

Aus dem Institut für Tierernährung und Stoffwechselphysiologie
der Christian-Albrechts-Universität zu Kiel

**Feeding strategies for sheep grazing the Inner Mongolian
steppe, China**

Dissertation

Zur Erlangung des Doktorgrades der
Agrar- und Ernährungswissenschaftlichen Fakultät
der Christian-Albrechts-Universität zu Kiel

vorgelegt von

Dipl. Biol. Britta Mareike Bösing

Kiel, 2013

Aus dem Institut für Tierernährung und Stoffwechselfysiologie
der Christian-Albrechts-Universität zu Kiel

**Feeding strategies for sheep grazing the Inner Mongolian
steppe, China**

Dissertation

Zur Erlangung des Doktorgrades der
Agrar- und Ernährungswissenschaftlichen Fakultät
der Christian-Albrechts-Universität zu Kiel

vorgelegt von

Dipl. Biol. Britta Mareike Bösing

Aus Heilbronn-Neckargartach

Kiel, 2013

Gedruckt mit Genehmigung der Agrar- und Ernährungswissenschaftlichen Fakultät der Christian-Albrechts-Universität zu Kiel.

Dekan:	Prof. Dr. Rainer Horn
1. Berichterstatter:	Prof. Dr. Andreas Susenbeth
2. Berichterstatter:	Prof. Dr. Friedhelm Taube
Tag der mündlichen Prüfung:	25.04.2013

Die Dissertation wurde dankenswerterweise von der Deutschen Forschungsgemeinschaft (DFG) gefördert

Contents

1	General introduction	1
1.1	Historical and socio-economic context of land use in Inner Mongolia	1
1.2	Importance of Inner Mongolian grassland and ecological consequences of overgrazing	3
1.3	The MAGIM- and LOTGrass-Project and the Xilin River catchment	7
1.4	Hypotheses within the framework of this dissertation	10
1.5	References	12
2	Animal responses to stocking density: Feed intake and live weight gain of sheep grazing the Inner Mongolian Steppe – Results of a Six Year Study –	17
2.1	Abstract	18
2.2	Introduction	19
2.3	Material and methods	20
2.3.1	Study area	20
2.3.2	Experimental design	22
2.3.3	Determination of herbage mass and dry matter	22
2.3.4	Animals	24
2.3.5	Feed and energy intake	24
2.3.6	Statistical analysis	25
2.4	Results	26
2.4.1	Feed intake and performance of sheep at different herbage allowance classes	26
2.4.2	Feed intake and performance of sheep at different stocking densities	30
2.5	Discussion	33
2.5.1	Effects of stocking density on feed intake and performance of individual animals	33
2.5.2	Effects of the year	34
2.5.3	Economical and ecological relevance	35
2.6	Conclusion	41
2.7	References	42

3	Effect of concentrate supplementation on herbage intake and live weight gain of sheep grazing a semi-arid grassland steppe of North-Eastern Asia in response to different grazing management systems and intensities	46
3.1	Abstract	47
3.2	Introduction	48
3.3	Material and Methods	49
3.3.1	Study area	49
3.3.2	Experimental design	49
3.3.3	Animals and feeding	50
3.3.4	Determination of herbage mass and laboratory analysis	51
3.3.5	Feed and energy intake	53
3.3.6	Statistical analysis	54
3.4	Results	55
3.4.1	Effect of concentrate supplementation	55
3.4.2	Effect of grazing system, grazing intensity, and experimental period	55
3.5	Discussion	60
3.5.1	Effect of concentrate supplementation	60
3.5.2	Effect of grazing system and grazing intensity	62
3.5.3	Economical and ecological relevance	63
3.6	Conclusions	65
3.7	References	65
4	General discussion and conclusion	70
4.1	Feeding strategies	71
4.1.1	Grazing intensity	71
4.1.2	Concentrate supplementation	73
4.1.3	Grazing system	76
4.2	Practical implications	78
4.3	References	79
5	Summary	82
6	Zusammenfassung	84

List of figures

- Figure 1.1a.** Hay making in August 2010 in the Xilin River catchment in the Inner Mongolian steppe. **b.** Dried sheep manure from the winter paddocks for heating and cooking in the countryside of Inner Mongolia. 3
- Figure 1.2** A fence line creating a contrast between pastures with a stocking density of 0 sheep/ha and 9.0 sheep/ha in August 2010 in the Xilin River Basin in Inner Mongolia. 4
- Figure 1.3** Monthly precipitation and mean monthly ambient air temperatures at the Inner Mongolian Grassland Ecosystem Research Station during 2005 – 2010. 5
- Figure 1.4** Idealized illustration of the experimental split-plot-design of alternating and continuous grazing management system. 8
- Figure 1.5** Location of the experimental area in the Xilin River Basin in Inner Mongolia, China; map based on Tong et al. (2004). 10
- Figure 2.1** Regression equations ($y=a+b\cdot x+c\cdot x^2$, because no progressive increase is expected, if $c>0$, c is considered as 0) between daily live weight gain of individual animals (LWG_a) and stocking density (x) during the grazing season of 2005 – 2010. 32
- Figure 2.2** Regression equations ($y=a+b\cdot x+c\cdot x^2$, because a non-progressive increase is expected, if $c>0$, c is considered as 0) between daily live weight gain per hectare (LWG_h) and stocking density (x) during the grazing season of 2005 – 2010. 32
- Figure 2.3** Regression equations ($y=e^a\cdot e^{b\cdot x}$) between the end-of-season standing biomass (ESSB) and stocking density (x) during the grazing season of 2005 – 2010 ($n=12$ per year). Grey line indicates for ESSB threshold of 656 g OM/ha. 38

- Figure 2.4** Regression equations ($y=a+b\cdot x$) between the vegetation ground cover and stocking density (x) during the grazing season 2006 – 2010. For regression equations and statistics see Table 2.5. Grey line indicates for threshold of 70% vegetation ground cover. 40
- Figure 3.1** Daily live weight gain (LWG) of supplemented (SUP) and non-supplemented (NSUP) sheep grazing the Inner Mongolian steppe during July, August and September 2010 from herbage allowance class 1 – 6 in continuous (dark grey box plots) and alternating grazing system (light grey box plots in 2010). 59
- Figure 4.1** Regression equations ($y=a\cdot e^{b\cdot x}$) between the end-of-season standing biomass (ESSB) and stocking density (x) during the grazing season of 2005 – 2010 with and without concentrate supplementation ($n=12$ per year). Grey line indicates for the ESSB threshold of 656 g OM/ha. 76

List of Tables

Table 2.1	Precipitation and mean ambient air temperatures determined near the experimental area per year and during May – September of 2005 – 2010 and minimum and maximum as well as total mean values of 1982 – 2004.	21
Table 2.2	Experimental scheme.	23
Table 2.3	Influence of herbage allowance (HA) classes on daily organic matter intake (OMI), metabolizable energy intake (MEI), and daily live weight gain (LWG) of individual animals (a) and per hectare (h) during the grazing season of 2005 - 2010.	28
Table 2.4	Regression equations ($y=a+b\cdot x+c\cdot x^2$, if $c>0$, c is considered as 0) between daily organic matter intake of individual animals (OMIa), daily live weight gain of individual animals (LWGa), organic matter intake per hectare (OMIh), daily live weight gain per hectare (LWGH) and stocking density (x) during the grazing season of 2005 – 2010.	31
Table 2.5	End-of-season standing biomass (ESSB) at the end of grazing season 2005 – 2010 and vegetation ground cover at the end of grazing season 2006 – 2010.	39
Table 2.6	Regression equations for end-of-season standing biomass (ESSB) at the end of grazing season of 2005 – 2010 ($y=e^a\cdot e^{b\cdot x}$) and ground cover at the end of grazing season 2006 – 2010 ($y=a+b\cdot x$).	40
Table 3.1	Experimental scheme.	52
Table 3.2	Composition across the experimental periods [g/kg dry matter], <i>in vitro</i> digestibility of organic matter (IVdOM), and metabolizable energy (ME) concentration [MJ/kg dry matter] of concentrate feed and herbage.	53
Table 3.3	Digestibility of organic matter (dOM), organic matter intake (OMI), digestible organic matter intake (DOMI), and metabolizable energy intake (MEI), and herbage of organic matter intake (herbageOMI) as well as daily live weight gain (LWG) of supplemented (SUP) and non-supplemented (NSUP) sheep grazing the Inner Mongolian steppe at different herbage allowance classes during July-September 2010.	56

- Table 3.4** Effects of concentrate supplementation (SUPPL), grazing system (SYS), herbage allowance (HA) classes, experimental period (EP) and their interactions on digestibility of organic matter (dOM), organic matter intake (OMI), digestible organic matter intake (DOMI), metabolizable energy intake (MEI), herbage organic matter intake (herbageOMI) as well as daily live weight gain (LWG) of sheep grazing the Inner Mongolian steppe during July-September 2010. 57
- Table 3.5** Digestibility of ingested organic matter (dOM), organic matter intake (OMI), digestible organic matter intake (DOMI), metabolizable energy intake (MEI), herbage organic matter intake (herbageOMI) per metabolic live weight ($LW^{0.75}$) as well as daily live weight gain (LWG) of supplemented (SUP) and non-supplemented (NSUP) sheep grazing the Inner Mongolian steppe during different experimental periods in 2010. 58

List of abbreviations

ADF	Acid detergent fiber
ADL	Acid detergent lignin
ALT	Alternating grazing system
CA	Crude ash
CON	Continuous grazing system
CP	Crude protein
CV	Coefficient of variation
d	Day
DM	Dry matter
dOM	Digestibility of ingested organic matter
DOMI	Digestible organic matter
EP	Experimental period
ESSB	End-of-season-standing biomass of vegetation
FAO	Food and Agriculture Organization of the United Nations
HA	Herbage allowance
herbageOMI	Herbage organic matter intake
HM	Herbage mass
HPRS	Household Production Responsibility System
IVdOM	In vitro digestibility of organic matter
kg ^{0.75} LW	kg metabolic live weight
LW	Live weight
LWG	Live weight gain
LWGa	Live weight gain per animal
LWGh	Live weight gain per ha
MEg	Metabolizable energy requirements for growth
ME	Metabolizable energy
MEI	Metabolizable energy intake
ME _m	Metabolizable energy requirements for maintenance
NDF	Neutral detergent fiber
NSUP	Non-supplemented animals
OM	Organic matter

Contents

OMI	Organic matter intake
OMIa	Organic matter intake per animal
OMIh	Organic matter intake per ha
RMSD	Root mean square deviation
RSD	Residual standard deviation
SD	Stocking density
SE	Standard error
SEM	Standard error of the mean
SUP	Supplemented animals
TiO ₂	Titanium dioxide

1 General introduction

1.1 Historical and socio-economic context of land use in Inner Mongolia

Over thousands of years, nomadic herders have grazed livestock on the vast grasslands of the Mongolian plateau (Douglas et al., 2006). Through the seasonal movements of their herds, herders have provided the basis of their country's economy without degrading its ecosystems (Li et al., 2007). However, significant differences in governmental policies and land use practices have developed between Inner and Outer Mongolia in the past century (Li et al., 2007). After the Qing Dynasty (1644 – 1911), Inner Mongolia was divided into Chinese administrative provinces, whereas in Outer Mongolia the pre-Qing structures continued to dominate.

Before this political transformation, the steppe region of Inner Mongolia was traditionally used by Mongol nomads. A 'banner prince' acted as custodian of the people and land, and his territory contained a number of separate pastures, each used in a certain season (Li et al., 2007). Individual households had customary rights to the use of particular pastures for the respective seasons (Li et al., 2007). The herders and farmers rented livestock herds or worked for the banners to earn an annual salary (Li et al., 2007). With no permanent settlement, the herders moved their livestock regularly according to the seasonal availability of herbage for their animals (Williams, 1996). This grassland management system kept grazing pressures at a low level. However, with the feudal empire being replaced by the Chinese Republic in 1911, all Mongol lands came under the ownership of the federal Chinese authorities (Li et al., 2007). At first, herders still possessed land-use rights irrespective of the land ownership (Li et al., 2007). Prior to the establishment of the People's Republic of China in 1947, the Inner Mongolian Autonomous Region was established following the Soviet model of minority politics. In 1958 the entire livestock and land was collectivized (Li et al., 2007). The Chinese government condemned the nomads' economy as antiquated, and as a result the nomads were forced to give up their nomadic way of life and settle in small villages, hamlets, or individual farms (Neupert, 1999). These policies eliminated large-scale pastoral movements between seasonal pastures and increased the tendency towards year-round grazing of livestock (Sneath,

1998). Additionally, the Chinese government instigated a massive Han Chinese settlement to Inner Mongolia between 1950 and 1980 to occupy what was considered a strategically important region (Williams, 1996; Neupert, 1999). While in other areas stocking densities remained constant or even decreased, sedentarization of nomads increased livestock populations, and consequently grazing pressure, especially around the newly established settlements (Yiruhan et al., 2001). According to Yiruhan et al. (2001), stocking densities were 0.1 sheep/ha in 1950 and increased to an average of 0.6 sheep/ha in 1980. In 1983, the Household Production Responsibility System (HPRS) was implemented in the Xilingol region to regulate the semi-private property rights. Also referred to as double-contract HPRS, this system consisted of two contracts, one regarding the rights of livestock and another regulating the access to grassland resources (Li et al., 2007). This new economic policy led to changing property rights in the form of privatization of land-use and animal production and allowed individual farmers to directly profit from increased meat or wool production. In the 20th Century, Inner Mongolia became a province of the People's Republic of China whereas Outer Mongolia continued to form the sovereign State of Mongolia. In 2012, approximately 24 million people live in Inner Mongolia (20 people/km²). The Han Chinese account for 80% of the population in Inner Mongolia, with only 4 million people (17%) belonging to the Mongol tribes (Han, 2011); the indigenous former-nomads are nowadays a minority in their own country.

Driven by business conditions and political regulations, farmers are now interested in short-term profits without acting for future utilization of the grassland resources. Animals are kept at high stocking densities close to settlements, with areas further away being used for hay making (Figure 1.1 a). During winter and summer, farmers still keep sheep in paddocks at night to accumulate manure for heating and cooking (Figure 1.1 b). Farmers' households largely depend on this free supply for their energy demands. For this reason the usage of paddocks is still an integral part of grazing management.

In summary, change in governance and land property rights, combined with the sedentarization of nomads and the increasing population in the last decades, have lead farmers to strive for maximum short-term economic output. With the demise of traditional – and highly sustainable – land-use practices and livelihoods based on animal husbandry, the grassland ecosystem has become over-used and income-generation from animal production has become highly compromised (Williams, 1996).

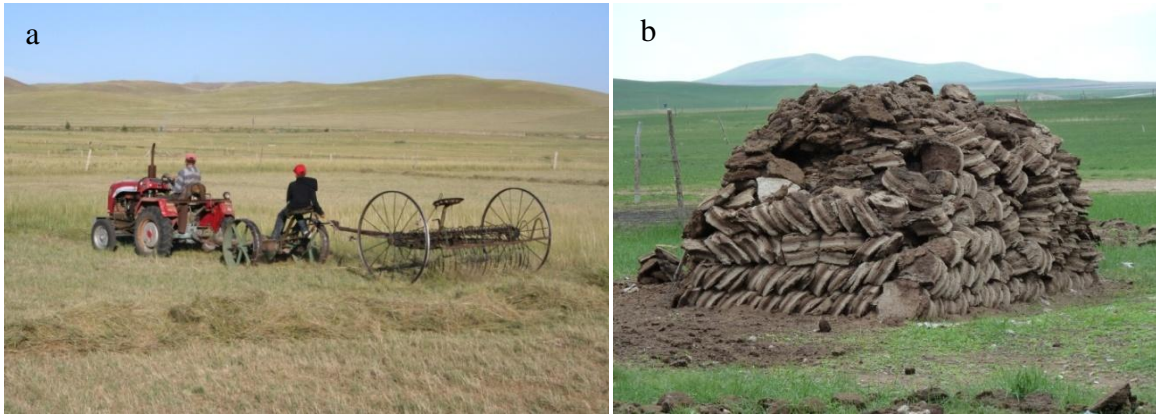


Figure 1.1a. Hay making in August 2010 in the Xilin River catchment in the Inner Mongolian steppe. **b.** Dried sheep manure from the winter paddocks for heating and cooking in the countryside of Inner Mongolia.

1.2 Importance of Inner Mongolian grassland and ecological consequences of overgrazing

Grasslands are one of the most important terrestrial biome types in the world, covering approximately 25% of the global land surface. China contains nearly 400 million hectares of grassland, accounting for about 12.5% of the global extent of this ecosystem. The most important and productive grasslands in China belong to Inner Mongolia (Yu et al., 2004; Fan et al., 2009). By providing forage for cattle and sheep production, the Inner Mongolian grasslands contribute significantly to the economy and food security of China (ECGRIM, Editorial Committee for Grassland Resources of Inner Mongolia, 1990, cited by Fan et al., 2009). Production of mutton meat in China has seen a high increase from 1,810 kt in 1996 to 2,513 kt in 1999, with 38% being produced in pastoral regions (FAO, 2003). Milk production increased from 7,358 kt in 1996 to 8,069 kt in 1999 with 28% produced in pastoral regions (FAO, 2003).

According to the Food and Agriculture Organization of the United Nations (FAO, 2012), annual forage yield in the temperate steppe of Inner Mongolia is about 889 kg dry matter (DM)/ha allowing for a stocking capacity of 1.42 ha/sheep/year. This equates to a stocking density (SD) of 0.7 sheep/ha (or 2.1 sheep/ha in a grazing period of 4 months) and 3.5 kg DM/d per sheep, which is well above the required amount of about 1 kg DM/d per sheep. According to the FAO (2012), a sheep unit is defined as one 40 kg ewe with lamb, with a daily intake of 5 – 7.5 kg of fresh grass. However, this standard differs to the values in the recent experimental study in which a sheep unit is defined as one hogget with an

initial live weight of 32 kg. Governmental regulations specify a stocking rate of 1 sheep/ha/year (SD in a grazing period of 4 months = 3 sheep/ha). Actual SDs, however, are much higher at 7.4 sheep/ha in a grazing period of 4 months (Tong et al., 2004). In Figure 1.2, the consequences of these different SDs can be clearly seen.



