on typical steppe in the short-term.

Additional keywords: grazing experiment, grazing intensity, semi-arid grassland, typical steppe, *Leymus chinensis*, *Stipa grandis*.

Introduction

The Xilin River semi-arid grassland is part of the Inner Mongolian typical steppe ecosystem (Kang *et al.* 2007). The high palatability of species makes the typical steppe ideal for grazing and hay making (Wang and Ripley 1997). Despite the relatively high grazing tolerance (Li *et al.* 2008), livestock farming, dominated by sheep and goats, causes serious degradation by substantially reducing canopy cover (Li *et al.* 2000). Consequently, the size and productivity of the typical steppe have decreased since the 1960s (Wang and Ripley 1997; Tong *et al.* 2004). This trend is mainly caused by the intensification and alteration of land use by the shift from semi-nomadic farming systems to intensified settled livestock farming within recent decades. Precipitation, however, is the key factor determining appropriate stocking rate by controlling productivity of semi-arid grasslands (Milchunas and Lauenroth 1993; Xiao *et al.* 1995; Biondini *et al.* 1998; Li *et al.* 2000; Bai *et al.* 2004). Apart from climatic and environmental conditions, management strategies also influence the grazing capacity of steppes. The timing and the intensity of grazing are the most important manageable factors influencing plant response to grazing (Trlica and Rittenhouse 1993). Therefore, alternative management practices must be employed to optimise stocking rate and productivity of the Inner Mongolian steppe ecosystem.

Several retrospective studies describe multiple effects of grazing on herbage in long-term grazed typical steppe (Wang and Ripley 1997; Wang 2004; Yu *et al.* 2004; Li *et al.* 2008).

These studies revealed effects of long-term grazing on herbage and sward structure when considering the history of grazing, which is confounded by the problem of qualitative grazing intensity estimation (Milchunas and Lauenroth 1993; McNaughton *et al*. 1996). Few controlled grazing experiments have been carried out on typical steppe analysing plant responses under controlled stocking rates.

The present study investigates short-term effects of grazing sheep on plant parameters such as herbage growth and herbage quality across a wide range of stocking rates in 2 different management systems. The alternative management system, known as the Mixed System (MS), is proposed to be more productive than the common local management system, known as the Traditional System (TS). Each system included 7 stocking rates and each stocking rate treatment included hay and grazing plots. With MS, pastures and hay making utilisation alternated annually, while with TS, plots were used consistently either for grazing or for hay making. Plots of MS that were assigned for grazing in 2005 were dedicated to hay making in 2006, and *vice versa*. We assume MS to be more tolerant to grazing since the year of hay making may allow plants to recover from grazing stress, which might be particularly obvious under high stocking rates. Furthermore, positive effects of excremental depositions during grazing years may accelerate N cycling (Augustine and McNaughton 2006), and thus N availability could be compensated or even over-compensated in MS. Therefore, nutrient losses caused by herbage removal through hay making might be, at least partly, compensated in MS. Overall we expected to find higher grazing carrying capacity in MS than in TS.

This study also aimed to identify potential indicators which are sensitive in the short-term to overgrazing within the range of stocking rates and management systems used.

Materials and methods

Study area

The study site is located in the Xilin River catchment on the Mongolian plateau, 1200 m above sea level, near the Inner Mongolia Grassland Ecosystem Research Station (IMGERS, 43°38′N, 116°42′E). This part of Inner Mongolia, P. R. China, is characterised by a continental, semi-arid climate, with mean annual (1982–2006) precipitation rate of 334 mm (coefficient of variance, CV = 22%) and mean annual temperature of 0.7°C. Typically, most of the precipitation falls within the growing season, thus favouring productivity of the steppe (Yu *et al*. 2004). Climate data were collected and generated by the IMGERS.

The growing season, characterised by mean monthly temperatures of at least 16°C, lasts for ~150 days from April to September for perennial plant species, whereas annual plants germinate later, typically following the period of highest rainfall in July (Bai *et al*. 2004). The investigated typical steppe ecosystem is characteristically dominated by the perennial rhizome grass, *Leymus chinensis*, and the perennial bunchgrass, *Stipa grandis* (Xiao *et al*. 1995; Bai *et al*. 2004). The predominant soil types of this region are Calcic Chestnuts and Calcic Chernozems, which cover acid volcanic parent rock. Soil texture is dominated by fine-sand loess mainly

derived by deflation. Thus, soil is highly susceptible to wind erosion.

Experimental design

The grazing experiment was established in 2005 on *Leymus chinensis*- and *Stipa grandis*-dominated steppe. The area had been moderately used for sheep grazing until 2003 and, afterwards, grass swards recovered for 2 years before the experiment started in June 2005. An area of 160 ha was fenced and divided into 28 grazing and 28 hay-making plots. Pastures and hay-making plots of the same stocking rate were constructed side by side. Seven different stocking rates of SR0, SR1.5, SR3, SR4.5, SR6, SR7.5, and SR9 for 0, 1.5, 3, 4.5, 6, 7.5, and 9 sheep/ha, respectively, were compared. The gradients of stocking rates, SR0, SR1.5, SR3, SR4.5, SR6, SR7.5, and SR9, characterised scenarios of ungrazed, very low, low, low-moderate, moderate, high, and very high grazing pressure, respectively. Compared with SR0, remnant vegetation at the end of the grazing season (September) was 109, 74, 38, 38, 25, and 15% in 2005, and 96, 59, 25, 22, 10, and 18% in 2006 for SR1.5, SR3, SR4.5, SR6, SR7.5, and SR9, respectively. The regional livestock farming is dominated by sheep and goats. However, sheep stocks are highest and most important for the farmers in the Xilin River catchment. Therefore, we decided to conduct the grazing experiment with sheep. The grazing animals were 15-month-old female sheep, averaging 35 kg liveweight, and were kept continuously on the plots throughout the grazing season. Except for SR1.5, the standard plot size was 2 ha. In order to achieve a minimum of 6 sheep per plot, SR1.5 comprised 4 ha. Stocking rates were compared between different grazing systems, the Mixed System (MS) and the Traditional System (TS). Each system included hay and pasture plots for each stocking rate treatment. Within MS, pasture and hay making were alternated annually, while the TS was characterised by separated inter-annual grazing and hay making. In line with the local hay-making practice a one-cut-system was applied to the hay plots. In the present paper, data from the hay-making plots are excluded.