Figure 1.2A fence line creating a contrast between pastures with a stocking density of 0 sheep/ha (left) and 9.0 sheep/ha (right) in August 2010 in the Xilin River Basin in Inner Mongolia.

High SDs may maximize short-term animal production per unit area (Glindemann et al., 2009), but they decrease long-term grassland productivity and therefore long-term animal production (Kawamura et al., 2005; Schönbach et al., 2009). Wilson and Macleod (1991), in discussing factors that may enhance or reduce overgrazing, defined an area as overgrazed when grazing causes a vegetation degradation and reduction in animal performance (e.g. live weight gain). They observed overgrazing as a loss of linearity between animal productivity and stocking rate with time. Similarly, Conant and Paustian (2002) define a pasture as overgrazed when productive capacity diminished.

Inner Mongolia is described as having a typical temperate steppe climate with continental influences resulting in long and cold winters and short, but hot, summers (Figure 1.3).

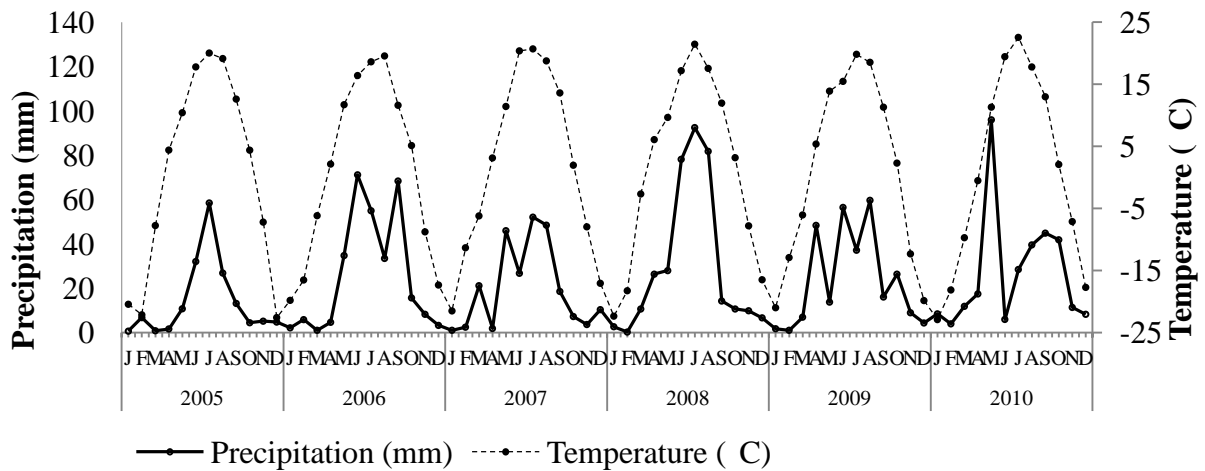


Figure 1.3 Monthly precipitation and mean monthly ambient air temperatures at the Inner Mongolian Grassland Ecosystem Research Station during 2005 –2010.

Semi-arid regions in Inner Mongolia are vulnerable to climate change (Christensen et al., 2004) because water is the limiting factor for vegetation growth (Bai et al., 2004). Water resources are already at a low level and, with increasing temperatures, the water availability for plants will decrease. During the last 50 years, ambient temperatures in the region have increased, whereas annual precipitation has decreased, the trends being more pronounced during the last three decades (Douglas et al., 2006; Lu et al., 2009). For example, according to a regression analysis of data measured at a weather station in the Xilin River Basin in Inner Mongolia, the mean annual ambient air temperature rose from 0.7 °C to about 1.4 °C in the period 1982 – 2004, whereas annual precipitation remained stable at 343 mm. According to Li et al. (2012), climatic conditions in the study region changed to an overall warmer and drier climate during the past 44 years (1961 – 2005) with an increase of mean annual ambient air temperature by 1.9°C and a decrease of annual precipitation by 12.5 mm. According to Fan et al. (2009), changes in the climatic conditions of Inner Mongolia could reduce the capacity of the grassland to store carbon. In the last 50 years, there has been rapid socio-economic development in Inner Mongolia with significant increases in population, urbanization, and intensified land-use practices. Lu et al. (2009) predict that climate change will not only affect the ecological and physiological features of the natural environment but also – as a consequence of decreasing grassland productivity – have severe consequences for human populations.

Land-use change, in the form of increasing stocking density, is considered a key driver of future biodiversity loss worldwide (Pereira et al., 2010). In particular, arid and semi-arid regions of the world are vulnerable to unsustainable land management measures.

These can have long-lasting negative effects on the productivity and diversity of rangeland vegetation and may even lead to near-irreversible desertification (Milton et al., 1994). Hence, specialists in the region have estimated that more than a third of the Inner Mongolian grassland has been degraded during the 20th century (Yu et al., 2004; Meyer, 2006). Over grazing is believed to be one of the most important reasons for steppe degradation leading to severe desertification (Li et al., 2000; Christensen et al., 2003; Yu et al., 2004; Li et al., 2012). Direct consequences of the intensified grassland use are the reduction in plant biomass production, the loss of biodiversity, an increased frequency of rodent and grasshopper infestations, and the occurrence of sand storms which even reach Beijing and which have attracted the world's attention (Han et al., 2008; Cease et al., 2012). These problems are now high on the political agenda and solutions are being sought to enhance the sustainability in these ecosystems. In 1990, the Chinese government attempted to protect the grassland with land-use policies. For instance, farm lease period was expanded by the governing authorities in order to incentivize more sensitive management of the grasslands (Zang, 2008), or highly degraded areas were enclosed with fences (Li et al., 2012). In response to this increasing awareness, since 2000 the Central Government of China has initiated several projects to protect rangelands (Han et al., 2008). One example is a large-scale project that aims to reduce the risk of sand and dust storms in China by creating a "Great Green Wall": a belt of trees to be planted over some 4,480 km from western Xinjiang to eastern Heilongjiang. This project started in 1970 and is projected to be completed in 2050, but has so far only shown marginal success (Yan et al., 2011). Despite political endeavors for long-term sustainable utilization of the grasslands, results on the ground are meager.

In order to avoid grassland degradation and restore the multiple functions of the Inner Mongolian steppe, the primary causes of degradation need to be identified and addressed. In semi-arid regions arable farming is mainly limited by the low precipitation, and so these areas are generally used for livestock husbandry. A growing human population and the increasing demand for products of animal origin worldwide heighten land-use intensity and lead to overgrazing in these regions. In addition, change in political governance and land property rights, as well as the sedentarization of nomads with short land leasing contracts, has led to short-term profiteering and consequent overgrazing. Since the farmers are still dependent on the grassland resources, it is necessary to conserve this ecosystem to safeguard their future income from livestock husbandry. To be able to protect

this ecosystem it is important to understand the relationship between management strategies and parameters that determine this system, like climate conditions and vegetation composition. In recent years, grazing-induced degradation processes have been the subject of many studies (Yu et al., 2004; Hoffmann et al., 2008; Wiesmeier et al., 2009; Schönbach et al., 2011). Furthermore, grazing effects on biomass production and animal performance have been extensively analyzed (Glindemann et al., 2009; Wang et al., 2009; Wan et al., 2011; Lin et al., 2012; Schönbach et al., 2012; Dickhoefer et al., submitted; Müller et al., submitted). In contrast, only a few studies highlight the effects of long-term sheep grazing and different management strategies on the ecology and economy. It is important to find management strategies that address carrying capacities and animal productivity. Previous work has shown that novel grazing management systems can help reduce the negative consequences of high SDs (Noy-Meir, 1975; Virgona et al., 2000). In order to analyze the effects of different grazing systems and intensities on sheep grazing over a period of several years, the MAGIM-project established a grazing experiment in 2005.

1.3 The MAGIM- and LOTGras-Project and the Xilin River catchment

The Sino-German MAGIM-project (“Matter fluxes of Grasslands in Inner Mongolia as influenced by stocking rate”) ran between 2004 and 2010 and was funded by the Deutsche Forschungsgemeinschaft (German Research Foundation). The aim of the project was to study the complex interactions between different grazing management strategies and the productivity of the Inner Mongolian steppe grassland, as well as feed intake and performance of sheep grazing. The major objectives of the MAGIM-project were to define the range of optimum grazing intensities in relation to long-term sustainability and to demonstrate the positive effects of moderate grazing intensities, in a regime of alternating grazing, on the sustainability of grassland use in Inner Mongolia. Compared to the contemporary practice of local farmers to continuously use the same grassland areas for cattle and sheep grazing, an alternating grassland use for hay making and grazing has been assumed to benefit the grassland in two ways (Owens et al., 1989). Firstly, it allows the vegetation to recover from grazing during hay-making years. Secondly, it provides an input of organic matter and nutrients to the rangelands in grazing years through animal

defecation and urination, thereby maintaining grassland productivity. The hypothesis to be tested was that the development of an adapted grazing system can increase animal performance and income of farmers while avoiding the negative effects of grazing and matter fluxes on the steppe vegetation. The project LOTGras (“Long-term strategies towards improved grassland productivity in semi-arid environments”, 2010 – 2013) focused on precise feed supplementation to improve sustainable animal productivity and avoid degradation of the plant community. Different grassland areas were analyzed for grazing system parameters including optimum herbage allowance (HA) class with respect to the performance of individual animals, animal production per unit of land area, biomass production of the grassland, soil quality, and nutrient fluxes. In this way, two grazing systems with six different HA classes (from very light to very heavy grazing) were established (Figure 1.4).

Herbage allowance classes	Mean stocking density (2005-2010) (sheep/ha)	Herbage allowance target ranges (kg DM/kg live weight)	Alternating system				Continuous system			
			Block 1		Block 2		Block 1		Block 2	
			Hay and grazing plots change annual				Hay	Grazing	Hay	Grazing
1	1.7 ± 0.2	>12					4 ha			
2	3.4 ± 0.5	>6.0 – 12.0					2 ha			
3	4.6 ± 0.4	>4.5 – 6.0					2 ha			
4	6.1 ± 0.6	>3.0 – 4.5					2 ha			
5	8.0 ± 0.6	>1.5 – 3.0					2 ha			
6	9.5 ± 0.6	>1.5					2 ha			

Figure 1.4 Idealized illustration of the experimental split-plot-design of alternating and continuous grazing management system. Mean stocking density (mean ± standard deviation). DM, dry matter.

HA classes were defined by HA, since it can better describe grazing intensity than stocking density (SD) if herbage mass (HM) varies between plots (Schönbach et al., 2009). To maintain constant HAs across the whole grazing period, the number of sheep per area was

adjusted to standing HM every month subsequent to animal weighing and HM determination. Stocking density was defined by the number of animals per hectare at a certain time (Scarnecchia, 1985). In the MAGIM-project, one sheep corresponds to one hogget with an initial live weight of 32 kg. Related to the current common procedure of farming in this region, a continuous grazing system (Continuous System, CON) with permanently used grazing plots and hay-making plots was established. The second system is a sophisticated alternating grazing system (Alternating system, ALT) where grazing plots and hay-making plots alternate annually.

The MAGIM- and LOTGras-projects were carried out in collaboration with the Institute of Botany, Chinese Academy of Science, Beijing. Since 1979, the institute has administered the “Inner Mongolia Grassland Ecosystem Research Station” (IMGERS; E 116°42', N 43°38') in the southern part of the Xilin River Basin, approximately 600 km north of Beijing and 70 km southeast of the district capital Xilinhot (Figure 1.5). The study area (160 ha) is part of the Xilingol grassland in the Chinese province of Inner Mongolia. It is located on an upper basalt platform near the Xilin River and belongs to IMGERS.

The basalt plateaus are mainly covered with fine-sand loess. The major soil types in this region are chestnuts and calcic chernozems (IUSS Working Group WRB, 2007; Hoffmann et al., 2008). The average elevation is about 1200 m above sea level. The climate in the Xilin River Basin is typical for the temperate steppe region, with high intra- and inter-annual variability in precipitation. The coefficient of variation is 22% (Xiao et al., 1995). The average annual temperature and precipitation are 1.4°C and 296 mm (2003 – 2010), respectively (Figure 1.3). From October to April, the climate is cold and dry with no plant growth, whereas the vegetation period from May until September is short and hot with only a few heavy rainfall events. Annual above-ground net primary production of the grassland is about 1.4 t dry matter/ha and highly variable depending on the amount of rainfall (Yu et al., 2004; Schönbach et al., 2011). The prevalent plant communities characterizing the typical steppe are dominated by the perennial bunchgrass *Stipa grandis* P. Smirn. and the rhizome grass *Leymus chinensis* Trin. Tzvel. (Bai et al., 2004).

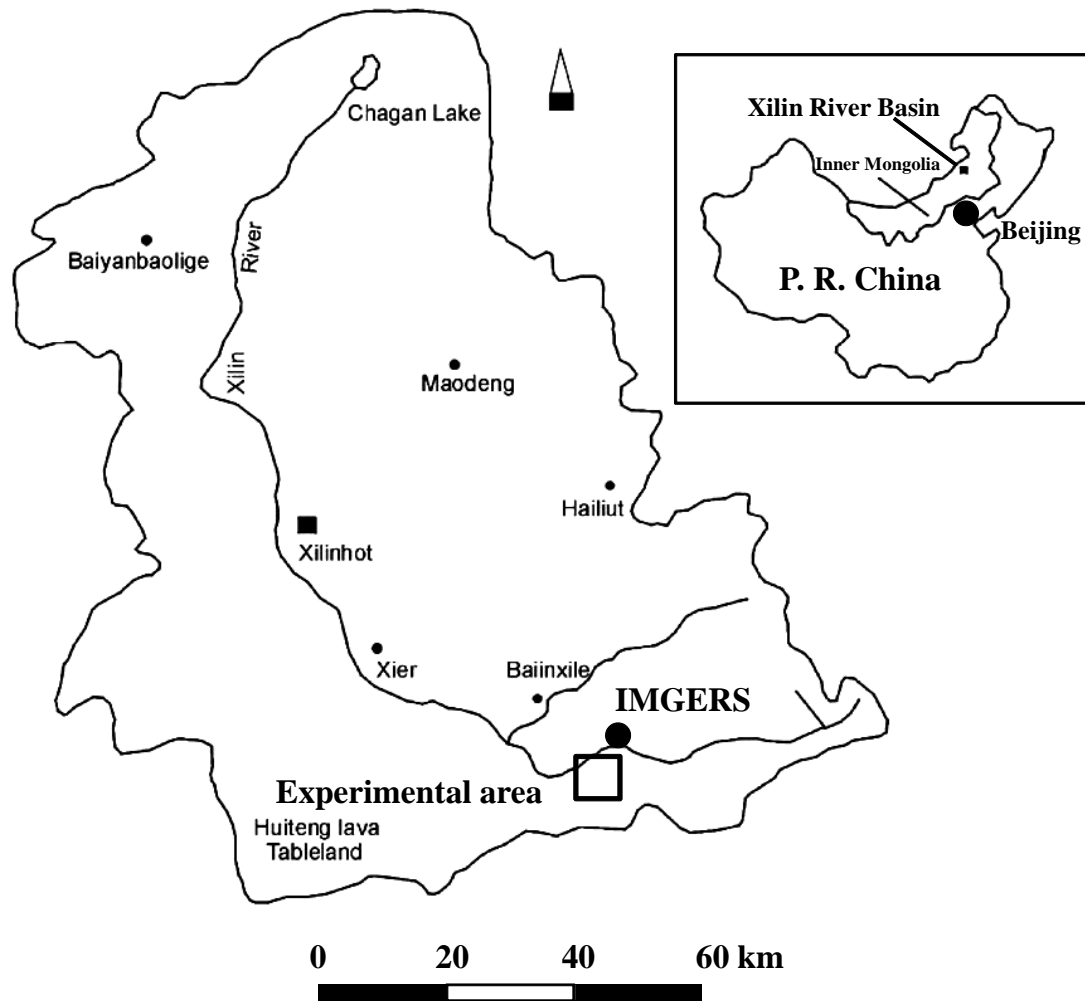


Figure 1.5 Location of the experimental area in the Xilin River Basin in Inner Mongolia, China; map based on Tong et al. (2004). IMGERS, Inner Mongolian ecosystem research station.

1.4 Hypotheses within the framework of this dissertation

This thesis analyzes data collected during six years of study (2005 – 2010). The project investigates the effects of increasing grazing intensities within an alternating grazing management system on animal feed intake and performance and, hence, the ecological and economic consequences of high stocking densities (Chapter 2). In addition, the effect of a concentrate feed supplementation on feed intake and live weight gain, and how this depends on grazing intensities, the two grazing management systems, and the progress of vegetation during the season, is evaluated based on data collected during the grazing season of 2010 (Chapter 3). An overview of land use and ecological problems of Inner Mongolia and the effects of grazing intensity on available herbage are given in Chapter 1. In Chapter 4 the implications of the results are discussed.