Sampling procedures

Grazing lasted from the beginning of June to the beginning of September, and successive samplings were made monthly at the beginning of June, July, August, and September. The duration of the grazing season was 98 and 90 days in 2005 and 2006, respectively. Before grazing started, 3 representative sampling areas were chosen within each plot to reflect the sward composition. Moveable exclosure cages were used to measure the productivity of grazed plots (McNaughton *et al*. 1996). They were installed and relocated within the previously chosen representative sampling areas. Directly after finishing the first sampling at the beginning of June, movable exclosures were set up at each sampling point and sheep were allocated to the plots. At each following sampling, exclosures were moved to new locations. Sampling was done by trained local workers at 3 sampling points in the 2-ha plots and at 6 sampling points in the 4-ha plot, each of which was located within the previously chosen sampling area inside and outside the exclosure cages. Litter was combed out before clipping standing above-ground herbage mass to 1 cm inside rectangular 0.5-m² frames

(0.25 m by 2 m). The collected fresh material was oven-dried at 60°C for 24 h, weighed, and pooled by plot to bulk samples for milling. Samples were ground to 1-mm particle size using a Cyclotec 1093 Sample Mill (Tecator, Sweden) for quality analysis. The herbage samples comprised living and standing dead material. Yields presented in this study were corrected for residual moisture at 105°C.

Sampling parameters

The herbage mass available for grazing sheep (H_g) comprised the herbage mass sampled outside the moveable exclosures. In combination with the ungrazed herbage mass sampled inside the exclosures (H_u), the monthly herbage increment and annual herbage accumulation were estimated. Annual herbage accumulation (H_a) was calculated by the herbage mass at the initial date of grazing (beginning of June) summed to the monthly herbage growth (Hodgson 1979). The H_a was estimated by the following equation:

$$H_a = W_{1g} + (W_{2u} - W_{1g}) + (W_{3u} - W_{2g}) + (W_{4u} - W_{3g}) \quad (1)$$

where W_i is the dry matter weight of H_g at sample time t_i ($i = 1, 2, 3, 4$: beginning of June, July, August, September, respectively). Indices u and g for ungrazed and grazed, respectively, are samples taken inside and outside the exclosure cages. Since the standing crop of these steppe communities reached its annual peak in August, the estimated community herbage mass approximated H_a of these ecosystems (Bai *et al.* 2004). Hence, for SR0, peak herbage mass sampled in August was equated with H_a.

The absolute growth rate (GR) and relative growth rate (RGR) (Fisher 1921) were calculated by the following equations:

$$GR = (W_{2u} - W_{1g})/(t_2 - t_1) \quad (2)$$

$$RGR = [\ln(W_{2u}) - \ln(W_{1g})]/(t_2 - t_1) \quad (3)$$

where W_i is the dry matter weight of H_g at sample time t_i ($i = 1, 2$) inside (u for ungrazed) and outside (g for grazed) the exclosure cages.

All herbage quality data presented here were gained by herbage mass sampled outside the exclosure cages, including green and standing dead parts. Annual means of herbage quality parameters were expressed as weighted averages related to the respective herbage mass. Contents of dry matter (DM), organic matter (OM), crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), acid detergent lignin (ADL), cellulase digestible organic matter (CDOM), and metabolisable energy (ME) were estimated by near-infrared spectroscopy (NIRS). All samples were scanned twice with a NIR-System 5000 monochromator (Perstrop Analytical Inc., Silver Spring, MD, USA) over a wavelength range of 1100–2500 nm in 2-nm intervals. For scanning, processing, calibration, and statistical analysis of spectra files the software NIRS 2 Infrasoft International (ISI, Port Mathilda, PA, USA) was used. For chemical laboratory analysis calibration (2005: $n = 138$, 2006: $n = 44$) and validation (2005: $n = 25$, 2006: $n = 10$), subsets of herbage samples were chosen. Herbage DM content was determined by drying at 105°C to constant mass, and OM

was derived from the difference between the dried sample and the residue (ash) after incineration of the sample for 3 h at 550°C. Herbage N content was determined by C/N analysis based on the DUMAS combustion method (Vario Max CN, Elementar Analysesysteme, Hanau, Germany) and, thereafter, CP contents were calculated as $6.25 \times N$. NDF, ADF, and ADL were analysed sequentially by using semi-automatic ANKOM[220] technology according to the procedures described by Van Soest *et al.* (1991). NDF and ADF were expressed including residual ash and ADL was expressed on an ash-free basis. *In vitro* CDOM and ME contents 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 (4). CA, CP, and EULOS were used for the calculation of herbage ME (5):

$$CDOM \, [\% \text{ of OM}] = 100 \, (940 - CA - 0.62 EULOS$$
$$- 0.000221 EULOS^2)/(1000 - CA) \quad (4)$$

$$ME \, [MJ/kgDM] = 13.98 - 0147CA - 0.0102 EULOS$$
$$- 0.00000254 EULOS^2 + 0.00234 CP \quad (5)$$

Statistical methods

The experiment was carried out as a split-plot design with 2 replicates. Main plots were dedicated to the system, whereas stocking rate was considered in the subplots. Paddocks were arranged in 2 blocks (flat and slope) to account for any gradient that might exist from the slope to the flat area. Each system contained 7 stocking rate treatments. ANOVA was performed for 2005 and 2006 separately by using the Mixed Model of SAS version 9.1 (SAS Institute Inc., Cary, NC, USA). Annual data of herbage quality and H_a were analysed by the following model:

$$y_{ijk} = \mu + S_i + B_j + I_k + S \times I_{ik} + (-1)^i C_{jk} + e_{ijk} \quad (6)$$

where y is the target variable, μ is the overall mean, S is the system (MS, TS), B is the block (flat, slope), I is the intensity represented by stocking rates, e is the random experimental error, and C is the covariate as specified below. All factors and interactions were treated as fixed factors.

For analysing parameters H_g, GR, RGR, and seasonal effects on herbage quality, ANOVA was performed by using repeated-measures in the Mixed Model of SAS with the following statistical model:

$$y_{ijkl} = \mu + S_i + B_j + I_k + M_l + S \times I_{ik} + S \times M_{il} + I$$
$$\times M_{kl} + S \times I \times M_{ikl} + (-1)^i C_{jk} + e_{ijkl} \quad (7)$$

where y is the target variable, μ is the overall mean, S is the system (MS, TS), B is the block (flat, slope), I is the intensity represented by stocking rates, M is the month or sampling time (June, July, August, September) representing season, e is the random experimental error, and C is the covariate. When applicable, the factor M was treated as a repeated effect. The analysis was done with an autoregressive co-variance structure.