The hypotheses were:

- I. Live weight gain (LWG) will increase with decreasing SD. We assume that the effect of SD will be highly dependent on precipitation and will therefore differ between years because of significant inter- and intra-annual variations. In dry years the effect of SD will be greater than in wet years, because of less herbage growth. The effects of overgrazing will be stronger within the course of the study and with advancing grazing season. With increasing SD grazing pressure on the grassland will increase, and less food will be available for the animals. With less herbage availability at higher SDs, the animals will not be able to select special grass and herb species. As a result, in the short-term the quality of herbage intake will be lower. Furthermore we assume that at higher SDs the animals will show higher grazing activity. As selective grazers, they will have to search longer for food when herbage mass is low, and consequently they need more energy for movement and more time for grazing.
- II. Concentrate feeding will enhance energy intake, and hence performance of sheep. This in turn will lead to a higher total animal yield per unit of land area, and will allow for a reduction in stocking densities and resultant reduction in grazing pressure on the grassland steppe. As the ground cover will be less depleted, this will furthermore contribute to preventing wind erosion during the winter months (Hoffmann et al., 2008). Due to rapid plant maturation and a limited herbage re-growth during the short vegetation period of only 4–5 months, herbage mass and nutritional value strongly declines with advancing grazing season. The effect of concentrate supplementation is assumed to increase towards the end of the vegetation period and will be more pronounced at high grazing intensities because herbage mass and nutritional quality, as well as the selective feeding behavior, are lower. It is also assumed that concentrate supplementation will increase herbage intake due to a greater diet digestibility and a faster gastro-intestinal passage.
- III. Grazing systems that include repeated resting periods will be more resilient to high grazing intensities. Biomass production and nutritional quality of the herbage in the study region have been found to be higher with an alternating grassland use for grazing and hay-making (Schönbach et al., 2011; ALT and CON represented the mixed and traditional grazing systems in their study). We furthermore hypothesize that the efficiency of concentrate supplementation will be higher in a continuous (CON) than alternating (ALT) grazing system due to the former having a lower ground cover,

different plant species composition of the vegetation, and thus, a lower mass and feeding value of the available forage. Moreover, the ability of animals to select for plant species or parts of higher feeding value is limited when food allowances are low. Altogether, this might result in greater increases in diet digestibility, lower forage replacement rates, and therefore an enhanced total feed intake of animals in CON compared to ALT systems.

1.5 References

- Bai, Y.F., Han, X.G., Wu, J.G., Chen, Z.Z., Li, L.H., 2004. Ecosystem stability and compensatory effects in the Inner Mongolia grassland. *Nature* 431, 181-184.
- Cease, A.J., Elser, J.J., Ford, C.F., Hao, S.G., Kang, L., Harrison, J.F., 2012. Heavy Livestock Grazing Promotes Locust Outbreaks by Lowering Plant Nitrogen Content. *Science* 335, 467-469.
- Christensen, L., Coughenour, M.B., Ellis, J.E., Chen, Z.Z., 2003. Sustainability of Inner Mongolian grasslands: Application of the Savanna model. *Journal of Range Management* 56, 319-327.
- Christensen, L., Coughenour, M.B., Ellis, J.E., Chen, Z.Z., 2004. Vulnerability of the Asian typical steppe to grazing and climate change. *Climatic Change* 63, 351-368.
- Conant, R.T., Paustian, K., 2002. Potential soil carbon sequestration in overgrazed grassland ecosystems. *Global Biogeochemical Cycles* 16, 90-91-90-99.
- Dickhoefer, U., Hao, J., Bösing, B.M., Lin, L.J., Susenbeth, A., submitted. Diet digestibility, feed intake and live weight gain of grazing sheep as affected alternating and continuous grazing systems.
- Douglas, A.J., Dennis, P.S., Daniel, M., Daalkhaijav, D., 2006. Mongolian rangelands in transition. *Secheresse* 17, 133-141.
- Fan, J.W., Wang, K., Harris, W., Zhong, H.P., Hu, Z.M., Han, B., Zhang, W.Y., Wang, J.B., 2009. Allocation of vegetation biomass across a climate-related gradient in the grasslands of Inner Mongolia. *Journal of Arid Environments* 73, 521-528.
- FAO, 2003. Transhumant Grazing Systems in Temperate Asia. In: Suttie, J.M., Reynolds, S.G. (Eds.), Chapter V - China's pasture resources - Zizhi Hu and Degang Zhang.

- Food and Agricultural Organization of the United Nations., Rome.
- FAO, 2012. Country Pasture/Forage Resource Profiles, China. In: Degang, P.H.Z.a.D.Z. (Ed.), 6. Opportunities for improvement of fodder resources. Food and Agricultural Organization of the United Nations. Rome.
- Glindemann, T., Wang, C., Tas, B.M., Schiborra, A., Gierus, M., Taube, F., Susenbeth, A., 2009. Impact of grazing intensity on herbage intake, composition, and digestibility and on live weight gain of sheep on the Inner Mongolian steppe. *Livestock Science* 124, 142-147.
- Han, E., 2011. From domestic to international: the politics of ethnic identity in Xinjiang and Inner Mongolia. *Nationalities Papers* 39, 941-962.
- Han, J.G., Zhang, Y.J., Wang, C.J., Bai, W.M., Wang, Y.R., Han, G.D., Li, L.H., 2008. Rangeland degradation and restoration management in China. *Rangeland Journal* 30, 233-239.
- Hoffmann, C., Funk, R., Wieland, R., Li, Y., Sommer, M., 2008. Effects of grazing and topography on dust flux and deposition in the Xilingele grassland, Inner Mongolia. *Journal of Arid Environments* 72, 792-807.
- IUSS Working Group WRB, 2007. World reference base for soil resources 2006, 2nd edition. World Soil Resources Reports No. 103, First Update. FAO, Rome.
- Kawamura, K., Akiyama, T., Yokota, H., Tsutsumi, M., Yasuda, T., Watanabe, O., Wang, S.P., 2005. Quantifying grazing intensities using geographic information systems and satellite remote sensing in the Xilingol steppe region, Inner Mongolia, China. *Agriculture, Ecosystems and Environment* 107, 83-93.
- Li, S., Verburg, P., Lv, S., Wu, J., Li, X., 2012. Spatial analysis of the driving factors of grassland degradation under conditions of climate change and intensive use in Inner Mongolia, China. *Regional Environmental Change* 12, 461-474.
- Li, S.G., Harazono, Y., Oikawa, T., Zhao, H.L., He, Z.Y., Chang, X.L., 2000. Grassland desertification by grazing and the resulting micrometeorological changes in Inner Mongolia. *Agricultural and Forest Meteorology* 102, 125-137.
- Li, W.J., Ali, S.H., Zhang, Q., 2007. Property rights and grassland degradation: A study of the Xilingol Pasture, Inner Mongolia, China. *Journal of Environmental*

Management 85, 461-470.

- Lin, L.J., Dickhoefer, U., Müller, K., Chenjie, W., Glindermann, T., Hao, J., Wan, H., Schönbach, P., Gierus, M., Taube, F., Susenbeth, A., 2012. Growth of sheep as affected by grazing system and grazing intensity in the steppe of Inner Mongolia, China. *Livestock Science* 144, 140-147.
- Lu, N., Wilske, B., Ni, J., John, R., Chen, J., 2009. Climate change in Inner Mongolia from 1955 to 2005-trends at regional, biome and local scales. *Environmental Research Letters* 4.
- Meyer, N., 2006. Desertification and restoration of grasslands in Inner Mongolia. *Journal of Forestry* 104, 328-331.
- Milton, S.J., Dean, W.R.J., Duplessis, M.A., Siegfried, W.R., 1994. A Conceptual-Model of Arid Rangeland Degradation - the Escalating Cost of Declining Productivity. *Bioscience* 44, 70-76.
- Müller, K., Dickhoefer, U., Chenjie, W., Schönbach, P., Wan, H., Schiborra, A., Tas, B.M., Gierus, M., Taube, F., Susenbeth, A., submitted. Impact of grazing intensity or herbage quality, feed intake, and live weight gain of sheep grazing the steppe of Inner Mongolia, China.
- Neupert, R.F., 1999. Population, nomadic pastoralism and the environment in the Mongolian Plateau. *Population and Environment* 20, 413-441.
- Noy-Meir, I., 1975. Stability of Grazing Systems: An Application of Predator-Prey Graphs. *Journal of Ecology* 63, 459-481.
- Owens, L.B., Edwards, W.M., Vankeuren, R.W., 1989. Sediment and Nutrient Losses from an Unimproved, All-Year Grazed Watershed. *Journal of Environmental Quality* 18, 232-238.
- Pereira, H.M., Leadley, P.W., Proenca, V., Alkemade, R., Scharlemann, J.P.W., Fernandez-Manjarres, J.F., Araujo, M.B., Balvanera, P., Biggs, R., Cheung, W.W.L., Chini, L., Cooper, H.D., Gilman, E.L., Guenette, S., Hurtt, G.C., Huntington, H.P., Mace, G.M., Oberdorff, T., Revenga, C., Rodrigues, P., Scholes, R.J., Sumaila, U.R., Walpole, M., 2010. Scenarios for Global Biodiversity in the 21st Century. *Science* 330, 1496-1501.

- Scarnecchia, D.L., 1985. The Relationship of Stocking Intensity and Stocking Pressure to Other Stocking Variables. *Journal of Range Management* 38, 558-559.
- Schönbach, P., Wan, H., Gierus, M., Müller, K., Lin, L., Bai, Y., Loges, R., Susenbeth, A., Taube, F., 2012. Effects of grazing intensity and precipitation on herbage accumulation, herbage quality and animal performance in a semi-arid grassland of Inner Mongolia. *Grass and Forage Science* 67, 535-545.
- Schönbach, P., Wan, H.W., Gierus, M., Bai, Y.F., Müller, K., Lin, L.J., Susenbeth, A., Taube, F., 2011. Grassland responses to grazing: effects of grazing intensity and management system in an Inner Mongolian steppe ecosystem. *Plant and Soil* 340, 103-115.
- Schönbach, P., Wan, H.W., Schiborra, A., Gierus, M., Bai, Y.F., Müller, K., Glindemann, T., Wang, C., Susenbeth, A., Taube, F., 2009. Short-term management and stocking rate effects of sheep grazing on herbage quality and productivity of Inner Mongolia steppe. *Crop and Pasture Science* 60, 1-12.
- Sneath, D., 1998. Ecology - State policy and pasture degradation in inner Asia. *Science* 281, 1147-1148.
- Tong, C., Wu, J., Yong, S., Yang, J., Yong, W., 2004. A landscape-scale assessment of steppe degradation in the Xilin River Basin, Inner Mongolia, China. *Journal of Arid Environments* 59, 133-149.
- Virgona, J.M., Avery, A.L., Graham, J.F., Orchard, B.A., 2000. Effects of grazing management on phalaris herbage mass and persistence in summer-dry environments. *Australian Journal of Experimental Agriculture* 40, 171-184.
- Wan, H.W., Bai, Y.F., Schönbach, P., Gierus, M., Taube, F., 2011. Effects of grazing management system on plant community structure and functioning in a semiarid steppe: scaling from species to community. *Plant and Soil* 340, 215-226.
- Wang, C.J., Tas, B.M., Glindemann, T., Mueller, K., Schiborra, A., Schoenbach, P., Gierus, M., Taube, F., Susenbeth, A., 2009. Rotational and continuous grazing of sheep in the Inner Mongolian steppe of China. *Journal of Animal Physiology and Animal Nutrition* 93, 245-252.
- Wiesmeier, M., Steffens, M., Kolbl, A., Kogel-Knabner, I., 2009. Degradation and small-

- scale spatial homogenization of topsoils in intensively-grazed steppes of Northern China. *Soil & Tillage Research* 104, 299-310.
- Williams, D.M., 1996. The barbed walls of China: A contemporary grassland drama. *Journal of Asian Studies* 55, 665-691.
- Wilson, A.D., Macleod, N.D., 1991. Overgrazing - Present or Absent. *Journal of Range Management* 44, 475-482.
- Xiao, X.M., Wang, Y.F., Jiang, S., Ojima, D.S., Bonham, C.D., 1995. Interannual Variation in the Climate and Aboveground Biomass of *Leymus chinensis* Steppe and *Stipa grandis* Steppe in the Xilin River Basin, Inner-Mongolia, China. *Journal of Arid Environments* 31, 283-299.
- Yan, Q.L., Zhu, J.J., Hu, Z.B., Sun, O.J., 2011. Environmental Impacts of the Shelter Forests in Horqin Sandy Land, Northeast China. pp. 815-824.
- Yiruhan, H.I., Nakamura, T., Shiyomi, M., 2001. Changes in floristic composition of grasslands according to grazing intensity in Inner Mongolia, China. *Grassland Science* 47, 362-369.
- Yu, M., Ellis, J.E., Epstein, H.E., 2004. Regional analysis of climate, primary production, and livestock density in Inner Mongolia. *Journal of Environmental Quality* 33, 1675-1681.
- Zang, Z.S., 2008. Main developments of national grassland works. *Grassland Science* 25, 1-3.

2 Animal responses to stocking density: Feed intake and live weight gain of sheep grazing the Inner Mongolian Steppe – Results of a Six Year Study –

B.M. Bösing^a, U. Dickhoefer^{a†}, J. Hao^a, L. Lin^a, K. Müller^a, C. Wang^{a#}, T. Glindemann^a,
B. Tas^{a§}, M. Gierus^c, F. Taube^c, A. Susenbeth^{a*}

^a *Institute of Animal Nutrition and Physiology, Christian-Albrechts-Universität zu Kiel, 24098 Kiel, Germany*

[†] *Present address: Institute of Animal Production in the Tropics and Subtropics, University of Hohenheim, 70599 Stuttgart, Germany*

[#] *Present address: College of Ecology and Environment, Inner Mongolia Agricultural University, Zhaowuda Road, 306 Huhhot, China*

[§] *Present address: Schothorst Feed Research, Meerkoetenweg 26, 8200 AM Lelystad, Netherlands*

^c *Institute of Crop Science and Plant Breeding – Grass and Forage Science/Organic Agriculture, Christian-Albrechts-Universität zu Kiel, 24098 Kiel, Germany*

** Corresponding author. Tel.: +49 431 880 2013; fax: +49 431 880 1528. E-mail address: susenbeth@aninut.uni-kiel.de*

2.1 Abstract

An increasing human population and the growing demand for food of animal origin lead to an intensification of sheep production and widespread overgrazing of the grassland steppe in Inner Mongolia. Strategies for a sustainable livestock husbandry that protect the steppe vegetation and at the same time, satisfy farmers' economic interests are strongly needed. Hence, this study analyzed the effects of decreasing herbage allowances (HA) on organic matter intake (OMI) and live weight gain (LWG) of grazing sheep. In July to September 2005 – 2010, a grazing experiment was conducted in the Xilin River Basin using 15-months old female Mongolian fat-tailed sheep (31.5 ± 2.0 kg live weight (LW)). Six HA classes were tested on two experimental plots each that were alternately used for grazing and hay-making each year; and ranged from 15.4 ± 4.0 to 1.5 ± 0.8 kg herbage dry matter/kg LW. In 6 sheep per plot (4 sheep only in 2009 – 2010) OMI and LWG were determined. Titanium dioxide was used to determine fecal excretion and digestibility of ingested organic matter was estimated from crude protein concentration in faeces. Fecal grab samples were collected during a period of five days each in July, August and September. The animals were weighed every month. Daily OMI of sheep ranged between 68 and 89 g/kg^{0.75} LW and was not affected by HA class ($P=0.303$), so that total OMI per unit of land area strongly increased with decreasing HA ($P<0.001$). As a consequence, ground cover and standing biomass in the end of the grazing seasons were below the ecologically critical thresholds defined in literature for this region at HAs of 4.2 ± 1.3 kg herbage dry matter/kg LW, equivalent to 4.4 sheep/ha. Herbage mass differed strongly between years. LWG of individual sheep only tended to decrease with decreasing HA ($P=0.060$). While total LWG per hectare was very similar at stocking densities (SD) ≤ 4.5 sheep/ha (i.e. HA class 3) in all years, however strongly differed between years at higher SDs ($P=0.001$). The increasing LWG_h with increasing SD in 2007 and 2010 supports the common practice of farmers to manage the grassland at high SDs despite possible negative effects on its vegetation. Whereas in 2005, 2006, and 2009, increasing SD above 4 sheep/ha resulted in no or only minor increases in the LWG_h, showing that revenues for farmers did not improve with increasing SDs. Ground cover and ESSB indicate the necessity from an ecological point of view to use the grassland steppe at SDs lower than those yielding the highest animal output per unit of land area. Considering the small increase in LWG per unit of land area observed in 3 of the 6 years at SD higher than 4 sheep/ha, the constant costs per animal (e.g. for winter feeding), and strong negative effects

of overgrazing on grassland productivity not detectable within a short period, lowering SDs may not reduce the economical profit of farmers in the long term.

2.2 Introduction

In the arid and semi-arid regions of Northeast Asia, grassland degradation has become a major environmental and economic problem. According to Lepers et al. (2005), Asia currently has the greatest proportion of areas showing rapid land cover change, in particular degradation in the dry regions. Especially in Mongolia and Northern China, land degradation has been induced by anthropogenic factors such as heavy livestock grazing, inadequate management of arable land, and uncontrolled cutting of trees for fuel. Livestock grazing is, beside political developments like the governmental change, the change in land property rights and the sedentarization of nomads as well as the increasing population, one of the main causes of grassland degradation in this region leading to extensive soil erosion and desertification processes (Li et al., 2000; Christensen et al., 2003; Yu et al., 2004). Instead of a nomadic grassland use as in the past, livestock keepers in Inner Mongolia at present use the land near their farms for continuous sheep and cattle grazing, while distant areas are used for hay-making. Moreover, Tong et al. (2004) referred a stocking density (SD) of 8.8 sheep/ha instead of a SD of 2.4 sheep/ha recommended by the government. However, a sustainable utilization of resources is important not only to support the livelihoods of local people due to saving the food resource of their livestock, but also to protect the global environment i.e. by increasing carbon sequestration (Schönbach et al., 2012).

This study aimed to analyze the influence of different herbage allowances (HA) on digestibility of ingested organic matter (DOM), organic matter intake (OMI), and live weight gain (LWG) per animal (a) and per ha (h) within a sophisticated grazing system where livestock grazing and hay-making were alternated annually on experimental plots. We hypothesized that lower HAs will limit the animals' capability to select for plant parts and species of higher nutritional quality and thereby reduce dOM and OMI. Together with an intensified grazing behavior and consequently higher energy requirements for physical activity, this would reduce the amount of energy available for growth and LWG of individual sheep. Using data collected during six experimental years, we therefore aimed to define a HA threshold above which feed use efficiency and performance of individual animals decreases. These thresholds are further discussed in terms of their ecological effects on grassland

vegetation. For better assessment of the ecological relevant parameters OMI and LWG the ecological parameters End-of-season biomass (ESSB) and groundcover were included.

2.3 Material and methods

2.3.1 Study area

The study was conducted in the Xilin River Basin in the Inner Mongolia Autonomous Region of China (E116°42', N43°38') during 2005 – 2010. The study area is located on the Mongolian Plateau at about 1200 m above sea level. It belongs to the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) which is administered by the Institute of Botany of the Chinese Academy of Science, Beijing. The area had been moderately used for sheep grazing until October 2003. Afterwards, it was not grazed until the grazing trial was established in May 2005. The semiarid continental climate is characterized by a mean annual precipitation of 296 mm (2003 – 2010) and a mean annual air temperature of 1.4°C. Nearly 80 % of the annual precipitation coincides with highest temperature in summer (May – August, see Table 2.1). Climate data were collected at the local weather station of the IMGERS. The vegetation period lasts for approximately 150 days from April to September (Bai et al., 2004). It is thus typical for the temperate steppe region with high intra- and inter-annual variability in precipitation. The average annual above-ground net primary production (ANPP) of the grassland in our study region is 1400 kg/ha (Schönbach et al., 2011). The perennial rhizome grass *Leymus chinensis* Trin. Tzvel. and the perennial bunch grass *Stipa grandis* P. A. Smirn. characterize the grassland plant community (Bai et al., 2004). The major soil types are calcic chestnuts and calcic chernozems (IUSS Working Group WRB, 2007).

Table 2.1 Precipitation and mean ambient air temperatures determined near the experimental area per year and during May – September of 2005 – 2010 and minimum and maximum as well as total mean values of 1982 – 2004.

Parameter	Year										Mean	1982-2004	
	2005	2006	2007	2008	2009	2010	2010	Mean	Minimum	Maximum			
<u>Precipitation (mm)</u>													
Annual sum	166	304	240	362	281	319	319	279	241	507	343		
<u>Vegetation period</u>													
May	11	35	46	28	14	96	38	45	8	84	31		
June	32	71	27	78	57	6	45	54	25	113	56		
July	59	55	52	93	37	29	54	48	43	269	98		
August	27	34	49	82	60	40	48	29	10	133	73		
September	13	68	19	14	16	45	29	204	7	96	36		
Sum	142	263	192	295	183	215	215	215	204	445	293		
<u>Ambient air temperature (°C)</u>													
Annual mean	0.7	1.4	2.2	1.6	1.2	0.9	1.3	1.3	-1.3	2.2	0.7		
<u>Vegetation period</u>													
May	10.4	11.7	11.4	9.7	13.9	11.3	11.4	11.4	8.7	13.1	11.3		
June	17.8	16.4	20.4	17.2	15.5	19.5	17.8	17.8	13.6	18.8	16.5		
July	20.0	18.6	20.7	21.5	19.8	22.6	20.5	20.5	16.5	22.6	19.0		
August	19.2	19.6	18.8	17.6	18.5	17.8	18.6	18.6	15.4	19.9	17.4		
September	12.6	11.6	13.6	12.0	11.3	13.0	12.4	12.4	8.7	13.7	10.8		
Mean	16.0	15.6	17.0	15.6	15.8	16.8	16.1	16.1	14.0	16.9	15.0		

2.3.2 Experimental design

The experiment was conducted during the vegetation period of 2005 – 2010. Sheep were transferred to the grazing area in middle of June and removed from pastures in middle of September, resulting in a grazing period of three months per year. The experimental area was divided in grazed areas that were used for sheep grazing and ungrazed areas that were utilized for cutting hay. Two adjacent plots had been used alternately for animal grazing in the first and for haying in the following year since 2005. Six different HA classes were realized on two plots each, a flat and a moderately sloped plot. Therefore measurements were carried out on a total of twelve grazing plots (6 HA classes • 2 plots). Fixed SD treatments were applied in 2005 and 2006. Since HA will better describe grazing intensity than SD, if herbage mass (HM) differs between experimental plots or throughout the grazing period (Sollenberger et al., 2005), we used HA classes from 2007 onwards to account for differences in the ANPP between our experimental plots. HA was expressed as kg herbage dry matter (DM) per kg of animal live weight (LW). To maintain constant HAs across the whole grazing period, the number of sheep per plot was adjusted to standing HM every month subsequent to animal weighing and HM determination (see section 2.3.3). HA target ranges were >12.0, >6.0 – 12.0, >4.5 – 6.0, >3.0 – 4.5, >1.5 – 3.0 and >1.5 kg DM/kg LW for HA classes 1 to 6, respectively.

In 2005 and 2006, HA was similar to HA target ranges (see Table 2.2) and SDs were 1.5, 3.0, 4.5, 6.0, 7.5, and 9.0 sheep/ha and very similar to the mean SD at HA class 1 – 6 across the grazing periods in 2007 – 2010 of 1.7 ± 0.2 , 3.4 ± 0.5 , 4.6 ± 0.4 , 6.1 ± 0.6 , 8.0 ± 0.6 , and 9.5 ± 0.6 sheep/ha, respectively. The size of each plot was 2 ha except for HA class 1 plots which covered 4 ha each to be able to keep a minimum of six animals per plot.

2.3.3 Determination of herbage mass and dry matter

Herbage mass was determined in three representative areas à 0.5 m^2 ($0.25 \text{ m} \cdot 2 \text{ m}$) per plot by cutting the sward at 1 cm above ground level. Herbage sampling took place once in the beginning of June and again in the middle July, August, and September each year. Herbage material was pooled by plot, dried at 60°C for 24 h, and ground to pass a 1 mm sieve. Pool samples were analyzed for DM concentrations by drying at 103°C till constant weight.

Table 2.2 Experimental scheme (Arithmetic mean \pm standard deviation).

Parameter	Year	HA classes					
		1	2	3	4	5	6
Standing herbage mass (kg DM/ha)	2005	616 \pm 150	749 \pm 219	652 \pm 72	647 \pm 57	546 \pm 91	792 \pm 193
	2006	570 \pm 103	595 \pm 391	348 \pm 112	424 \pm 11	493 \pm 61	360 \pm 23
	2007	872 \pm 112	740 \pm 26	594 \pm 90	640 \pm 53	635 \pm 154	750 \pm 276
	2008	576 \pm 182	692 \pm 49	616 \pm 14	611 \pm 48	634 \pm 160	629 \pm 11
	2009	846 \pm 10	799 \pm 219	846 \pm 81	889 \pm 222	697 \pm 23	742 \pm 120
	2010	1035 \pm 141	785 \pm 100	873 \pm 172	913 \pm 107	850 \pm 89	800 \pm 92
Stocking density (sheep/ha)	2005	1.5 \pm 0.0	3.0 \pm 0.0	4.5 \pm 0.0	6.0 \pm 0.0	7.5 \pm 0.0	9.0 \pm 0.0
	2006	1.5 \pm 0.0	3.0 \pm 0.0	4.5 \pm 0.0	6.0 \pm 0.0	7.5 \pm 0.0	9.0 \pm 0.0
	2007	2.1 \pm 0.3	3.3 \pm 0.4	3.9 \pm 0.5	5.0 \pm 1.5	6.7 \pm 0.6	9.0 \pm 2.2
	2008	1.6 \pm 0.1	3.0 \pm 0.0	3.8 \pm 0.3	5.2 \pm 0.4	7.6 \pm 0.8	9.6 \pm 2.2
	2009	1.8 \pm 0.3	3.8 \pm 0.3	4.3 \pm 0.3	5.5 \pm 0.5	8.3 \pm 0.9	9.8 \pm 0.4
	2010	2.0 \pm 0.1	3.9 \pm 0.2	5.3 \pm 0.4	7.0 \pm 0.0	8.5 \pm 0.0	10.3 \pm 0.6
Initial LW (kg)	2005	30.1 \pm 1.9	30.2 \pm 0.9	32.4 \pm 1.8	32.9 \pm 1.2	29.9 \pm 1.1	32.1 \pm 0.1
	2006	30.2 \pm 1.1	32.2 \pm 3.3	31.6 \pm 2.1	31.9 \pm 0.4	31.6 \pm 1.4	30.5 \pm 1.2
	2007	32.8 \pm 1.7	30.9 \pm 0.8	31.4 \pm 0.1	30.3 \pm 0.6	31.1 \pm 0.4	31.4 \pm 0.2
	2008	31.5 \pm 1.5	31.5 \pm 0.3	33.5 \pm 1.0	33.1 \pm 2.1	35.0 \pm 0.0	34.2 \pm 1.1
	2009	35.6 \pm 0.0	35.3 \pm 5.7	36.0 \pm 2.4	35.3 \pm 0.1	36.2 \pm 0.2	35.1 \pm 0.2
	2010	30.6 \pm 0.3	30.1 \pm 0.3	30.4 \pm 1.0	30.6 \pm 0.3	29.9 \pm 0.5	30.3 \pm 0.1
Herbage allowance (kg DM/kg LW)	2005	18.2 \pm 4.6	8.3 \pm 1.9	3.7 \pm 0.8	2.7 \pm 0.8	2.2 \pm 0.6	1.6 \pm 0.8
	2006	16.7 \pm 1.7	7.6 \pm 1.6	2.2 \pm 0.6	1.8 \pm 1.0	1.5 \pm 0.9	0.9 \pm 0.5
	2007	10.4 \pm 2.6	6.2 \pm 0.7	4.3 \pm 1.1	4.3 \pm 1.7	2.0 \pm 0.6	1.9 \pm 0.9
	2008	18.1 \pm 1.8	9.4 \pm 0.8	5.4 \pm 0.6	3.4 \pm 0.3	1.5 \pm 0.6	1.0 \pm 0.5
	2009	11.4 \pm 0.9	6.2 \pm 1.9	4.9 \pm 0.7	3.8 \pm 1.2	2.2 \pm 0.8	1.4 \pm 0.6
	2010	17.6 \pm 2.2	6.7 \pm 0.3	4.7 \pm 0.9	3.5 \pm 0.6	2.6 \pm 0.7	2.2 \pm 0.9

HA, herbage allowance; DM, dry matter; LW, live weight. n=2, 2 plots; n=6, 3 months • 2 plots. *LW based on mean LW determined on two consecutive days of all sheep per plot (further details see material and methods).

2.3.4 Animals

Every year, about 150 female sheep of the Inner Mongolian fat-tailed breed were used for the experiment. The animals were purchased from local farmers, neither pregnant nor lactating, and about 15 months old. Before the experiment started, sheep were ear-tagged, subjected to anthelmintic treatment, and weighed on two consecutive days using a portable balance (accuracy 0.1 kg). The animals were divided into four LW groups (very light, light, medium, and heavy). Out of each LW group animals were randomly allocated to one of the twelve grazing plots to equalize mean LW per plot. Mean initial LWs of all study animals in June 2005 – 2010 were 31.6 ± 2.7 , 31.3 ± 1.5 , 31.3 ± 1.0 , 31.9 ± 1.7 , 31.9 ± 3.3 , and 30.8 ± 1.1 kg at HA classes 1 – 6, respectively. All sheep were weighed again on two consecutive days in the middle of July, August, and September. The mean LW of the two days was used to calculate the animals' LWG during each month. All animals were allowed to graze the natural grassland day and night. Water and mineral lick stones were freely available throughout the whole grazing periods. Details of the experimental scheme are given in Table 2.2. In 2006, animals at HA classes 5 and 6 had to be removed from the plots in the beginning of September, due to an early winter onset and too little HM on offer, so that no animal data could be collected for these HA classes in this month.

2.3.5 Feed and energy intake

Daily OMI of sheep was calculated from fecal organic matter (OM) excretion and dOM according to Eq.1.

$$\text{OMI [g/d]} = \text{fecal OM excretion [g/d]} / (1 - \text{dOM}) \quad (\text{Eq.1})$$

Fecal OM excretion was determined using the inert marker titanium dioxide (TiO_2) assuming a fecal recovery rate of 100% (Glindemann et al., 2009a). On ten consecutive days in the beginning of July, August, and September each year, a pulse dose of 2.5 g TiO_2 /d was orally administered to the four sheep per plot using a gelatin capsule. During each of these periods, fecal grab samples were obtained from the rectum on days 6 – 10 (sampling period). The samples were frozen immediately after collection. At the end of each sampling period, they were thawed, pooled by individual sheep and period, and homogenized. For chemical analyses two sub-samples were generated. One sub-sample was analyzed for nitrogen (N)

concentration according to the Kjeldahl procedure, for DM concentration by oven-drying at 103°C for 24 h, and for crude ash contents by incineration at 550°C for 12 h (Naumann and Bassler, 2004). The other sub-sample was oven-dried at 60°C for 36 h and ground to pass a 1 mm screen. TiO₂ was extracted according to the Kjeldahl procedure following descriptions by Brandt and Allam (1987) modified by Glindemann et al. (2009a). Subsequently, TiO₂ concentrations in the extracts were measured using a spectrophotometer (Jenway 6300 spectrophotometer, Bibby Scientific Limited, Staffordshire, UK) at a wavelength of 405 nm. Fecal OM output was calculated from daily TiO₂ administration and fecal TiO₂ concentration assuming a fecal recovery of 100% (Glindemann et al., 2009a; Eq. 2).

$$\text{Fecal excretion [g OM/d]} = \text{TiO}_2 \text{ dosage [g/d]} / \text{fecal TiO}_2 \text{ concentration [g/kg OM]} \cdot 1000 \quad (\text{Eq.2})$$

dOM was calculated from CP concentration in fecal OM using the non-linear regression equation of (Wang et al., 2009; Eq. 3) which was derived from 721 individual observations in sheep.

$$\text{dOM} = 0.899 - 0.644 \cdot \exp(-0.5774 \cdot \text{fecal CP [g/kg OM]}/100) \quad (\text{Eq.3})$$

Metabolizable energy (ME) concentrations of ingested OM were calculated from dOM according to the formula given by Aiple (1992; Eq. 4).

$$\text{ME [MJ/kg OM]} = -0.9 + 17.0 \cdot \text{dOM} \quad (\text{Eq.4})$$

Intake of ME (MEI) was calculated by multiplying OMI by dietary ME concentration.

2.3.6 Statistical analysis

All data were analyzed using the software program R version 2.14.0 (The R Foundation for Statistical Computing, Vienna, Austria). Mean values across the three experimental periods (July, August, and September) were calculated for each measured parameter. For 2006, means at HA class 5 and 6 were only calculated from values measured in July and August, due to missing data at these HA classes in September that year (see section 2.4). Hence, a total

number of 72 observations were obtained (6 HA classes • 6 years • 2 plots). A linear mixed model (ANOVA) was applied including the experimental variable HA class (HA class 1 – 6), year (2005 – 2010), and their interaction as fixed effects as well as the plots and the interaction of repetition and HA class (i.e. plot effect) were defined as random effects. Year was treated as repeated measurement with an autocorrelation structure. Arithmetic means and standard error of the means were calculated for each HA class and year. Effects were considered significant at $P \leq 0.050$. P-values between >0.050 and ≤ 0.100 were considered as a trend. Moreover, coefficients of variation (CV) were calculated for each HA class as an indicator for the inter-annual variation in measured parameters. Linear, quadratic, and exponential analyses were applied to describe the relationships between the SD (1.5 – 10.3 sheep/ha; independent variable) and LWGa, LWGh, OMIa, and OMIh (dependent variables) during each year. For further interpretations, the mathematical models (mathematical conditions for regression equation: $y = a + b \cdot x + c \cdot x^2$, because a non-progressive increase is expected, if $c > 0$, c is considered as 0; $y = e^a \cdot e^{b \cdot x}$) was chosen with the smallest residual error (RMSE) and the smallest Akaike information criterion-value. For LWGh in 2008 a linear instead of a quadratic model was chosen despite the superior statistical results for the latter, because of the strong decrease in HA class 6 (see Table 2.3). In 2005 the quadratic equation is only limited accurately because from 4 sheep/ha upwards no appreciable increase of LWGh with increasing SD is determined (see Table 2.3).

2.4 Results

2.4.1 Feed intake and performance of sheep at different herbage allowance classes

Across all HA classes and study years, dOM ranged between 52.6 – 61.9 %. It did not differ between HA classes ($P=0.419$) and no significant interactions between HA class and year were observed ($P=0.118$). There was an influence of year ($P<0.001$), and CV in dOM steadily increased from HA class 1 (43.5 %) and HA class 2 (40.4 %) to HA class 6 (54.4 %). There were no differences between HA classes in daily OMIa ($P=0.303$; Table 2.3) and MEI ($P=0.289$), the latter ranging between 0.51 and 0.86 MJ/kg^{0.75} LW. OMIa and MEI differed between years ($P<0.001$ for both parameters) which was, however, only due to differences between years observed at HA class 3. At this HA class, daily intake values were lower in 2010 (62.7 g/kg^{0.75} LW; 0.51 MJ/kg^{0.75} LW) than in 2006 (96.1 g/kg^{0.75} LW, $P=0.030$;

0.86 MJ/kg^{0.75} LW, $P < 0.010$). At all other HA classes the intake values OMIa and MEI were similar in all years ($P \geq 0.209$; $P \geq 0.134$). There were no interactions between HA class and year for OMIa ($P = 0.419$) and MEI ($P = 0.307$).

LWGa ranged between 36 g and 135 g/d. In contrast to digestibility and intake values there was a tendency of a HA class effect on LWGa ($P = 0.060$; Table 2.3). Moreover, a significant interaction between HA class and year was determined for LWGa ($P = 0.004$). This was not due to differences between HA classes' treatments within individual study years. Instead, LWGa differed between years ($P < 0.001$) at HA class 3 – 6 ($P \leq 0.021$), while it was similar in all years at HA class 1 and 2 ($P \geq 0.155$). Correspondingly, CV in LWGa increased with increasing HA class from 21.9 % and 17.0 % at HA class 1 and HA class 2, respectively, to 46.8 % at HA class 6, confirming the higher inter-annual variation in the performance of individual animals at higher HA classes. While at HA class 1 – 3 OMIh ($P \geq 0.892$) and LWGh ($P \geq 0.996$) were similar in all study years, both parameters differed between years at HA class 4 – 6 ($P \leq 0.010$, $P \leq 0.039$). Similar to LWGa, CV in LWGh continuously increased from 33.2 % at HA class 1 and 19.6 % at HA class 2 to 45.4 % at HA class 6, indicating a higher inter-annual variation in LWGh.