Since the grazing history has led to heterogeneous grazing patterns and different species composition, especially between the systems within the flat block, a covariate adjustment was done. The covariate (*C*) was introduced to the model to minimise this heterogeneity and is defined as:

$$C = (V_1 - V_2)/2 \qquad (8)$$

where *C* is the covariate and V_i ($i = 1, 2$) is the value of yield or quality parameter in system 1 (MS) or 2 (TS) for the same stocking rate and the same block (slope or flat) in the year 2005, assuming no difference between MS and TS in the first year. Accordingly, no system-related effect could arise in 2005 as there was no rotation during the first year.

All data generated by the ANOVA were predicted least square means. When a significant *F*-test was detected ($P < 0.05$), a *t*-test followed for pre-planned contrasts and the differences of least square means were adjusted by the Bonferroni-Holm procedure (Köhler *et al.* 2007). For regression analysis the linear model of SAS was applied.

Results

Climate data and species composition

Annual precipitation of 166 mm during the first experimental year 2005 was far below the average, while 304 mm during the year 2006 approximated the long-term average. In 2005 and 2006, highest precipitation rates were recorded in June and July. In the dry year 2005, May–September precipitation was only 128 mm, with a peak of 59 mm in July, whereas in 2006, May–September precipitation was 195 mm, peaking at 71 mm in June (Fig. 1).

The proportion of species in total sampled DM was assessed for 2005 and 2006 at the July sampling. In 2005, *Leymus chinensis* reached 36% in herbage DM in the TS, but only 24% in the MS. In 2006, differences between the systems were smaller, and proportions of *Leymus chinensis* in total sampled DM were 18% in the MS and 24% in the TS. Noticeably, annual plants such as *Salsola collina* increased to greater cover values and were determined in the wetter year 2006 only (Table 1).

Herbage mass

In 2005 and 2006, H_g was significantly affected by sampling time ($P < 0.001$) and stocking rate ($P < 0.001$), but not by the system (Table 2). Increasing stocking rates had a strong negative effect on H_g (Fig. 2). Remanent vegetation measured at the end of the grazing season reached 108, 117, 80, 41, 40, 27, and 16 g DM/m^2 for SR0, SR1.5, SR3, SR4.5, SR6, SR7.5, and SR9, respectively, in 2005, and 113, 108, 66, 29, 25, 12, and 16 g DM/m^2 for SR0, SR1.5, SR3, SR4.5, SR6, SR7.5, and SR9, respectively, in 2006. Sampling time and stocking rate also affected yields interactively in both 2005 ($P < 0.001$) and 2006 ($P < 0.001$). In June 2005, when the experiment started, all stocking rate treatments showed similar H_g, whereas in August and September, H_g significantly decreased under increasing stocking rates (Fig. 2). In 2006, significant differences among stocking rates could already be detected in June as H_g decreased at SR3, SR4.5, SR7.5, and SR9 (Fig. 2). The H_g of SR0, SR1.5, and SR3 increased over the season to a peak in August, while SR4.5, SR6, SR7.5, and SR9 showed decreasing yields after a peak in early July. In 2006, H_g at SR9 remained at low levels throughout the growing season as variation between sampling times was not significant.
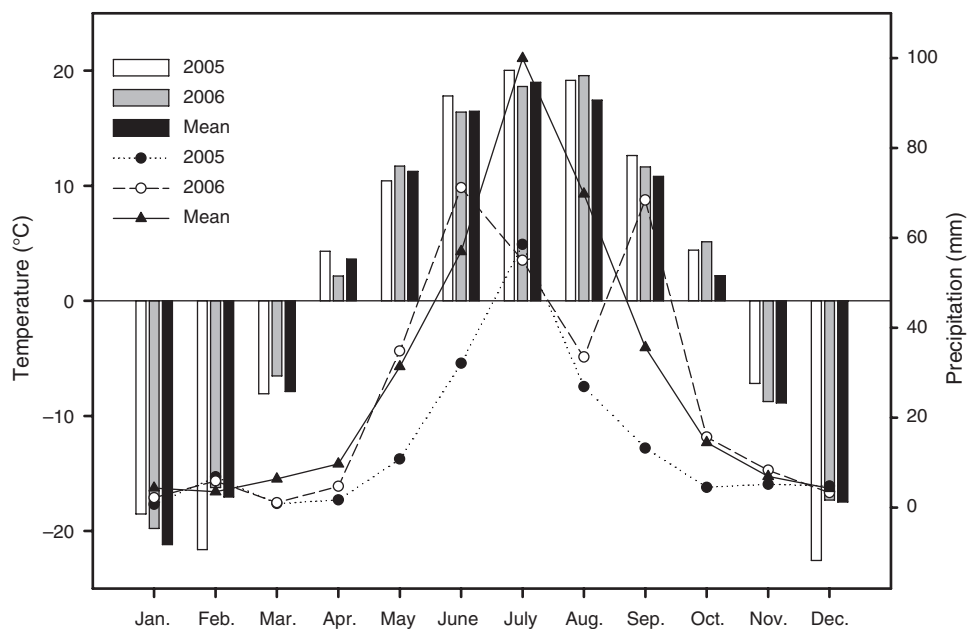

Fig. 1. Mean monthly air temperature [°C, bars] and precipitation rates [mm, lines] measured at the Inner Mongolia Ecosystem Research Station (IMGERS) in 2005 and 2006. White, grey, and black bars represent 2005, 2006, and mean (1982–2003) temperatures, respectively, and lines with white circles, black circles, and black triangles represent 2005, 2006, and mean (1982–2003) precipitation, respectively.

Table 1.   Species composition determined at the July sampling in 2005 and 2006 in the Mixed System (MS) and the Traditional System (TS) (% of dry matter)

	2005				2006			
	MS		TS		MS		TS	
	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.
Stipa grandis	26.33	6.88	24.73	2.56	30.22	3.89	27.27	0.47
Leymus chinensis	23.69	7.23	36.31	8.13	18.20	1.54	24.29	0.11
Cleistogenes squarrosa	11.03	3.52	9.74	1.74	12.82	5.74	13.20	2.01
Agropyron cristatum	14.27	1.43	7.54	0.79	11.10	3.28	7.03	1.48
Carex korshinsky	10.62	1.94	9.30	3.91	5.88	1.88	5.82	0.23
Achnatherum sibiricum	1.90	2.14	3.38	0.68	–	–	–	–
Potentilla (ac., ta., bi.)	3.55	2.86	1.19	0.49	–	–	–	–
Annual species (*Chenopodicae*)	–	–	–	–	2.73	2.51	1.14	0.63
Remaining species[A]	3.89	0.46	3.45	0.83	6.17	3.00	4.95	0.03
Standing dead (bulk)	4.72	0.98	4.36	1.89	12.86	2.21	16.30	0.94

[A]Includes all species with proportions of >0% and <1% in herbage dry matter.