Table 2.3 Influence of herbage allowance (HA) classes on daily organic matter intake (OMI), metabolizable energy intake (MEI), and daily live weight gain (LWG) of individual animals (a) and per hectare (h) during the grazing season of 2005 - 2010 (Arithmetic means and standard error of mean (SEM), n=6 per HA class).

Parameter	Year	HA classes						Mean	SEM	P-value		
		1	2	3	4	5	6			HAclass	year	HAclass:year
OMIa [g/kg ^{0.75} LW]	2005	84.8	89.6	80.2 ^{AB}	77.8	63.2	77.4	78.8	6.0	0.303	<0.001	0.419
	2006	92.2	85.4	96.1 ^A	87.8	79.6	90.0	89.0	6.0			
	2007	88.0	76.4	77.4 ^{AB}	91.2	79.2	65.6	79.6	6.0			
	2008	80.5	82.8	82.4 ^{AB}	79.4	73.3	74.2	78.8	6.0			
	2009	83.0	82.2	81.0 ^{AB}	81.9	70.9	84.5	80.6	6.0			
	2010	66.7	63.9	62.7 ^B	70.4	69.9	75.0	68.1	6.0			
	Mean	82.5	80.0	80.0	81.4	72.3	77.1	79.0				
	2005	0.76	0.80	0.70 ^{AB}	0.67	0.54	0.66	0.69	0.06	0.289	<0.001	0.307
	2006	0.82	0.75	0.86 ^A	0.79	0.73	0.82	0.80	0.06			
	2007	0.79	0.67	0.70 ^{AB}	0.83	0.69	0.57	0.71	0.06			
2008	0.76	0.77	0.79 ^{AB}	0.75	0.70	0.71	0.75	0.06				
2009	0.76	0.73	0.73 ^{AB}	0.73	0.63	0.74	0.72	0.06				
2010	0.55	0.52	0.51 ^B	0.57	0.58	0.63	0.56	0.06				
Mean	0.74	0.71	0.71	0.72	0.64	0.68	0.70					
LWGa [g]	2005	83	91	64 ^A	44 ^A	45 ^A	36 ^A	61	12	0.060	<0.001	0.004
	2006	82	77	83 ^{AB}	81 ^{AB}	96 ^{AB}	124 ^B	88	12			
	2007	132	101	132 ^B	135 ^B	130 ^B	98 ^{AB}	121	12			
	2008	98	93	137 ^B	106 ^{AB}	91 ^{AB}	43 ^A	95	12			
	2009	118	84	87 ^{AB}	88 ^{AB}	59 ^A	62 ^{AB}	83	12			
	2010	92	73	86 ^{AB}	96 ^B	86 ^{AB}	76 ^{AB}	85	12			
	Mean	101	86	98	92	84	70	89				

To be continued

Table 2.3 continued

Parameter	Year	HA classes						Mean	SEM	P-value			
		1	2	3	4	5	6			HAclass	year	HAclass:year	
OMIh [g/ha]	2005	1852 ^a	3858 ^a	5122 ^a	6809 ^{Ab}	7011 ^{Aab}	10513 ^{BCb}	5861	678	<0.001	0.004	0.457	
	2006	1964 ^a	3776 ^{ab}	6210 ^{ac}	7495 ^{ABbc}	8357 ^{ABbc}	11517 ^{ABc}	6130	678				
	2007	2804 ^a	3693 ^{ab}	4609 ^{ab}	6970 ^{ABab}	8094 ^{ABab}	9017 ^{ACb}	5865	678				
	2008	1941 ^a	3645 ^{ab}	4942 ^{ab}	6278 ^{ABabc}	8623 ^{ABbc}	10504 ^{ABc}	5989	678				
	2009	2495 ^a	4986 ^{ab}	5666 ^{ab}	7115 ^{ABab}	9667 ^{ABbc}	13046 ^{BDc}	7162	678				
	2010	1933 ^a	3556 ^{ab}	5000 ^{ab}	7621 ^{Bbc}	9069 ^{Bbc}	11268 ^{ADc}	6408	678				
	Mean	2165	3919	5258	7048	8477	10946	6238					
	LWGh [g/ha]	2005	125	274	289	265 ^A	335 ^A	326 ^A	269	77	<0.001	<0.001	0.001
		2006	118 ^a	209 ^a	321 ^a	522 ^{ABab}	722 ^{ACab}	1117 ^{BCb}	449	77			
		2007	275 ^a	326 ^{ab}	514 ^{ab}	645 ^{ABab}	874 ^{Cab}	844 ^{Cb}	580	77			
2008		165	288	525	574 ^{AB}	690 ^{AC}	404 ^A	441	77				
2009		216	321	383	476 ^{AB}	459 ^{AB}	589 ^A	407	77				
2010		182 ^a	288 ^a	448 ^{ab}	669 ^{Bab}	731 ^{BCab}	767 ^{Bb}	514	77				
Mean	180	284	413	525	630	648	443						

LW, live weight; HA, herbage allowance.

Different superscripts indicate significant differences ($P \leq 0.05$) between HA classes within one year (a, b; within rows) and between years within one HA class (A, B; within columns). Within the statistical model there were no comparisons of means allowed.

2.4.2 Feed intake and performance of sheep at different stocking densities

The previous analysis of variance in dOM, MEI, OMIa, OMIh, LWGa, and LWGh between HA classes (see section 2.3) do not allow quantitative estimations of differences. Hence, in the following section the influences of animal stocking densities on OMIa, OMIh, LWGa, and LWGh are described functionally using regression analysis models. The relationship between SD and the measured parameters show similar trends in most years. These trends are more pronounced when expressed per unit of land area than per animal. OMIa linearly decreased with increasing SD in most study years (RMSE: 0.26 g/kg^{0.75} LW; Table 2.4). Nevertheless, the regression slopes for OMIa differed between years and were higher in 2005 (-2.26 g/kg^{0.75} LW per sheep; P-value for the slope: P=0.021) and 2007 (-1.71 g/kg^{0.75} LW per sheep; P-value for the slope: P=0.076) than in 2008 (-1.21 g/kg^{0.75} LW per sheep; P-value for the slope: P=0.207) and 2009 (-0.53 g/kg^{0.75} LW per sheep; P-value for the slope: P=0.546). In 2006 and 2010, OMIa was unaffected by SD (slope: -0.08 g/kg^{0.75} LW per sheep; P-value for the slope: P=0.964) or even linearly increased with increasing SD (slope: +1.17 g/kg^{0.75} LW per sheep; P-value for the slope: P=0.185). Correspondingly, LWGa linearly decreased with increasing SD in 2005, 2007, 2008, and 2009 (RMSE: 1.39 g/d) with estimated slopes of -7.52 g/d (P-value for the slope: P=0.001), -1.51 g/d (P-value for the slope: P=0.497), -6.00 g/d (P-value for the slope: P=0.009), and -6.31 g/d (P-value for the slope: P=0.003) per sheep respectively. Instead, LWGa was similar across all SDs in 2006 (slope: -0.25 g/d per sheep; P-value for the slope: P=0.952) and 2010, (slope:-0.63 g/d per sheep; P-value for the slope: P=0.756; Table 2.4; Figure 2.1).

In all years, OMIh increased with increasing SD. Linear regressions well described the relationships (RMSE: 202 g/ha) with similar estimated slopes of 886 g/ha (2007; P-value for the slope: P<0.001) to 1279 g/ha (2006; P-value for the slope: P<0.001) per additional sheep/ha (Table 2.4). LWGh linearly increased with increasing SD in 2006 (+80 g/ha per sheep/ha; P-value for the slope: P=0.002), 2007 (+88 g/ha per sheep/ha; P-value for the slope: P<0.001), and 2008 (+47 g/ha per sheep/ha; P-value for the slope: P=0.001), whereas quadratic regression lines better fitted the relationships in 2005, 2009, and 2010 (Table 2.4; Figure 2.2). As already indicated by the increasing CV (see section 2.3.1) differences between years in the absolute LWGh values were more pronounced at high than at low SD.

Table 2.4 Regression equations ($y=a+b\cdot x+c\cdot x^2$, if $c>0$, c is considered as 0) between daily organic matter intake of individual animals (OMIa), daily live weight gain of individual animals (LWGa), organic matter intake per hectare (OMIh), daily live weight gain per hectare (LWGh) and stocking density (x) during the grazing season of 2005 – 2010 (Coefficient value \pm standard deviation, $n=12$ per year).

Parameter	Year	a	P-value	b	P-value	c	P-value	RMSD*
OMIa [g/kg ^{0.75} LW]	2005	90.7 \pm 5.5	< 0.001	-2.3 \pm 0.9	0.021			8.4
	2006	90.7 \pm 7.1	< 0.001	-0.1 \pm 1.7	0.964			
	2007	88.6 \pm 5.5	< 0.001	-1.7 \pm 0.9	0.076			
	2008	85.1 \pm 5.5	< 0.001	-1.2 \pm 0.9	0.207			
	2009	83.6 \pm 5.5	< 0.001	-0.5 \pm 0.9	0.546			
	2010	60.9 \pm 5.9	< 0.001	1.2 \pm 0.9	0.185			
LWGa [g]	2005	100.1 \pm 12.9	< 0.001	-7.5 \pm 2.2	0.001			17.3
	2006	81.4 \pm 16.9	< 0.001	-0.2 \pm 4.1	0.952			
	2007	129.3 \pm 12.9	< 0.001	-1.5 \pm 2.2	0.497			
	2008	126.1 \pm 12.9	< 0.001	-6.0 \pm 2.2	0.009			
	2009	118.5 \pm 12.8	< 0.001	-6.3 \pm 2.0	0.003			
	2010	88.6 \pm 13.7	< 0.001	-0.6 \pm 2.0	0.756			
OMIh [g/ha]	2005	423 \pm 584	0.472	1036 \pm 100	< 0.001			863
	2006	65 \pm 735	0.930	1279 \pm 178	< 0.001			
	2007	1214 \pm 584	0.043	886 \pm 100	< 0.001			
	2008	112 \pm 583	0.849	1119 \pm 100	< 0.001			
	2009	335 \pm 580	0.567	1205 \pm 92	< 0.001			
	2010	-643 \pm 620	0.305	1147 \pm 92	< 0.001			
LWGh [g/ha]	2005	58 \pm 129	0.659	70 \pm 56	0.224	-4.5 \pm 5.3	0.395	117
	2006	-10 \pm 97	0.918	80 \pm 24	0.002			
	2007	118 \pm 77	0.134	88 \pm 7	< 0.001			
	2008	196 \pm 77	0.014	47 \pm 4	0.001			
	2009	64 \pm 152	0.678	89 \pm 59	0.136	-4.0 \pm 4.8	0.401	
	2010	-91 \pm 145	0.536	130 \pm 53	0.019	-4.2 \pm 4.3	0.324	

LW, live weight; RMSD, root mean square deviation.

*RMSD for the linear model for 2005 - 2010; For quadratic model for LWGh RMSD: 102.

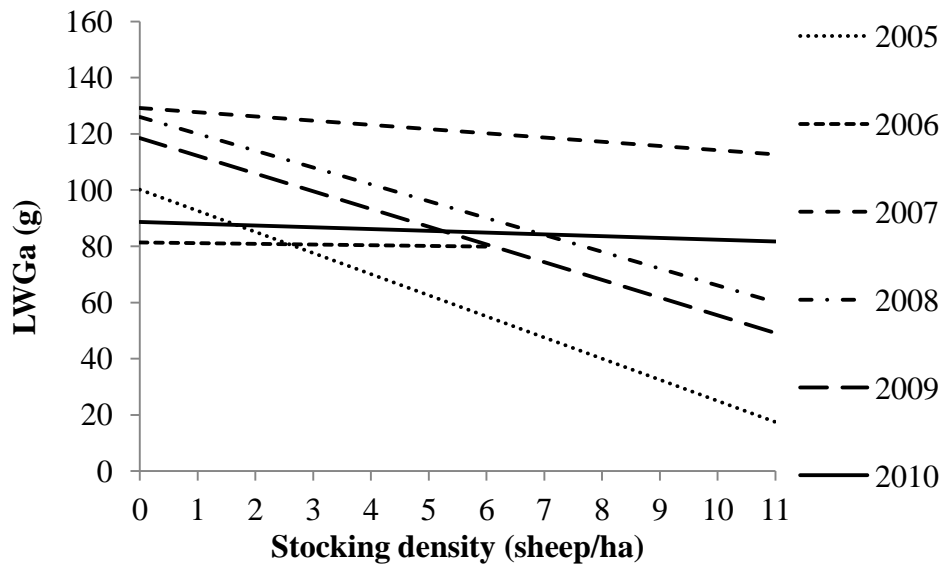


Figure 2.1 Regression equations ($y=a+b\cdot x+c\cdot x^2$, because no progressive increase is expected, if $c>0$, c is considered as 0) between daily live weight gain of individual animals (LWGa) and stocking density (x) during the grazing season of 2005 – 2010 ($n=12$ per year)^I.

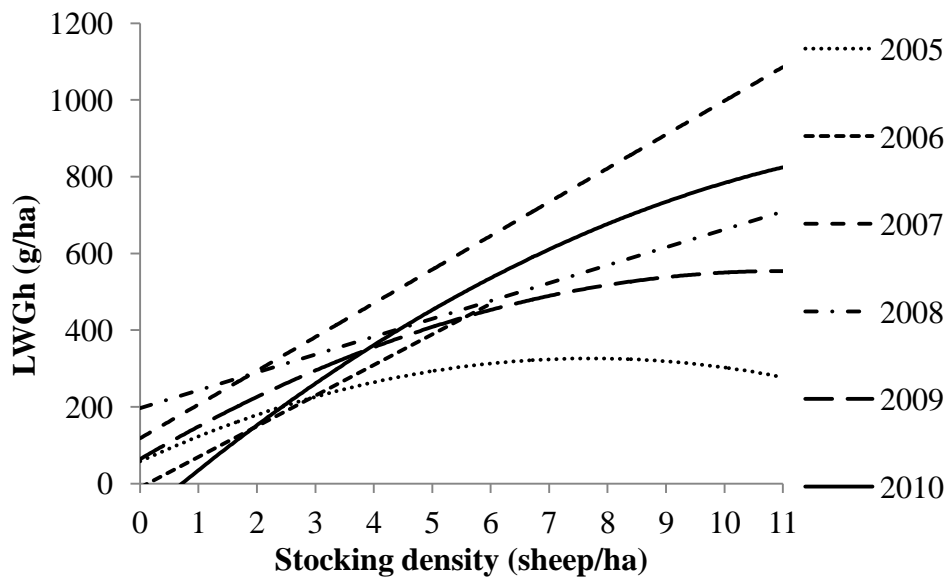


Figure 2.2 Regression equations ($y=a+b\cdot x+c\cdot x^2$, because a non-progressive increase is expected, if $c>0$, c is considered as 0) between daily live weight gain per hectare (LWGh) and stocking density (x) during the grazing season of 2005 – 2010 ($n=12$ per year)^{II}.

^IFor regression equations and statistics see Table 2.4. In 2006 experiment was stopped in September in SD >6 sheep/ha.

^{II}For regression equations and statistics see Table 2.4. In 2005 from 4 sheep/ha no appreciable increase of LWG/ha with increasing stocking density, for details see discussion. In 2006 experiment was stopped in September in SD >6 sheep/ha.

2.5 Discussion

2.5.1 Effects of stocking density on feed intake and performance of individual animals

In most of the six study years, HA class did not influence any of the measured parameters at the level of the individual animal. This is in contrast to our primary expectations that lower HAs might negatively affect feed intake and performance of sheep due to less herbage mass on offer and the lower capability for selecting plant species or plant parts of higher nutritional quality at low than at high HAs (Animut et al., 2005b) which in turn reduces dOM of ingested herbage. Moreover, at low HA animals have to intensify their search for feed and consequently, need more energy for locomotion and grazing, leading to reduced amounts of energy available for growth. However, in contrast, dOM did not decline, possibly due to restricted selection of feed and the fact that standing herbage quality in our study area increased with decreasing HA as a result of a constant removal and re-growth of plant biomass at higher SDs maintaining herbage mass on offer at a less mature stage (Schönbach et al., 2009). Similarly, OMIa and MEI did not differ between HA classes and only minor declines in feed intake were observed with increasing SD in 2006 – 2010 according to the regression analyses. Nevertheless, HA decreased from 15.4 kg DM at HA class 1 to 1.5 kg DM/kg LW at HA class 6. Average removal of standing plant biomass by sheep grazing at HA class 6 exceeded 90 % of initial herbage mass in the beginning of the grazing seasons in 2005 – 2008 (Schönbach et al., 2011) which is much higher than the removals at heavy grazing treatments in other studies (Milchunas et al., 1994; Biondini et al., 1998).

In general, these results show that although extreme ranges between HA classes were realized, only minor differences in OMIa between HA classes were determined. However decreasing HA can negatively affect feed intake of sheep grazing the Inner Mongolian steppe at least in some years. In 2005 OMIa declined by $2.3 \text{ g/kg}^{0.75} \text{ LW}$ per additional sheep according to the regression analysis and we had to remove the animals from the grazing plots at HA classes 5 and 6 in the beginning of September 2006 due to the lack of herbage. In other years sheep have been able to compensate for the decrease in HAs e.g. by consuming all above-ground plant biomass and probably some parts of the below-ground biomass and by intensifying their grazing behavior. Many studies have shown that intensified grazing behavior increases the animals' ME demands for physical activity and will thus reduce the ME available for growth or milk production (Animut et al., 2005a; Lachica and Aguilera,

2005; Lin et al., 2011; Sejian et al., 2012). Lin et al. (2011) found that HA class had an impact on total daily grazing time of sheep within the frame of our research project, indicating that compensatory grazing behavior influence ME available for growth.

As a result of the minor difference in the animals' feed intake only a tendency of effect of HA class on LWGa was found according to the ANOVA. Performance of sheep did not decrease with increasing SD in 2006, 2007, and 2010 according to the regression analysis. However in 2005, 2008, and 2009, LWGa clearly declined by -7.5, -6.0, and -6.3 g/d per additional sheep/ha, respectively, equivalent to 6 – 12 % of the mean LWGa of sheep in these years. Numerical differences in OMIa and MEI between HA classes and the slight decreases in the animals' feed intake with increasing SD at least partly explain the negative effect of SD on LWGa in these years.

2.5.2 Effects of the year

All measured parameters differed between years. During 1982 – 2004 the mean annual precipitation and rainfall during May –September were 343 mm and 293 mm, respectively. Compared to these values, precipitation in 2007, 2009, and in particular in 2005 were low, whereas the amounts of rain- and snowfall were highest and similar to the long-term averages in 2008 (see Table2.1). Water availability is the key limiting factor for plant biomass production in this region (Bai et al., 2004; 2008). Schönbach et al. (2009; 2011) found differences in herbage ANPP between study years that corresponded to differences in the annual amounts of rain- and snowfall. Similarly, DOM, LWGa, and LWGh were lower than in any of the other study years in 2005 when annual precipitation and rainfall during the vegetation period were lowest (Table 2.1) and the decline in LWGa with increasing SD was greatest in this year. However, a higher precipitation level did not necessarily result in a higher feed intake or performance of sheep. Hence, in 2008, when annual precipitation and rainfall during the vegetation period exceeded those in the other years, none of the measured animal parameters were greatest in 2008, showing that besides the amount of rainfall other factors such as intra-annual distribution of rainfall and ambient temperatures may determine grassland productivity and performance of sheep. This is supported by Ren et al. (in press) who worked in the same experimental area who found that the temporal distribution of precipitation and ambient temperatures in March – June determine herbage growth and plant species composition more than annual rates of precipitation and mean temperatures. All

parameters significantly differ between years above HA class 3. Moreover, CV increased with increasing HA class. This suggests that animals kept on grassland managed at low HA are less resilient to climatic variability and that inter-annual variation in herbage mass and quality will lead to greater differences in feed intake and performance of grazing livestock than with high HAs.

2.5.3 Economical and ecological relevance

Economical relevance

Besides the production of wool and dung, the sale of live animals is the main revenue for sheep farmers in Inner Mongolia (Kemp et al., 2011). Farmers are paid per animal but the value is higher when animals are obviously in a good body condition and show a higher LW. Hence, total LWG per unit of (rented) land area during a given time span is the most important determinant for the profitability of sheep production in this region. Due to a decrease in feed intake and performance of individual animals with increasing SD, several studies in this and similar environments (Fynn and O'Connor, 2000; Glindemann et al., 2009b; Lin et al., 2012) found that LWGh only increases until a certain SD threshold. From an economical point of view, farmers may aim to manage their rangelands close to this SD threshold to maximize revenues from livestock production (Kemp et al., 2011). This supports for short-time the common practice of farmers to manage the grassland at high SDs despite possible negative effects on its vegetation in long-time (see next section). This procedure is also observed in the dairy sector in Uganda. Ndambi et al. (2008) made an economical analysis in milk production systems and found out that labor input per animal decreases with increasing herd size and that larger herds are more profitable than smaller herds.

In our study, we only found a strong negative effect of SD on LWGa in some of the study years (see section 2.4.2) and that a quadratic or a linear regression equation well described the relationship between SD and LWGh in most of the years within the range of the tested SDs (1.5 – 10.3 sheep/ha; Figure 2.2). In 2007, 2008, and 2010, maximum LWGh was calculated at SDs greater than those tested in our study (<11 sheep/ha). In 3 of 6 years the maximum economical output per unit of area land occurred at the highest SD. In 2006, LWGh strongly increased with increasing SD. Nevertheless, sheep at HA classes 5 and 6 had to be removed from the grazing plots before the end of the grazing season due to too little herbage mass on offer, suggesting that a critical SD threshold was reached at HA class 4 (i.e. 6.0 sheep/ha) in this year. When LWGa progressively decreases with increasing SD, LWGh

does not proportionally increase leading to diminishing return, and the potential economic maximum was reached in 2005 and 2009. SD threshold for maximum animal production derived from the regression equation was 11.1 sheep/ha in 2009. Whereas due to the small increase of LWGh in 2005 no maximum can be calculated in this year. The minor changes in LWGh above 4 sheep/ha are merely random (see Table 2.3). The slopes of the quadratic regressions were very low, so that an increase in SDs from 4.5 to 7.7 sheep/ha in 2005 and from 7.5 to 11.1 sheep/ha in 2009 only increased LWGh by 28.5 and 53 g/ha, respectively, equivalent to about 10 % of the maximum LWGh during each year. So in 2005 the maximum LWGh is around 4 sheep/ha, and in 2006, and 2009 6 sheep/ha and 11 sheep/ha, respectively.

In 3 years this minor gain in LW output per ha with increasing SD may not cover the increasing expenditures with increasing SD such as hay-feeding during the winter months. Contrary to the general assumption that the highest maximum economic profitable grassland use can be generated at very high SD we found that at least in 3 of 6 study years the highest LWGh was clearly reached below the highest SD. Due to the lack of information a solid economical evaluation cannot be performed here, however has to include prices of hay, concentrate and mineral feed, prices per sheep dependent on LW and body condition and for wool, mortality rate, farm investments, vet costs as well as manure and lignite costs (to evaluate savings for heating with manure instead of buying lignite).

Ecological relevance

Many studies underline that the currently high SD should be reduced in order to avoid long-term alterations in the structure (i.e. plant species composition, number of species, ground surface structure, ground cover) and functioning (i.e. matter fluxes, carbon storage) of the Inner Mongolian grassland ecosystem. Results of a study by Schönbach et al. (2011; GI6 \triangleq HA class 6 i.e. 9 – 10 sheep/ha) within the frame of our research project show that litter accumulation was 84 % and ground cover 43 % lower at HA class 6 (i.e. 9 – 10 sheep/ha) compared to those at ungrazed plots. Cease et al. (2012) suggested that heavy livestock grazing and consequently, steppe degradation promote outbreaks of *Oedaleus asiaticus*, the dominant locust species of North Asian grasslands, due to differences plant protein contents. Zheng et al. (2011) demonstrated that plant height, individual plant biomass, and leaf-to-stem ratio of the two dominant species decreased with increasing SD. Ren et al. (in press) found that HA classes (GI \triangleq HA class) had only a minor effect on the botanical

composition and the species diversity of the herbaceous vegetation in our experimental plots. However, above-ground biomass of the dominant and preferentially grazed species *L. chinensis* decreased with increasing HA class (Ren et al., in press). These studies confirm that heavy grazing will greatly hamper long-term ecosystem functioning of the Inner Mongolian steppe.

The amount of plant biomass remaining on pasture in the end of the grazing season (i.e. end-of-season standing biomass, ESSB) is often used as an indicator to evaluate the ecological consequences of livestock grazing (Milchunas et al., 1994; Biondini et al., 1998; Schönbach et al., 2011). Christensen et al. (2003) modeled grazing effects on the vegetation in the Inner Mongolian steppe and concluded that, for maintaining long-term biomass production, herbage removal by livestock should not exceed 51 % of ANPP in this region, equal to an ESSB of 49 % of the ANPP. According to the mean ANPP in the study area of 1400 kg DM/ha (Schönbach et al., 2011) and mean crude ash concentrations of 6.3 % (Schönbach personal communication), this would equal to an ESSB of 656 kg OM/ha. ESSB exponentially decreased with increasing SD in 2005 – 2010 (data partly published by Schönbach et al. 2011; Figure 2.3). According to the respective regression equations (Table 2.6), ESSB exceeded the minimum threshold of 656 kg OM/ha at SDs of ≤ 2.8 , ≤ 2.0 ≤ 5.1 , ≤ 4.0 , ≤ 5.6 , and ≤ 5.1 sheep/ha in 2005, 2006, 2007, 2008, 2009, and 2010, respectively. Moreover, Hoffmann et al. (2008) found on sites close to our experimental plots that a lower density of vegetation cover favors wind erosion which shows that the degree of soil erosion is largely affected by stocking density.

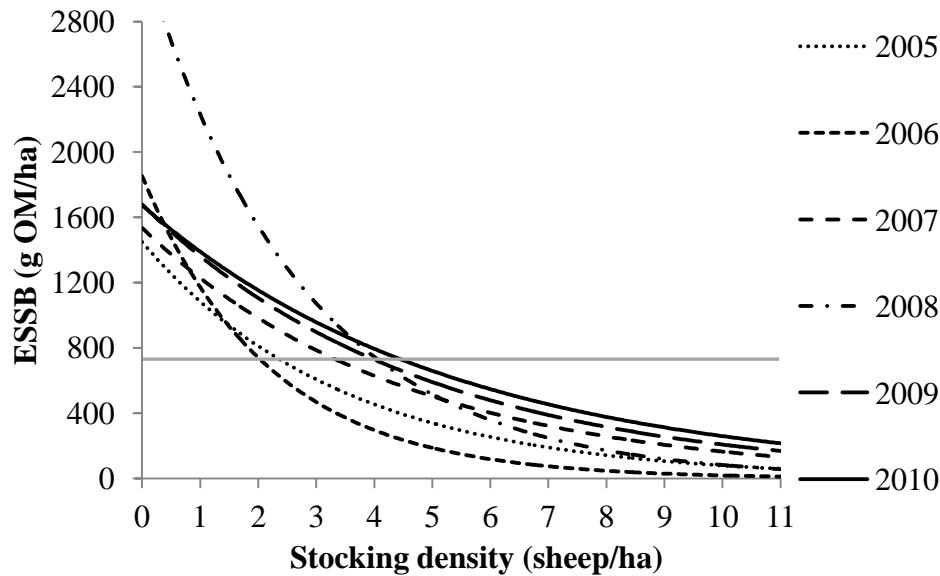


Figure 2.3 Regression equations ($y=e^a \cdot e^{b \cdot x}$) between the end-of-season standing biomass (ESSB) and stocking density (x) during the grazing season of 2005 – 2010 ($n=12$ per year)ⁱⁱⁱ. Grey line indicates for ESSB threshold of 656 g OM/ha (for details see discussion). Data partly published by Schönbach et al. (2011).

A ground cover $\leq 70\%$ (i.e. 30% bare soil) will strongly increase soil erosion by wind and surface runoff water and thus land degradation (Schönbach et al., (2011). Ground cover of the vegetation in the end of the grazing season linearly decreased with increasing SD (derived from data partly published by Schönbach et al., 2011; see Table 2.5, Table 2.6 and Figure 2.4). It was below the minimum threshold of 70% at SDs of ≤ 3.1 , ≤ 3.4 , ≤ 2.9 , ≤ 5.9 , and ≤ 6.4 in 2006, 2007, 2008, 2009, and 2010, respectively (ground cover was not determined in 2005). Across the study years, the SD threshold values range between 2.0 – 5.1 and 3.1 – 6.4 sheep/ha when ground cover or ESSB are used as an indicator, respectively. Hence, both parameters lead to similar critical SD and show that i) the critical SD to prevent long-term grassland degradation varies between years; and ii) SD thresholds were lowest in 2005 and 2006 when ANPP and HM on offer might have been limited by a very low precipitation in 2005, while they were highest in 2008 when rainfall was similar to the long-term average (see section 2.4.2).

ⁱⁱⁱFor regression equations and statistics see Table 2.6.

Table 2.5 End-of-season standing biomass (ESSB) at the end of grazing season 2005 – 2010 and vegetation ground cover at the end of grazing season 2006 – 2010 (Arithmetic means \pm standard deviation, n=2 per year).

Parameter	Year	HA classes					
		1	2	3	4	5	6
ESSB (kg/ha)	2005	871 \pm 172	642 \pm 80	352 \pm 25	278 \pm 34	239 \pm 10	119 \pm 128
	2006	836 \pm 14	631 \pm 53	195 \pm 27	119 \pm 72	103 \pm 110	51 \pm 59
	2007	857 \pm 463	656 \pm 194	809 \pm 187	985 \pm 645	287 \pm 202	132 \pm 2
	2008	1266 \pm 32	1065 \pm 63	832 \pm 49	643 \pm 117	199 \pm 67	81 \pm 17
	2009	820 \pm 198	838 \pm 260	784 \pm 179	792 \pm 581	452 \pm 319	170 \pm 143
	2010	1215 \pm 307	813 \pm 35	528 \pm 101	609 \pm 94	303 \pm 85	253 \pm 53
Ground cover (%)	2006	74 \pm 3	75 \pm 9	66 \pm 9	52 \pm 15	53 \pm 2	46 \pm 5
	2007	83 \pm 6	70 \pm 4	59 \pm 1	61 \pm 6	43 \pm 4	39 \pm 8
	2008	73 \pm 6	75 \pm 8	57 \pm 9	63 \pm 2	55 \pm 4	43 \pm 6
	2009	83 \pm 4	76 \pm 6	69 \pm 6	74 \pm 1	70 \pm 11	53 \pm 0
	2010	83 \pm 4	76 \pm 6	69 \pm 6	74 \pm 1	70 \pm 11	53 \pm 0

HA, herbage allowance.

Partly published by Schönbach et al. (2011).

Table 2.6 Regression equations for end-of-season standing biomass (ESSB) at the end of grazing season of 2005 – 2010 ($y=e^a \cdot e^{b \cdot x}$) and ground cover at the end of grazing season 2006 – 2010 ($y=a+b \cdot x$; Coefficient value \pm standard deviation, $n=12$ per year).

Parameter	Year	a	P-value	b	P-value	RMSD*
ESSB (kg OM/ha)	2005	7.3 \pm 0.4	<0.001	-0.3 \pm 0.1	<0.001	0.5
	2006	7.5 \pm 0.4	<0.001	-0.5 \pm 0.1	<0.001	
	2007	7.3 \pm 0.4	<0.001	-0.2 \pm 0.1	<0.001	
	2008	8.1 \pm 0.4	<0.001	-0.4 \pm 0.1	<0.001	
	2009	7.4 \pm 0.4	<0.001	-0.2 \pm 0.1	<0.001	
	2010	7.4 \pm 0.4	<0.001	-0.2 \pm 0.1	0.001	
Ground cover (%)	2006	82.9 \pm 4.5	<0.001	-4.2 \pm 0.8	<0.001	6.9
	2007	89.1 \pm 4.5	<0.001	-5.7 \pm 0.8	<0.001	
	2008	80.9 \pm 4.5	<0.001	-3.8 \pm 0.8	<0.001	
	2009	86.5 \pm 4.5	<0.001	-2.8 \pm 0.7	<0.001	
	2010	87.9 \pm 4.8	<0.001	-2.8 \pm 0.7	<0.001	

RMSD, root mean square deviation.

*RMSD for the linear model for 2005 – 2010

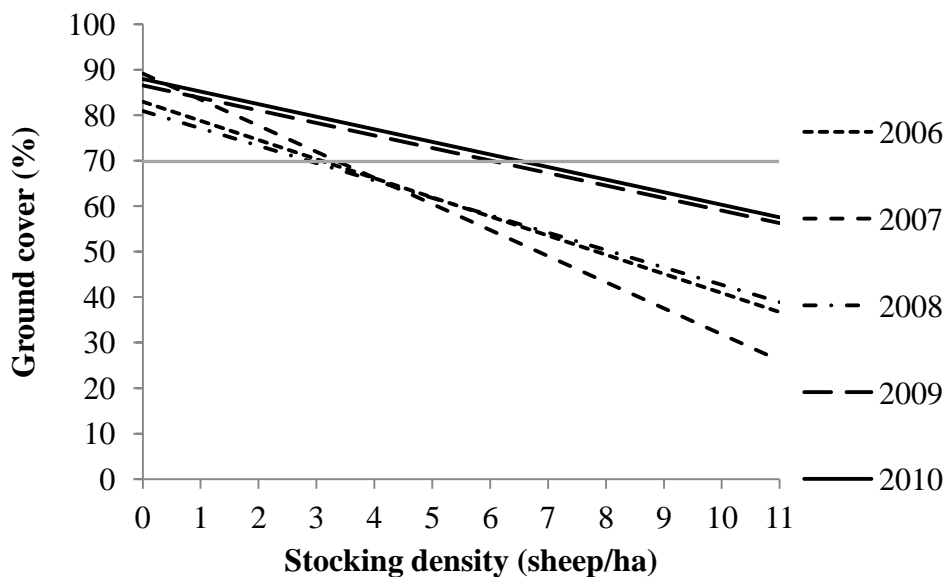


Figure 2.4 Regression equations ($y=a+b \cdot x$) between the vegetation ground cover and stocking density (x) during the grazing season 2006 – 2010 ($n=12$ per year)^{IV}. For regression equations and statistics see Table 2.5. Grey line indicates for threshold of 70% vegetation ground cover (for details see discussion). Data partly published by Schönbach et al. (2011).

Therefore, these results clearly indicate that, irrespective of differences between years, due to ecological reasons to use the grassland steppe at SDs much lower than those yielding the highest animal output per unit of land area. Schönbach et al. (2011) could show that an

^{IV} For regression equations and statistics see Table 2.6.

alternating use of the grassland for hay-making and grazing increases ANPP and ground cover of the steppe vegetation and can thus at least partly mitigate the negative effects of high SDs. Furthermore they suggest that in the long term, maximum SD that should not be exceeded to maintain a sufficient ESSB and ground cover in the end of the grazing season might be higher than those suggested above. Moreover, a moderate concentrate feeding reduces herbage consumption of grazing sheep with increasing their LWG (Bösing et al., submitted). Therefore, grazing system and feed supplementation might diminish the discrepancy between the ecologically derived SD thresholds and those leading to a maximum animal performance per unit of land area.