Herbage growth

Both GR and RGR were most strongly affected by main effect sampling time and to a lesser extent by stocking rate (Table 3). As shown in Fig. 2b and c, maximum growth rates in 2005 were recorded during June at SR1.5 with a GR of 1.6 g DM/m^2.day corresponding to a RGR of 1.8%/day, and declined afterwards continuously to a minimum during August with a negative GR at SR0 and SR4.5 of –0.2 g DM/m^2.day and a RGR of –0.3%/day for SR4.5. In 2006, GR remained at high levels during June and July with a maximum of 1.7 g DM/m^2.day in July at SR1.5. During August 2006, GR declined to a minimum of –0.7 g DM/m^2.day recorded at SR0. The maximum RGR of 2.4%/day was found during June at SR4.5.

Within the different growth periods, growth rates were highly dynamic among stocking rates (Fig. 2), and significant differences could only be detected in August 2006, when GR at SR0 was significantly lower than in all other treatments, except SR9. The RGR showed inverse patterns between the years without any significant differences among stocking rates within the same period. Whereas in the dry year 2005 the RGR was relatively constant among stocking rates during each period, the RGR increased in the relatively wet year 2006 during June, July, and August with stocking rate, but also showed a sharp decrease during August at SR9 (Fig. 2c).

Annual herbage accumulation

The mean H$_a$ of 118.83 g DM/m^2 in 2005 was the same for MS and TS due to covariate adjustment. In 2006, annual herbage accumulation was 121.08 g DM/m^2 for MS and 137.46 g DM/m^2 for TS without significant difference. Table 4 summarises the treatment means and ANOVA results of different stocking rates for H$_a$. Accordingly, stocking rate was the main affecting factor, as H$_a$ decreased with increasing stocking rate in 2005 ($P < 0.001$) and 2006 ($P < 0.01$). The lowest H$_a$ of 97.67 and 76.77 g DM/m^2 was realised at SR9 in 2005 and 2006, respectively, while maximum yields of 156.50 and 167.74 g DM/m^2 were achieved at SR1.5 in 2005 and 2006, respectively.

Herbage quality

Sampling time was the main factor affecting herbage quality (Table 2). Seasonal effects were documented in 2005 and 2006 by decreasing contents of CP ($P < 0.001$), CDOM ($P < 0.001$), and ME ($P < 0.001$) over time. Concomitant contents of NDF ($P < 0.001$), ADF ($P < 0.001$), and ADL ($P < 0.001$) increased.

Beside seasonal effects, stocking rate affected several herbage quality parameters (Table 4). Herbage CP content showed significant positive response to increased stocking rates in 2005 ($P < 0.001$) and 2006 ($P < 0.01$). Significant differences in herbage CP were found between SR0 and SR9 in 2005. In 2006, CP content of the SR9 treatment was significantly higher than of the SR0, SR1.5, and SR3 treatments. ANOVA also revealed effects of stocking rate on CDOM in 2005 and 2006 at $P < 0.05$. Subsequent to Bonferroni-Holm adjustment, however, no significant differences among stocking rates were determined. Estimated ME was affected by stocking rate in 2005 ($P < 0.01$) as herbage ME was significantly lower at SR1.5 than at SR4.5 and SR9. The analysed herbage material generally contained high fibre with mean annual concentrations of 718 and 679 g NDF/kg DM in 2005 and 2006, respectively. In 2005, NDF was affected by stocking rate ($P < 0.01$) as fibre contents increased with increasing stocking rates. ADF was also affected by stocking rate in 2005, but no clear trend over the stocking rates could be determined. ADL contents at SR9 in 2005 and at SR7.5 in 2006 were significantly lower than at SR0, SR1.5, SR3, SR4.5, and SR6 treatments.

Discussion

In 2006, both productivity levels and the nutritional values of herbage produced were higher than in 2005, corresponding to the higher precipitation rates of May and June 2006. Precipitation in 2006 was 34.8 mm and 71.2 mm in May and June, respectively, while in 2005, only 10.8 mm and 32.1 mm could be measured for the same periods (Fig. 1). Several authors discussed the strong influence of precipitation amounts and precipitation variability on the productivity of the Inner Mongolia grassland (Bai *et al.* 2004; Ni 2004). Both the amount and the variability of precipitation are used to delimit equilibrium from non-equilibrium systems (e.g. Ho 2001; Boone and Wang 2007). Accordingly, non-equilibrium is rather expected in arid and semi-arid environments with annual precipitation of 250–500 mm and an annual precipitation variability exceeding 30%. The investigated steppe site showed a variation of

Table 2. Effect of season on herbage mass (Hg) and herbage quality

*P<0.05; **P<0.01; ***P<0.001; n.s., not significant. Within rows, means followed by the same letters are not significantly different (P<0.05). CP, crude protein; NDF, neutral detergent fibre; ADF, acid detergent fibre; ADL, acid detergent lignin; CDOM, cellulase digestibility; ME, metabolisable energy