In 2007, 2008, and 2010 the calculated maximum output in LWG_h on the basis of regression analysis were at the highest SD in our experiment and were 50 % higher than the measured ecological maximum SD threshold. Climate in 2005 was in comparison with the long-time climate data an exceptional extremely dry year and in 2006 the experiment had to be cut short. The maximum output per area of land unit in 2005, 2006, and in 2009 was below the maximum SD, showing that in these years the SD with the economical maximum (4.0 sheep/ha, 6.0 sheep/ha, and 11.1 sheep/ha) is close to the ecological maximum SD threshold (2.0 – 6.4 sheep/ha). In long-term due to negative predicted changes in herbage composition in future ecological and economical maximums will converge.

2.6 Conclusion

Individual animals are only marginal influenced in LWG and OMI by high SD despite a very low HA and LWG per area of land unit is highest at very high SD. Thus farmers act in short term properly from an economical point of view. To prevent soil erosion during winter months and thus, to maintain long-term grassland productivity it is necessary to reduce SDs to <2.0 – 6.4 sheep/ha depending on climate conditions. Ground cover and ESSB indicate that 3 of the 6 study years, it is necessary from an ecological point of view to use the grassland steppe at SDs more than 50% lower than those yielding the highest animal output per unit of land area. We assume that in future the ecological maximum SD and economical optimum will converge due to predicted changes in herbage composition. This development is already recognized in the other 3 study years where the economical maximum SD (mean: 7 sheep/ha) is close to the ecological maximum SD (mean: 4 sheep/ha). Considering the limited increase in output per area in some years and higher costs (e.g. vet, winter feed) at greater herd sizes,

lowering SD may not reduce the economical profit of farmers in long-term and furthermore supplementation of concentrate feed can mitigate the negative effect of high SD.

2.7 References

- Aiple, K.P., Steingass, H., Menke, K.H., 1992. Suitability of a buffered fecal suspension as the inoculum in the Hohenheim Gas Test. 1. Modification of the method and its ability in the prediction of organic-matter digestibility and metabolizable energy content of ruminant feeds compared with rumen fluid as inoculum. *Journal of Animal Physiology and Animal Nutrition* 67, 57-66.
- Animut, G., Goetsch, A.L., Aiken, G.E., Puchala, R., Detweiler, G., Krehbiel, C.R., Merkel, R.C., Sahl, T., Dawson, L.J., Johnson, Z.B., Gipson, T.A., 2005a. Grazing behavior and energy expenditure by sheep and goats co-grazing grass/forb pastures at three stocking rates. *Small Ruminant Research* 59, 191-201.
- Animut, G., Goetsch, A.L., Aiken, G.E., Puchala, R., Detweiler, G., Krehbiel, C.R., Merkel, R.C., Sahl, T., Dawson, L.J., Johnson, Z.B., Gipson, T.A., 2005b. Performance and forage selectivity of sheep and goats co-grazing grass/forb pastures at three stocking rates. *Small Ruminant Research* 59, 203-215.
- Bai, Y.F., Han, X.G., Wu, J.G., Chen, Z.Z., Li, L.H., 2004. Ecosystem stability and compensatory effects in the Inner Mongolia grassland. *Nature* 431, 181-184.
- Bai, Y.F., Wu, J.G., Xing, Q., Pan, Q.M., Huang, J.H., Yang, D.L., Han, X.G., 2008. Primary production and rain use efficiency across a precipitation gradient on the Mongolia plateau. *Ecology* 89, 2140-2153.
- Biondini, M.E., Patton, B.D., Nyren, P.E., 1998. Grazing Intensity and Ecosystem Processes in a Northern Mixed-Grass Prairie, USA. *Ecological Applications* 8, 469-479.
- Bösing, B.M., Susenbeth, A., Hao, J., Ahnert, S., Ohm, M., Dickhoefer, U., submitted. Effect of concentrate supplementation on herbage intake and live weight gain of sheep grazing a semi-arid grassland steppe of North-Eastern Asia in response to different grazing management systems and intensities.
- Brandt, M., Allam, S.M., 1987. Analytik von Titandioxid im Darminhalt und Kot nach Kjeldahlaufschluß. *Archives of Animal Nutrition* 37, 453-454.

- Cease, A.J., Elser, J.J., Ford, C.F., Hao, S.G., Kang, L., Harrison, J.F., 2012. Heavy Livestock Grazing Promotes Locust Outbreaks by Lowering Plant Nitrogen Content. *Science* 335, 467-469.
- Christensen, L., Coughenour, M.B., Ellis, J.E., Chen, Z.Z., 2003. Sustainability of Inner Mongolian grasslands: Application of the Savanna model. *Journal of Range Management* 56, 319-327.
- Fynn, R.W.S., O'Connor, T.G., 2000. Effect of stocking rate and rainfall on rangeland dynamics and cattle performance in a semi-arid savanna, South Africa. *Journal of Applied Ecology* 37, 491-507.
- Glindemann, T., Tas, B.M., Wang, C., Alvers, S., Susenbeth, A., 2009a. Evaluation of titanium dioxide as an inert marker for estimating fecal excretion in grazing sheep. *Animal Feed Science and Technology* 152, 186-197.
- Glindemann, T., Wang, C., Tas, B.M., Schiborra, A., Gierus, M., Taube, F., Susenbeth, A., 2009b. Impact of grazing intensity on herbage intake, composition, and digestibility and on live weight gain of sheep on the Inner Mongolian steppe. *Livestock Science* 124, 142-147.
- Hoffmann, C., Funk, R., Wieland, R., Li, Y., Sommer, M., 2008. Effects of grazing and topography on dust flux and deposition in the Xilingele grassland, Inner Mongolia. *Journal of Arid Environments* 72, 792-807.
- IUSS Working Group WRB, 2007. World reference base for soil resources 2006, 2nd edition. World Soil Resources Reports No. 103, First Update. FAO, Rome.
- Kemp, D., Brown, C., Guodong, H., Michalk, D., Zhibiao, N., Jianping Wu, Xu, Z., 2011. Chinese grasslands: problems, dilemmas and finding solutions. In: Kemp, D.R., Michalk, L. (Eds.), *Development of sustainable livestock systems on grasslands in north-western China*. Springer Netherlands, pp. 301-324.
- Lachica, A., Aguilera, J.F., 2005. Energy expenditure of walk in grassland for small ruminants. *Small Ruminant Research* 59, 105-121.
- Lepers, E., Lambin, E.F., Janetos, A.C., DeFries, R., Achard, F., Ramankutty, N., Scholes, R.J., 2005. A synthesis of information on rapid land-cover change for the period 1981-2000. *Bioscience* 55, 115-124.

- Li, S.G., Harazono, Y., Oikawa, T., Zhao, H.L., He, Z.Y., Chang, X.L., 2000. Grassland desertification by grazing and the resulting micrometeorological changes in Inner Mongolia. *Agricultural and Forest Meteorology* 102, 125-137.
- Lin, L.J., Dickhoefer, U., Müller, K., Chenjie, W., Glindermann, T., Hao, J., Wan, H., Schönbach, P., Gierus, M., Taube, F., Susenbeth, A., 2012. Growth of sheep as affected by grazing system and grazing intensity in the steppe of Inner Mongolia, China. *Livestock Science* 144, 140-147.
- Lin, L.J., Dickhoefer, U., Müller, K., Wurina, Susenbeth, A., 2011. Grazing behavior of sheep at different stocking rates in the Inner Mongolian steppe, China. *Applied Animal Behaviour Science* 129, 36-42.
- Milchunas, D.G., Forwood, J.R., Lauenroth, W.K., 1994. Productivity of Long-Term Grazing Treatments in Response to Seasonal Precipitation. *Journal of Range Management* 47, 133-139.
- Naumann, K., Bassler, R., 2004. Bestimmung von Rohprotein Mittels Dumas-Verbrennungsmethode. In: Dieterle, P. (Ed.), *Methodenbuch, Band 3, Die chemische Untersuchung von Futtermitteln*. VDLUFA-Verlag, Bonn, pp. 1-5.
- Ndambi, O.A., Garcia, O., Balikowa, D., Kiconco, D., Hemme, T., Latacz-Lohmann, U., 2008. Milk production systems in Central Uganda: a farm economic analysis. *Tropical Animal Health and Production* 40, 269-279.
- Ren, H., Schönbach, P., Wan, H., Gierus, M., Taube, F., in press. Effects of grazing intensity and environmental factors on species composition and diversity in typical steppe of Inner Mongolia, China. DOI: 10.1371/journal.pone.0052180.
- Schönbach, P., Wan, H., Gierus, M., Müller, K., Lin, L., Bai, Y., Loges, R., Susenbeth, A., Taube, F., 2012. Effects of grazing intensity and precipitation on herbage accumulation, herbage quality and animal performance in a semi-arid grassland of Inner Mongolia. *Grass and Forage Science* 67, 535-545.
- Schönbach, P., Wan, H.W., Gierus, M., Bai, Y.F., Müller, K., Lin, L.J., Susenbeth, A., Taube, F., 2011. Grassland responses to grazing: effects of grazing intensity and management system in an Inner Mongolian steppe ecosystem. *Plant and Soil* 340, 103-115.
- Schönbach, P., Wan, H.W., Schiborra, A., Gierus, M., Bai, Y.F., Müller, K., Glindemann, T.,

- Wang, C., Susenbeth, A., Taube, F., 2009. Short-term management and stocking rate effects of sheep grazing on herbage quality and productivity of Inner Mongolia steppe. *Crop and Pasture Science* 60, 1-12.
- Sejian, V., Naqvi, S.M.K., Ezeji, T., Lakritz, J., Lal, R., Maurya, V., Sejian, V., Kumar, K., Singh, G., Naqvi, S.M.K., 2012. Walking Stress Influence on Livestock Production. *Environmental Stress and Amelioration in Livestock Production*. Springer Berlin Heidelberg, pp. 75-95.
- Sollenberger, L.E., Moore, J.E., Allen, V.G., Pedreira, C.G.S., 2005. Reporting forage allowance in grazing experiments. *Crop Science* 45, 896-900.
- Tong, C., Wu, J., Yong, S., Yang, J., Yong, W., 2004. A landscape-scale assessment of steppe degradation in the Xilin River Basin, Inner Mongolia, China. *Journal of Arid Environments* 59, 133-149.
- Wang, C.J., Tas, B.M., Glindemann, T., Rave, G., Schmidt, L., Weissbach, F., Susenbeth, A., 2009. Fecal crude protein content as an estimate for the digestibility of forage in grazing sheep. *Animal Feed Science and Technology* 149, 199-208.
- Yu, M., Ellis, J.E., Epstein, H.E., 2004. Regional analysis of climate, primary production, and livestock density in Inner Mongolia. *Journal of Environmental Quality* 33, 1675-1681.
- Zheng, S.X., Lan, Z.C., Li, W.H., Shao, R.X., Shan, Y.M., Wan, H.W., Taube, F., Bai, Y.F., 2011. Differential responses of plant functional trait to grazing between two contrasting dominant C3 and C4 species in a typical steppe of Inner Mongolia, China. *Plant and Soil* 340, 141-155.

3 Effect of concentrate supplementation on herbage intake and live weight gain of sheep grazing a semi-arid grassland steppe of North-Eastern Asia in response to different grazing management systems and intensities

B.M. Bösing ^a, A. Susenbeth ^{a*}, J. Hao ^a, S. Ahnert ^a, M. Ohm ^{b#}, U. Dickhoefer ^{a†}

^a *Institute of Animal Nutrition and Physiology, Christian-Albrechts-Universität zu Kiel, 24098 Kiel, Germany*

^b *Institute of Crop Science and Plant Breeding, Christian-Albrechts-Universität zu Kiel, 24098 Kiel, Germany*

[#] *Present address: Institut für Ökologischen Landbau, 23847 Westerau, Germany*

[†] *Present address: Institute of Animal Production in the Tropics and Subtropics, University of Hohenheim, 70599 Stuttgart, Germany*

* *Corresponding author. Tel.: +49 431 880 2013; fax: +49 431 880 1528. E-mail address: susenbeth@aninut.uni-kiel.de*

3.1 Abstract

An increasing human population and growing demand for food of animal origin intensified livestock production and lead to overgrazing and desertification in semi-arid grasslands. Strategies for sustainable livestock production that protect steppe vegetation and satisfy farmers' economic interests are strongly needed. This study analyzed the effects of a moderate concentrate supplementation on organic matter digestibility (dOM), organic matter intake (OMI), herbage OMI, metabolizable energy intake (MEI), and live weight (LW) gain of sheep grazing at different intensities to evaluate its potential contribution to profitable livestock production at conservative stocking densities (SD).

In summer 2010, a grazing experiment was conducted in the Xilin River Basin, the Inner Mongolian steppe, China (E116°42' N43°38') using 337 female Mongolian fat-tailed sheep (30.2±4.3 kg LW). The effect of concentrate supplementation was tested in two different grazing management systems and six herbage allowance (HA) classes. While experimental plots had only been used for grazing in previous years in the continuous system, grazing and hay-making had been alternated annually on plots of the alternating system. SDs ranged from light to heavily grazed with 2.1 to 10.3 sheep/ha and were adjusted every month to maintain similar HA across the grazing season. Per plot, four sheep each received 250 g/d of a corn-wheat-based concentrate feed (SUP), while four non-supplemented (NSUP) sheep were used as control. Fecal samples were collected on five days each in July, August, and September. dOM was estimated from fecal crude protein concentration and feces excretion quantified using the marker titanium dioxide. OMI, herbage OMI, and MEI were calculated. The animals were weighed monthly to determine daily LW gain.

dOM was higher in SUP than NSUP sheep (0.557 vs. 0.533, RSD: 0.016; $P < 0.001$). As a consequence, daily OMI and LW gain of SUP sheep (74 g/kg^{0.75} LW; 121 g) were higher than of NSUP sheep (68 g/kg^{0.75} LW, RSD: 6.4; $P < 0.001$; 86 g, RSD: 24.6; $P < 0.001$) despite a decrease in herbage OMI of 0.41 g per 1 g concentrate feed ($P < 0.001$). Grazing system had no influence on dOM, OMI, or LW gain of sheep ($P > 0.751$). The effects of supplementation were independent of HA class ($P > 0.462$), and for OMI, herbage OMI, MEI and LW gain higher in the beginning than in the end of the experiment ($P < 0.013$). Moderate concentrate supplementation to grazing sheep strongly increases LW gain of individual animals and might offer a valuable contribution to maintain output per area at lower SDs. A reduced herbage OMI alleviates grazing pressure and can thus maintain long-term grassland productivity.

3.2 Introduction

As a consequence of an increasing population and a growing demand for animal products livestock densities worldwide have strongly increased in the last decades (Mortimore, 1993). In pastoral systems of the semi-arid and arid regions of North-Eastern Asia, overgrazing is thus considered as the main reason for degradation and desertification of natural rangelands (Zhao et al., 2005; Akiyama and Kawamura, 2007).

Due to higher feed and energy intakes and consequently, higher animal performances, supplemental feeding may allow for a reduction in stocking densities (SD) to protect the vegetation without compromising for the total animal mass output per unit of land area (Caton and Dhuyvetter, 1997). However, the efficiency of supplementation (i.e. additional output per kg of feed offered) is affected by several factors such as the species, breed, or age of the animal (Southgate et al., 1982; Lourenco et al., 2000) and the type of supplement feed offered (Fahmy et al., 1992). Moreover, the amount and nutritional quality of the plant biomass available for grazing (Caton and Dhuyvetter, 1997) and thus any grazing management decisions may directly or indirectly alter the efficiency of supplemental feeding. Hence, this study analyzed the effects of concentrate supplementation on feed intake and performance of sheep grazing the semi-arid steppe vegetation in Inner Mongolia at different SDs and grassland management systems.

We hypothesized that i) efficiency of concentrate supplementation will be higher at a continuous grazing management system (CON) than in a alternating grazing management system (ALT) due to a lower ground cover, differences in the botanical composition of the vegetation, and thus, an inferior mass and feeding value of the available forage at CON. Moreover, the ability of animals to select for plant species or parts of higher feeding value is limited, when feed allowances are low. Altogether, this might result in greater increases in diet digestibility, lower forage replacement rates, and therefore an enhanced total feed intake of animals at CON than at an ALT system. Similarly, mass and nutritional quality of the vegetation as well as the selective feeding behavior is inferior at low than at high herbage allowance (HA). Hence, we expected that ii) the effect of concentrate supplementation will be more pronounced at very low HA and iii) in the end of vegetation and grazing period.

3.3 Material and Methods

3.3.1 Study area

The study was conducted in the Xilin River Basin in the Inner Mongolia Autonomous Region of China (E116°42' N43°38') during vegetation period (May – September) of 2010. The study area is located on the Mongolian Plateau at about 1200 m above sea level. It belongs to the Inner Mongolia Grassland Ecosystem Research Station which is administered by the Institute of Botany of the Chinese Academy of Science, Beijing. The area had been moderately used for sheep grazing until October 2003. Afterwards, it had not been grazed until a multiannual grazing trial already was established in June 2005 which comprised our study. The semiarid continental climate is characterized by a mean annual precipitation of 296 mm (2003 – 2010) and a mean annual air temperature of 1.4°C. Thus, it is typical for the temperate steppe region with high intra- and inter-annual variability in precipitation. The Eurasian steppe is the largest connected grassland ecosystem of the world (Bai et al., 2008). About 73% of provincial area is grassland (0.9 million km²) and used for sheep, goat, cattle, and camel grazing in pastoral livestock and mixed crop-livestock farming systems. Annual above-ground net primary production of the grassland (ANPP) is about 1423 kg dry matter (DM)/ha (Schönbach et al., 2011) and highly variable depending on the amount of rainfall (Yu et al., 2004). The perennial rhizome grass *Leymus chinensis* Trin. Tzvel. and the perennial bunchgrass *Stipa grandis* P. Smirn. characterize the typical steppe plant communities (Bai et al., 2004). The major soil types are calcic chestnuts and calcic chernozems (IUSS Working Group WRB, 2007). The grassland steppe is a fragile ecosystem and extensively degraded by severe overgrazing (Christensen et al., 2004).