| | Sampling time | | | | | Source of variation (ANOVA)[A] | | | | | | | | |
	June	July	Aug.	Sept.	s.e.	S	B	I	M	S×I	S×M	I×M	S×I×M	C
d.f.						1	1	6	3	6	3	18	18	1
Hg 2005 (g DM/m²)	65.7b	82.7a	78.8a	61.6b	3.0	n.s.	***	***	***	n.s.	n.s.	***	n.s.	***
Hg 2006 (g DM/m²)	51.5b	69.8a	67.1a	54.8b	3.6	n.s.	*	***	***	n.s.	n.s.	***	n.s.	*
CP 2005 (g/kg DM)	106.9a	97.3b	91.9b	78.9c	1.2	n.s.	***	*	***	n.s.	n.s.	n.s.	n.s.	***
CP 2006 (g/kg DM)	146.7a	138.2a	126.2b	107.5c	3.5	n.s.	*	*	***	n.s.	n.s.	n.s.	n.s.	n.s.
NDF 2005 (g/kg DM)	703.5b	725.5a	723.4a	720.3a	1.9	n.s.	***	**	***	n.s.	*	n.s.	n.s.	*
NDF 2006 (g/kg DM)	673.1b	675.5b	681.9b	694.8a	3.5	n.s.	**	n.s.	***	n.s.	n.s.	*	n.s.	n.s.
ADF 2005 (g/kg DM)	335.4c	340.1c	345.4b	350.8a	1.4	n.s.	***	**	***	n.s.	n.s.	n.s.	n.s.	*
ADF 2006 (g/kg DM)	321.1bc	317.7c	327.9b	338.9a	2.8	n.s.	*	n.s.	***	n.s.	*	n.s.	n.s.	n.s.
ADL 2005 (g/kg DM)	32.7d	40.7c	49.2b	53.4a	0.5	n.s.	n.s.	***	***	n.s.	n.s.	n.s.	n.s.	*
ADL 2006 (g/kg DM)	35.2c	37.0c	51.6b	54.5a	0.6	n.s.	n.s.	n.s.	***	*	*	n.s.	n.s.	n.s.
CDOM 2005 (g/kg OM)	645.9a	594.4b	574.8c	556.1d	3.7	n.s.	**	n.s.	***	n.s.	n.s.	n.s.	n.s.	n.s.
CDOM 2006 (g/kg OM)	686.8a	648.8b	614.2c	589.7d	4.2	n.s.	***	n.s.	***	n.s.	n.s.	n.s.	n.s.	n.s.
ME 2005 (MJ/kg DM)	9.0a	8.3b	7.9c	7.6d	0.1	n.s.	***	n.s.	***	n.s.	n.s.	n.s.	n.s.	n.s.
ME 2006 (MJ/kg DM)	9.5a	9.0b	8.7c	8.2d	0.1	n.s.	**	n.s.	***	n.s.	n.s.	**	n.s.	n.s.

[A] S, B, I, and M are the factors system, block, intensity (stocking rates), and month (sampling time), respectively. C is the covariate.

Table 3. Effect of stocking rate on mean seasonal growth rate (GR) and relative growth rate (RGR)

*P<0.05; **P<0.01; ***P<0.001; n.s., not significant. Within rows, means followed by the same letters are not significantly different (P<0.05)

| | Stocking rate (sheep/ha) | | | | | | | | Source of variation (ANOVA)[A] | | | | | | | | |
	0	1.5	3	4.5	6	7.5	9	s.e.	S	B	I	M	S×I	S×M	I×M	S×I×M	C
d.f.									1	1	6	3	6	3	18	18	1
GR 2005 (g DM/m².day)	0.47ab	0.95a	0.57ab	0.26b	0.69ab	0.46ab	0.31b	0.12	n.s.	n.s.	**	***	n.s.	n.s.	n.s.	n.s.	n.s.
GR 2006 (g DM/m².day)	0.58a	1.07a	0.91a	1.05a	0.98a	0.83a	0.53a	0.12	n.s.	**	*	***	n.s.	*	*	n.s.	n.s.
RGR 2005 (%/day)[B]	0.57ab	0.91a	0.60ab	0.33ab	0.72ab	0.66ab	0.32b	0.13	n.s.	n.s.	*	***	n.s.	n.s.	n.s.	n.s.	*
RGR 2006 (%/day)[B]	0.71a	0.99a	1.07a	1.82a	1.55a	1.79a	1.32a	0.30	n.s.	n.s.	n.s.	***	n.s.	n.s.	n.s.	n.s.	n.s.

[A] S, B, I, and M are the factors system, block, intensity (stocking rates), and month (periods), respectively. C is the covariate.
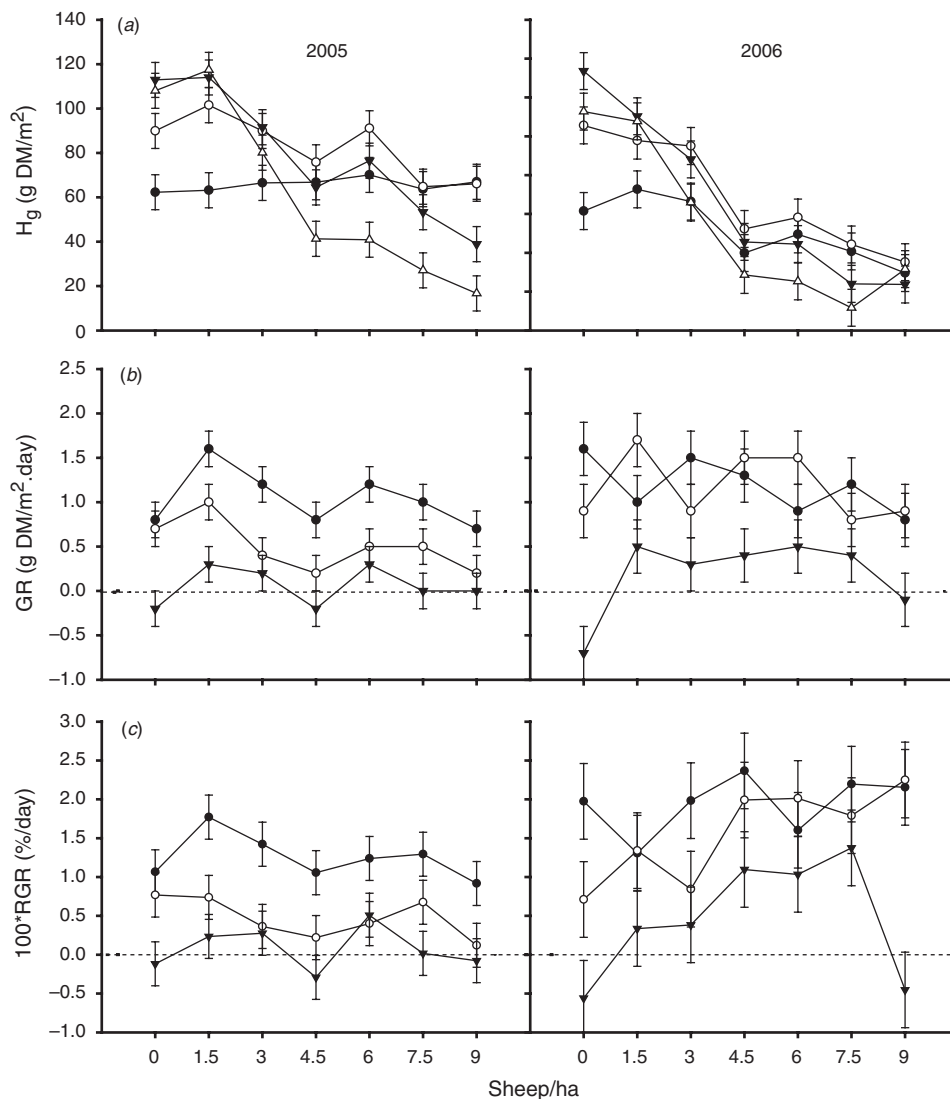[B] 100*RGR.

Fig. 2. Effect of stocking rate and season on: (*a*) herbage mass (H_g), (*b*) growth rate (GR), and (*c*) relative growth rate (RGR). Figures on the left side represent data for the year 2005 and on the right side data for the year 2006. Samplings for H_g were always taken during the first week of June (●), July (○), August (▼), and September (△), and growth rates (GR and RGR) were estimated for periods June (●), July (○), and August (▼).

annual precipitation of only 22%, indicating an equilibrium pattern; however, the 334 mm average annual precipitation was within the range that supported the occurrence of non-equilibrium vegetation dynamics. We found at least some important features of equilibrium rangelands, notably vegetation responses to increasing stocking rates, but also strong influences of inter-annual precipitation variability, a characteristic of non-equilibrium systems. Therefore, this steppe ecosystem encompasses elements of both equilibrium and non-equilibrium systems, which seems to be mostly true for semi-arid grasslands (Fernandez-Gimenez and Allen-Diaz 1999; Briske *et al.* 2003; Vetter 2005). Wessels *et al.* (2007) generally challenged the application of the non-equilibrium theory and concluded that heavy grazing causes a substantial reduction in vegetation productivity, despite a strong short-term influence of inter-annual variation in rainfall. Briske *et al.*

(2003) stated that equilibrium and non-equilibrium systems cannot be distinguished only on the basis of unique processes or functions, but rather by the evaluation of system dynamics at various temporal and spatial scales. Grassland restoration is a long-term process (Zhang *et al.* 2005), and short-term effects of grazing may sometimes be diminished by rainfall variability.

Aside from grassland productivity, herbage quality also benefited from precipitation since water availability and plant N-uptake are reported to be positively correlated, especially in arid and semi-arid environments (Biondini *et al.* 1998; Gebauer and Ehleringer 2000; Giese *et al.* 2009).

The observed block differences between the flat and the slope area might reflect both soil moisture gradient and earlier onset of the growing season due to exposition. Intra-block differences were minimised by covariate adjustment.

Table 4. Effect of stocking rate on herbage accumulation (H$_a$) and herbage quality

$*P<0.05$; $**P<0.01$; $***P<0.001$; NS not significant. a, b, c, d within rows, means followed by different small letters are significant different ($P<0.05$). CP, crude protein; NDF, neutral detergent fibre; ADF, acid detergent fibre; ADL, acid detergent lignin; CDOM, cellulase digestibility; ME, metabolisable energy. Herbage quality parameters are annual means expressed as weighted averages

	Stocking rate (sheep/ha)							s.e.	Source of variation (ANOVA)[A]				
	0	1.5	3	4.5	6	7.5	9		S	B	I	S×I	C
d.f.									1	1	6	6	1
H$_a$ 2005 (g DM/m^2)	112.9bc	156.5a	123.6abc	93.6c	138.4ab	109.3bc	97.7c	7.4	n.s.	***	***	n.s.	***
H$_a$ 2006 (g DM/m^2)	133.6ab	167.7a	145.8a	132.3ab	136.0ab	112.7ab	76.8b	11.8	n.s.	**	**	n.s.	*
CP 2005 (g/kg DM)	91.1ab	85.5b	95.8a	97.7a	93.6ab	97.4a	99.8a	1.7	n.s.	***	***	n.s.	***
CP 2006 (g/kg DM)	116.5b	113.8b	116.0b	138.0ab	127.2ab	150.4ab	157.3a	7.6	n.s.	**	**	n.s.	n.s.
NDF 2005 (g/kg DM)	702.7b	719.1a	718.5a	715.5ab	721.9a	722.9a	723.5a	2.6	n.s.	***	**	n.s.	***
NDF 2006 (g/kg DM)	675.0a	687.9a	683.8a	680.6a	684.2a	671.5a	670.5a	7.2	n.s.	**	n.s.	n.s.	n.s.
ADF 2005 (g/kg DM)	336.1b	349.7a	338.9ab	337.2ab	344.5ab	345.1ab	342.6ab	2.4	n.s.	**	*	n.s.	*
ADF 2006 (g/kg DM)	327.5a	333.8a	332.2a	323.0a	330.8a	315.6a	312.7a	6.2	n.s.	*	n.s.	n.s.	n.s.
ADL 2005 (g/kg DM)	42.5a	44.1a	44.6a	42.8a	44.7a	43.9a	40.1b	0.5	n.s.	n.s.	**	n.s.	***
ADL 2006 (g/kg DM)	47.0a	45.2a	45.8a	42.5a	43.1ab	39.3b	42.8ab	1.1	n.s.	n.s.	**	**	*
CDOM 2005 (g/kg OM)	599.7a	585.6a	592.2a	603.7a	588.2a	596.5a	600.7a	3.4	n.s.	***	*	n.s.	***
CDOM 2006 (g/kg OM)	634.5a	624.4a	626.3a	640.8a	632.7a	659.4a	657.7a	7.7	n.s.	***	*	n.s.	n.s.
ME 2005 (MJ/kg DM)	8.3ab	8.1b	8.1ab	8.3a	8.1ab	8.2ab	8.3a	0.1	n.s.	***	**	n.s.	***
ME 2006 (MJ/kg DM)	8.9a	8.8a	8.8a	9.0a	8.7a	9.2a	9.1a	0.1	n.s.	**	n.s.	n.s.	n.s.

[A]S, B, I, and M are the factors system, block, and intensity (stocking rates), respectively. C is the covariate.

Herbage mass

When grazing began in June 2005, H_g was similar among all stocking rates (Fig. 2*a*), suggesting that swards were quite stable at the beginning of the experiment. Carry-over effects from the first year of grazing were obvious in the second year. Due to previous year's grazing, H_g of SR3, SR4.5, SR7.5, and SR9 was already reduced at the beginning of the 2006 grazing season (Fig. 2). Grazing and grazing-attended stress loads, such as trampling, usually reduce the above-ground biomass because of grazing-induced tissue removal and damage. Due to higher feed intake per unit area, H_g decreased linearly with increasing stocking rates, and thus intensity from ungrazed to very heavy grazing was well reflected by the stocking rate gradient. At the end of the grazing season, H_g of SR9 was reduced by 85% in 2005 and 82% in 2006 compared with SR0. The strong reduction in H_g at SR9 compared with SR0 demonstrated the heavy grazing pressure. Sheep were already taken off the SR9 treatment in August due to herbage shortage and, therefore, no further reduction in H_g between August and September was measurable in 2006 (Fig. 2). Thus, the H_g reduction of 82% between the SR9 and SR0 treatment in 2006 referred to August sampling. For Inner Mongolian typical steppe ecosystems, Wang and Ripley (1997) and Wang (2004) reported similar depleting effects of grazing on standing herbage mass.

Several authors reported a negative relationship between H_g and herbage intake per unit animal (e.g. Garcia *et al*. 2003; Glindemann *et al*. 2009). Since we also found a negative relationship between H_g and stocking rate, intake per sheep might be negatively affected on intensively grazed treatments, without this having been shown in this study.

Herbage growth

The parameter RGR is an important measure of plant response to grazing, representing the production per unit of producing tissue (Hilbert *et al*. 1981) and, thus, RGR is well suited to answer the question of whether grazing causes compensatory responses in plants (Ferraro and Oesterheld 2002). Any significant increase in RGR as a result of grazing indicates compensatory growth, however, without necessarily implying increasing herbage accumulation (Hilbert *et al*. 1981). In this study the RGR showed inverse patterns between the years. During the dry year 2005 a significant effect of stocking rate on RGR revealed a damage response to grazing under SR9 compared with SR1.5. Up to SR7.5, however, neither damage nor compensatory responses could be statistically confirmed (Table 3). In contrast to the negative response to SR9 in 2005, the RGR during the higher rainfall year 2006 was not negatively affected by grazing, not even by SR9. RGR data in 2006 rather indicate a non-significant tendency of compensatory plant response to moderate and high grazing pressure (Fig. 2*c*, Table 3). The inverse growth response patterns between the years suggest a greater rain-use efficiency of more intensively grazed plants. Varnamkhasti *et al*. (1995) discussed this effect for lightly grazed swards. According to studies reviewed by Ferraro and Oesterheld (2002), compensatory responses to grazing are common. Various mechanisms for compensatory responses to grazing have been identified. The allocation of photosynthates, both previously stored and currently produced, from roots and stems to new leaf, the decreasing self-shading and increasing interception of solar radiation by remaining leaves, the increased photosynthetic efficiency and reduced senescence of young regrown leaves, and the greater rain-use efficiency are among them (Noy-Meir 1993; Turner *et al*. 1993; Varnamkhasti *et al*. 1995).

The damage effect of SR9 on RGR during the year 2005 might not be exclusively due to high stocking rates, but may also be influenced by the drought. This suggests short-term damage responses to very high grazing pressure under drought condition. The analysed plant communities, however, seemed to be tolerant to grazing in the short-term since no damage response on RGR could be reported up to SR7.5 in 2005 and SR9 in 2006. Absolute herbage growth, represented by GR, showed a similar pattern between the years as negative responses to SR9 became evident, while SR1.5 rather supported GR (Table 3).

Annual herbage accumulation

In 2005 and 2006, H_a at SR9 compared with SR1.5 was reduced by 38% and 55%, respectively. Differences in H_a were reflected by GR (Fig. 2*b*), and additionally by lower H_g at initial time of grazing in 2006 (Fig. 2*a*), which enhanced the depleting effect of SR9 in the second season. We observed a decrease in H_a from SR1.5 to SR9, especially in 2006. The results indicate positive effects of low grazing pressure suggested by highest productivity at SR1.5. Hence, the SR1.5 treatment represents an optimum ratio of herbage removal by grazers and growth. By contrast, SR9 represented an extreme grazing scenario, which already strongly reduced grassland yield characteristics in the short-term, with significantly lower H_a compared with SR1.5 and SR3 (Table 4).

Negative short-term effects of heavy grazing on H_g identified in this study are in line with global patterns (Milchunas and Lauenroth 1993; Ferraro and Oesterheld 2002). In line with the grazing optimisation hypothesis (McNaughton 1979; Milchunas and Lauenroth 1993; Milchunas *et al*. 1995), we observed positive effects of grazing on productivity up to a certain level. However, maximum response to grazing was already reached at light grazing regimes, represented by SR1.5.

Herbage quality

Plants matured rapidly after June, especially in 2005, because of high temperature and low soil moisture. Accordingly, sampling time was the main factor affecting herbage quality, with decreasing concentrations of CP, ME, and CDOM and increasing fibre fractions such as NDF, ADF, and ADL over time. Several authors (e.g. Buxton 1996; Garcia *et al*. 2003) reported the strong influence of the plant development stage on herbage quality. When plant cells stop growing the maturation and lignification process will begin (Jung 1997), and cellulose, hemicellulose, and lignin increase, while cell substances such as proteins, lipids, and minerals decrease (Osbourne 1980). Correspondingly, we found increasing ADL, ADF, and NDF contents over the season. Herbage CP, ME, and CDOM in September were 26, 15, and 14%, respectively, lower than in June (Table 2). Therefore, constraints to animal performance might be expected, notably at the end of the

vegetation period. Correspondingly, Glindemann *et al.* (2009) documented decreasing individual animal performance over the season, when analysing 2005 animal data of the same grazing trial.

Despite considerable herbage removal by sheep during the grazing season (Fig. 2*a*), effects on herbage quality were not consistent. In general, herbage quality was enhanced by intensive grazing, particularly resulting in linearly increasing CP contents and linearly decreasing cell-wall lignification.

Compared with mean CP contents of temperate grasses averaging 129 g CP/kg DM (Minson 1990), we found similar contents of 131 g CP/kg DM in 2006 but lower contents of 94 g CP/kg DM in 2005. Higher herbage CP content in 2006 was probably caused by higher precipitation, which improved plant N-uptake (Gebauer and Ehleringer 2000), and by carry-over effects from the first year, promoting protein-rich re-growth for the early second grazing season, especially on intensively grazed swards. Contents of herbage CP never went below the critical limit of 70 g CP/kg DM for efficient ruminal fermentation, as recommended by Van Soest (1994).

In this study, herbage CP content increased with stocking rate intensification, confirming previous studies (Noy-Meir 1993; Milchunas *et al.* 1995; Pavlu *et al.* 2006). Pastures grazed intensively were characterised by re-growth, and due to permanent grazing the maturation and lignification processes decelerated (Milchunas *et al.* 1995; Garcia *et al.* 2003), inducing increasing herbage CP contents. Our observations are also supported by Noy-Meir (1993), who stated that grazing may lead to increasing root N-uptake and enhanced N-translocation from roots to remaining and re-growing leaves. Further effects have been discussed in the literature, such as the positive influence of N-input from animal dung and urine on plant N-uptake in grasslands (McNaughton *et al.* 1996, 1997; Kurz *et al.* 2006). Since N mineralisation is reduced, the effect of excremental N input might be limited during drier years (Giese *et al.* 2009). Our data suggest that intensive grazing favoured, in the short-term, the decrease in lignified plant parts and the re-growth of new tissue, with increased CP content and decreased lignification.

Limited by high lignin contents, CDOM never went above 70%. The strong negative correlation between ADL and CDOM (Fig. 3) suggested increasing digestibility with increasing stocking rates. In this study, short-term effects of grazing on CDOM were inconsistent among stocking rates in 2005, but in 2006 a consistent trend could be detected as digestibility of herbage mass was maximised at SR7.5 and SR9. Nevertheless, differences in CDOM between the minimum at SR1.5 (624.4 g CDOM/kg OM) and the maximum at SR7.5 (659.4 g CDOM/kg OM) were only small (Table 4).

As mentioned previously, samples taken late in the season contained less ME, suggesting that grazing resulted in lower energy intake from herbage over the season. This assumption is supported by findings of Glindemann *et al.* (2009) who reported decreasing herbage quality and intake by sheep in the course of the grazing season. For the present experiment, Wang *et al.* (2009) assumed the ME requirement for maintenance and daily liveweight gain of 100 g for a 35-kg sheep to be 7.4 MJ/sheep.day. Since herbage ME intake by sheep never
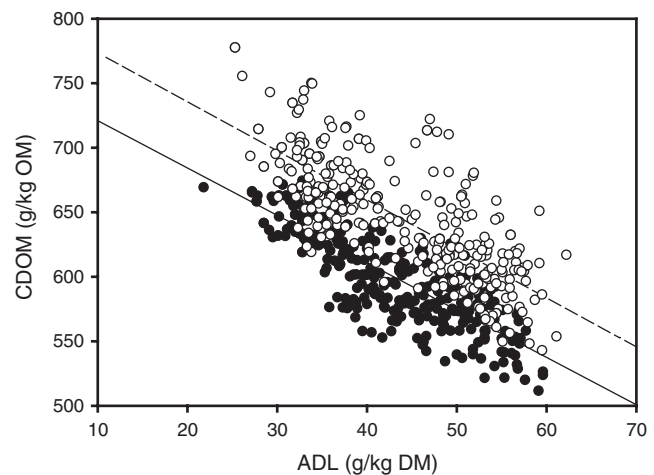

Fig. 3. Relationship between herbage acid detergent lignin (ADL) and cellulase digestibility of organic matter (CDOM) in 2005 (●) and 2006 (○). CDOM 2005 [g/kg OM] $= -3.70X + 757.68$, $r^2 = 0.66$***, RMSE $= 21.10$; and CDOM 2006 [g/kg OM] $= -3.80X + 811.35$, $r^2 = 0.58$***, RMSE $= 29.03$.

went below this limit, the analysed herbage material is adequate for sheep nutrition, and energy deficit is not expected. Generally, effects of stocking rate on ME were low and inconsistent between years (Table 4). Consequently, applying ME as an indicator for investigating short-term effects of stocking rate on herbage of typical steppe is not supported by the data of the present experiment.

The sampled material contained high fibre, especially in the dry year 2005, and NDF was never less than 700 and 670 g NDF/kg DM in 2005 and 2006, respectively (Tables 2, 4). The development of thick cell walls, aimed to reduce transpiration losses, is typical for plants under water stress (Ridley and Todd 1966; Frank *et al.* 1996) and, therefore, high plant fibre contents found in this study are plausible. Despite significance, relative fibre increment over the season for NDF was only 2 and 3% and for ADF, 4 and 5% in 2005 and 2006, respectively. Since short-term effects of stocking rate on NDF and ADF were low and inconsistent between years, corresponding to findings of Pavlu *et al.* (2006), NDF and ADF content of plant communities of the Inner Mongolia typical steppe as an indicator for overgrazing is not supported by the present data.

Unlike NDF and ADF fractions, lignification of cell walls over the season was much more pronounced. In relation to the maximum, ADL contents increased from June to September by 39 and 35% in 2005 and 2006, respectively (Table 2). Since lignification is negatively correlated with digestibility (Fig. 3), high ADL contents constrain herbage quality (Minson 1990; Van Soest 1994), especially at the end of the grazing season (Table 2). Cell-wall lignification was consistently influenced by grazing in both years: ADL content was reduced at SR7.5 and SR9 (Table 4), suggesting that grazing decelerated the maturation and lignification process of plant cells. The significant effect of the stocking rate and system interaction on ADL in 2006 revealed higher lignin contents of moderately and

intensively grazed treatments in the MS compared with the TS. Two reasons seem plausible. First, varying species composition of pastures in the MS and TS (Table 1) probably led to different ADL levels and, second, more senescent material accumulated during the hay-making year (2005) in the MS and hence, higher ADL contents appeared in 2006 compared with in the TS. Although limited by methodology, such as the solubilisation of lignin during the ADF step (Jung 1997), sequentially determined ADL could be a potential indicator for over-grazing in the short-term, as pronounced and consistent responses to increasing stocking rates were observed, which cannot only be attributed to a change in botanical composition.

Conclusions

(1) Different short-term indicators sensitive to grazing were evaluated and identified. The expected negative effect of grazing on H_g was well reflected by a strong negative linear relationship with stocking rate. Hence, grazing pressure from ungrazed to very heavy grazing was well reflected by the stocking rate gradient. Grassland productivity was negatively affected by heavy grazing and, therefore, H_a is considered as a potential sensitive short-term indicator. Among the analysed herbage quality parameters, CP and ADL linearly reflected the stocking rate treatments. Accordingly, they were most promising as indicators due to the strong short-term effects of grazing and the consistency between years. All herbage quality parameters were mainly influenced by season, while grazing effects were comparably low.

(2) Irrespective of the management system, H_a response to grazing was best at light and worst at heavy grazing pressure, represented in this study by SR1.5 and SR9, respectively. This suggests that the grazing optimisation point had already been reached at SR1.5. Plants, however, showed tolerance to grazing stress in the short-term, especially during the wetter year 2006, indicated by grazing responses of RGR to increasing stocking rates. Grazing led to increased herbage quality, which is demonstrated by increasing CP and decreasing ADL contents.

(3) In the short-term, no or only marginal effects of grazing management systems on herbage could be observed. Neither performance nor quality of herbage was affected by the system. Consequently, the hypothesised advantages of the MS compared with the TS could not be proved in the short-term.

Acknowledgments

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