3.3.2 Experimental design

Sheep were transferred to the grazing area on 12th of June and removed from pastures on 10th of September, resulting in a grazing period of 91 days. The experimental area (128 ha) was divided in grazed areas that were used for sheep grazing and ungrazed areas that were utilized for cutting hay. We investigated two different grazing management systems. The first system was an ALT grazing system where the same plots had been used alternately for animal grazing in the first and for haying in the next year since 2005. The second system was a CON grazing system where the same plots had either been used for animal grazing or for harvesting

forage every year. The latter system is similar to the current grassland management in Inner Mongolia. In every system six different HA classes were realized on two replicates each. Therefore measurements were carried out on a total of 24 randomized grazing plots (2 systems • 6 HA classes • 2 replicates). Since HA will better describe grazing intensity than SD, if herbage mass (HM) differs between experimental plots or throughout the grazing period (Sollenberger et al., 2005), we used HA classes to account for differences in the ANPP between our experimental plots. HA was expressed as kg DM of herbage per kg of live weight (LW) per plot. To maintain constant HAs across the whole grazing period, the number of sheep per plot was adjusted to standing HM every month subsequent to animal weighing and HM determination (see section 2.3). HA target ranges were >12.0, >6.0 – 12.0, >4.5 – 6.0, >3.0 – 4.5, >1.5 – 3.0 and ≤ 1.5 kg DM/kg LW for HA classes 1 to 6, respectively. Mean SDs were 2.2 ± 0.6 , 4.3 ± 1.3 , 5.9 ± 1.9 , 7.3 ± 2.1 , 8.8 ± 2.5 , and 10.3 ± 2.9 sheep/ha at HA class 1 – 6, respectively. The size of each plot was 2 ha except for HA class 1 plots which were 4 ha in order to be able to keep a minimum of eight animals per plot.

3.3.3 Animals and feeding

A total of 337 female sheep of the Inner Mongolian fat-tailed breed were used for the experiment. The animals were purchased from local farmers, neither pregnant nor lactating, and about 15-months old. Before the experiment started, sheep were ear-tagged, treated against internal parasites, and weighed on two consecutive days using a portable balance (accuracy 0.1 kg). Mean initial LW of all study animals in June 2010 was 30.2 ± 1.9 kg. The animals were divided into four LW groups (very light, light, medium, and heavy). Out of each LW group animals were randomly allocated to one of the 24 grazing plots to equalize mean LW per plot. All sheep were weighed again on two consecutive days first day in the morning and second day in the evening to adjust the influence of gut filling in the middle of July, August, and September. The mean LW of the two days was used to calculate the animals' LW gain (LWG) during each month. Water and mineral lick stones were freely available throughout the whole grazing experiment. To determine the effect of a concentrate supplementation on total feed as well as herbage intake, diet digestibility, and LWG, we took samples of 192 sheep in total and 96 sheep were supplemented (SUP) with 250 g/d of a concentrate feed at the same time each day. All sheep per plot were caught in corrals every day and four SUP sheep per plot were individually fed in small reassigned bags. Four of the

non-supplemented (NSUP) sheep per plot were used as control groups. Details of the experimental scheme are given in Table 3.1.

The concentrate feed was purchased from a local company (Buridu feed company, Xilinhot). According to the declaration of the producer, it contained (on fresh matter basis) 40% corn, 19% by-products like bean, vegetable, and cotton dregs, 13% wheat bran, 9% corn germ meal, 8% millet bran, 6% minerals, and 5% corn husks. One sample of the concentrate feed was collected every week (about 100 g), and pooled to one sample at the end of each month for chemical analyses (see next section).

3.3.4 Determination of herbage mass and laboratory analysis

In three representative areas à 0.5 m² (0.25 • 2 m) per plot HM was determined by cutting the sward at 1 cm above ground level. Herbage sampling took place once in the beginning of June and again in the middle of July, August, and September. Herbage material was pooled by plot, dried at 60°C for 24 h, and ground to pass a 1 mm sieve. Pool samples of concentrate feed (n = 3) were analyzed for DM concentrations by drying at 105°C till constant weight and for crude ash by incineration at 550°(Naumann and Bassler, 2004; Table 3.2). Crude protein (CP) concentrations were calculated from nitrogen (N) content ($CP = 6.25 \cdot N$) that were determined by Dumas combustion (Naumann and Bassler, 2004). For feed samples, neutral detergent fiber (NDF), and acid detergent fibre (ADF) concentrations, both without residual ash, as well as acid detergent lignin (ADL) concentrations were analyzed by a semi-automatic ANKOM 200 Fiber Analyser (Ankom technology, Macedon, New York, USA) according to the procedures described by Van Soest et al. (1991). Contents of metabolizable energy (ME) and *in vitro* digestible organic matter were determined by Hohenheimer gas test as described by Menke and Steingass (1987). For herbage pool samples (n = 96) contents of DM, organic matter, CP, NDF, ADF, ADL, cellulase digestible OM, and ME were determined by Near-Infrared-Retro-Spectroscopy (NIRS). For details on NIRS calibration and validation see Schönbach et al. (2009).

Table 3.1 Experimental scheme (Arithmetic means across the three experimental periods \pm standard deviations, n=12).

Parameter	SYS*	Herbage allowance classes						Mean
		1	2	3	4	5	6	
Standing herbage mass † (kg DM/ha)	ALT	1305 \pm 227	937 \pm 105	831 \pm 236	814 \pm 193	648 \pm 276	654 \pm 377	865 \pm 348
	CON	2181 \pm 514	1654 \pm 711	1546 \pm 279	670 \pm 311	640 \pm 298	330 \pm 239	1170 \pm 779
Stocking density (sheep/ha)	ALT	2.0 \pm 0.0	4.0 \pm 0.0	5.3 \pm 0.4	7.0 \pm 0.0	8.5 \pm 0.0	10.3 \pm 0.6	6.2 \pm 2.8
	CON	2.3 \pm 0.2	4.7 \pm 0.5	6.5 \pm 0.9	7.5 \pm 0.5	9.0 \pm 0.5	10.3 \pm 0.2	6.7 \pm 2.7
Initial LW (kg)	ALT	30.3 \pm 1.0	30.1 \pm 2.6	29.2 \pm 1.9	30.3 \pm 1.3	28.9 \pm 2.0	28.3 \pm 2.0	29.5 \pm 1.8
	CON	30.5 \pm 0.8	30.1 \pm 2.2	31.1 \pm 1.9	31.6 \pm 2.3	31.4 \pm 2.4	29.9 \pm 1.7	30.8 \pm 1.9
Herbage allowance* (kg DM/kg LW)	ALT	17.6 \pm 2.7	6.7 \pm 0.0	4.7 \pm 0.2	3.5 \pm 0.3	2.6 \pm 0.3	2.2 \pm 0.5	6.2 \pm 5.6
	CON	26.4 \pm 8.0	11.8 \pm 3.0	7.5 \pm 0.1	2.9 \pm 1.1	2.5 \pm 0.6	1.3 \pm 0.2	8.7 \pm 9.4

* For details on grazing system and herbage allowance target ranges, see description in the text.

† Determined in the beginning of the experiment in the middle of June

DM, dry matter; LW, live weight; SYS, grazing system; ALT, alternating grazing system; CON, continuous grazing system.

Table 3.2 Composition across the experimental periods [g/kg dry matter], *in vitro* digestibility of organic matter (IVdOM), and metabolizable energy (ME) concentration [MJ/kg dry matter] of concentrate feed (n=3) and herbage (n=96).

	Concentrate feed	Herbage
CA	113	59
CP	198	115
NDF	281	691
ADF	144	329
ADL	46	45
IVdOM	73	65
ME	11.2	9.1

CA, crude ash; CP, crude protein; NDF, neutral detergent fiber (without residual ash); ADF, acid detergent fiber (without residual ash); ADL, acid detergent lignin.

3.3.5 Feed and energy intake

Daily OM intake (OMI) of sheep was calculated from fecal OM excretion and digestibility of ingested OM (dOM) according to Eq.1.

$$\text{OMI [g/d]} = \text{fecal OM excretion [g/d]} / (1 - \text{dOM}) \quad (\text{Eq.1})$$

Fecal OM excretion was determined using the inert marker titanium dioxide (TiO₂). On ten consecutive days in the beginning of July, August, and September, a pulse dose of 2.5 g TiO₂/d was orally administered to the four SUP and the four NSUP sheep per plot using a gelatin capsule. During each of these periods, fecal grab samples were obtained from the rectum on days 6 – 10 (sampling period). The samples were frozen immediately after collection. At the end of each sampling period, they were thawed, pooled by individual sheep and period, and homogenized. For further analyses two sub-samples were generated. One sub-sample was analyzed for N concentration according to the Kjeldahl procedure, for DM concentration by oven-drying at 105°C for 24 h, and for crude ash contents by incineration at 550°C for 12 h (Naumann and Bassler, 2004). The other sub-sample was oven-dried at 60°C for 36 h and ground to pass a 1 mm screen. TiO₂ was extracted according to the Kjeldahl procedure following descriptions by Brandt and Allam (1987) modified by Glindemann et al. (2009a). Subsequently, TiO₂ concentrations in the extracts were measured using a spectrophotometer (Jenway 6300 spectrophotometer, Bibby Scientific Limited, Staffordshire, UK) at a wavelength of 405 nm. Fecal OM output was calculated from daily TiO₂

administration and fecal TiO₂ concentration assuming a fecal recovery of TiO₂ of 100% (Glindemann et al., 2009a).

$$\text{Fecal excretion [g OM/d]} = \text{TiO}_2 \text{ dosage [g/d]} / \text{fecal TiO}_2 \text{ concentration [g/kg OM]} \cdot 1000 \quad (\text{Eq.2})$$

dOM was calculated from CP concentration in fecal OM using the non-linear regression equation of Wang et al. (2009) which was derived from 721 individual observations of digestibility trials with sheep.

$$\text{dOM} = 0.899 - 0.644 \cdot \exp(-0.5774 \cdot \text{fecal CP [g/kg OM]}/100) \quad (\text{Eq.3})$$

Intake of herbage OM (herbageOMI) of SUP sheep was calculated by subtracting the ingested amount of concentrate feed (g OM/d) from daily OMI, while herbageOMI equaled OMI in NSUP sheep.

ME concentrations of ingested OM were calculated from dOM according to the formula given by Aiple et al. (1992).

$$\text{ME [MJ/kg OM]} = -0.9 + 17.0 \cdot \text{dOM} \quad (\text{Eq.4})$$

Intakes of digestible OM (DOMI) and ME (MEI) were calculated by multiplying OMI by dOM and dietary ME concentrations, respectively.

3.3.6 Statistical analysis

The effects of concentrate supplementation (SUP; SUP, NSUP), grazing system (SYS; CON, ALT), HA class (HA class; 1, 2, 3, 4, 5, and 6), experimental period (EP; July, August, September), and their interactions on dOM, OMI, DOMI, herbageOMI, MEI, and LWG were analyzed by a mixed model (lme) using the software program R version 2.12.0 (The R Foundation for Statistical Computing, Vienna, Austria).

Fixed factors were SUP, SYS, HA class, and EP and their interactions. The repetition and the interaction between repetition and SYS and the interaction between repetition, SYS, and HA class was treated as random effect. Repeated measures were EPs.

Pair-wise t-tests were used to detect differences between SUP and NSUP sheep,

between HA classes, and between experimental periods. Level of significance was $P \leq 0.05$ and P -values of $>0.05 - \leq 0.10$ were considered as a trend. To test correlations between measured parameters and variables linear regression analysis was used.

3.4 Results

3.4.1 Effect of concentrate supplementation

Concentrate supplementation increased dOM, OMI, DOMI, MEI, and LWG ($P < 0.001$ for all parameters, Table 3.3 and 3.4). While across the grazing season, dOM, OMI, and MEI averaged 0.557, 74.3 g/kg^{0.75} LW, and 0.64 MJ/kg^{0.75} LW in NSUP sheep, respectively, digestibility and intake values were 0.533, 67.6 g/kg^{0.75} LW, and 0.55 MJ/kg^{0.75} LW in SUP sheep. Daily LWG of NSUP sheep at different HA classes ranged between 71.4 g and 94.3 g, and between 105.5 g and 125.9 g in SUP sheep. Daily herbage OMI was lower in SUP (60.9 g/kg^{0.75} LW) than in NSUP sheep (67.6 g/kg^{0.75} LW; $P < 0.001$). There were no interactions between concentrate supplementation and HA classes ($P \geq 0.462$) or between concentrate supplementation and grazing system ($P \geq 0.671$) for any of the measured parameters.

3.4.2 Effect of grazing system, grazing intensity, and experimental period

Grazing system had no direct influence on any of the analyzed parameters ($P \geq 0.751$). Effects of grazing system were only observed in interaction with experimental period or in triple interaction with HA classes and experimental period. Hence, only mean values across both systems are presented (Table 3.3 and 3.5). Significant interactions between grazing system and experimental period were found for OMI, DOMI, herbage OMI, MEI, and LWG ($P \leq 0.019$). At CON intake values were higher in July than in August ($P \leq 0.021$) and in September ($P < 0.001$) as well as higher in August than in September ($P < 0.001$). In contrast, the differences were only significant for September when compared to the two previous months at ALT ($P < 0.001$ for all parameters). Similarly, the effect of concentrate supplementation on LWG of sheep decreased with advancing vegetation period ($P < 0.001$, see Table 3.5). While daily LWG of SUP sheep (186.0 g) was 64.1 g higher than that of NSUP (121.9 g) sheep in July ($P < 0.001$), the difference in LWG between SUP (65.0 g) and NSUP sheep (43.1 g) was smaller in September with only 21.9 g/d ($P = 0.020$). Moreover, daily LWG

was 25.1 g higher in ALT (66.6 g) than in CON (41.5 g) in September (P=0.012; see Figure 3.1).

Table 3.3 Digestibility of organic matter (dOM), organic matter intake (OMI), digestible organic matter intake (DOMI), and metabolizable energy intake (MEI), and herbage of organic matter intake (herbageOMI) as well as daily live weight gain (LWG) of supplemented (SUP) and non-supplemented (NSUP) sheep grazing the Inner Mongolian steppe at different herbage allowance classes during July-September 2010. (Arithmetic mean, residual standard deviation (RSD); n=12).

Parameter	Herbage allowance classes*						RSD	Mean
	1	2	3	4	5	6		
<u>dOM</u>								
SUP	0.557 ^A	0.552 ^A	0.556 ^A	0.554 ^A	0.563 ^A	0.560 ^A	0.016	0.557 ^A
NSUP	0.538 ^{B,ab}	0.526 ^{B,ab}	0.525 ^{B,a}	0.524 ^{B,ab}	0.535 ^{B,ab}	0.547 ^{B,b}	0.016	0.533 ^B
<u>OMI [g/kg^{0.75}LW]</u>								
SUP	71.4	72.3	74.9 ^A	74.7	77.4	75.0	6.4	74.3 ^A
NSUP	68.8	63.4	64.5 ^B	69.3	69.7	69.8	6.4	67.6 ^B
<u>DOMI [g/kg^{0.75}LW]</u>								
SUP	39.8	40.0 ^A	41.7 ^A	41.4	43.6	42.1	4.2	41.4 ^A
NSUP	37.1	33.5 ^B	34.0 ^B	36.5	37.4	38.3	4.2	36.1 ^B
<u>MEI [MJ/kg^{0.75}LW]</u>								
SUP	0.61	0.61 ^A	0.64 ^A	0.64	0.67	0.65	0.07	0.64 ^A
NSUP	0.57	0.51 ^B	0.52 ^B	0.56	0.57	0.59	0.07	0.55 ^B
<u>herbageOMI [g/kg^{0.75}LW]</u>								
SUP	58.4	59.0	61.5	61.6	64.0	61.2	6.4	60.9 ^A
NSUP	68.8	63.4	64.5	69.3	69.7	69.8	6.4	67.6 ^B
<u>LWG [g]</u>								
SUP	125.9	118.4	129.3	121.5	126.2	105.5	24.6	121.1 ^A
NSUP	92.0	86.6	89.2	94.3	82.2	71.4	24.6	85.9 ^B

* For a detailed description of herbage allowance classes see Table 1.

Different superscripts indicate significant differences (P≤0.05) between grazing intensities for SUP or NSUP

Table 3.4 Effects of concentrate supplementation (SUPPL), grazing system (SYS), herbage allowance (HA) classes, experimental period (EP) and their interactions on digestibility of organic matter (dOM), organic matter intake (OMI), digestible organic matter intake (DOMI), metabolizable energy intake (MEI), herbage organic matter intake (herbageOMI) as well as daily live weight gain (LWG) of sheep grazing the Inner Mongolian steppe during July-September 2010.

Parameter	Level of significance									
	SUPPL	SYS	HAclass	EP	SYS×EP	HAclass×EP	SUPPL×EP	SUPPL×SYS	SUPPL×HAclass	SYS×HAclass×EP
DOM	<0.001	0.901	0.075	<0.001	0.050	0.277	0.254	0.724	0.462	0.873
OMI [g/kg ^{0.75} LW]	<0.001	0.751	0.447	<0.001	0.019	0.001	0.969	0.868	0.484	0.757
DOMI [g/kg ^{0.75} LW]	<0.001	0.787	0.282	<0.001	0.012	0.009	0.995	0.989	0.519	0.904
MEI [MJ/kg ^{0.75} LW]	<0.001	0.786	0.268	<0.001	0.012	0.011	0.996	0.999	0.525	0.912
herbageOMI [g/kg ^{0.75} LW]	<0.001	0.754	0.481	<0.001	0.018	<0.001	0.819	0.909	0.487	0.753
LWG [g]	<0.001	0.766	0.418	<0.001	<0.001	0.013	<0.001	0.671	0.759	0.024

Significant (P≤0.05) effects are printed in bold.

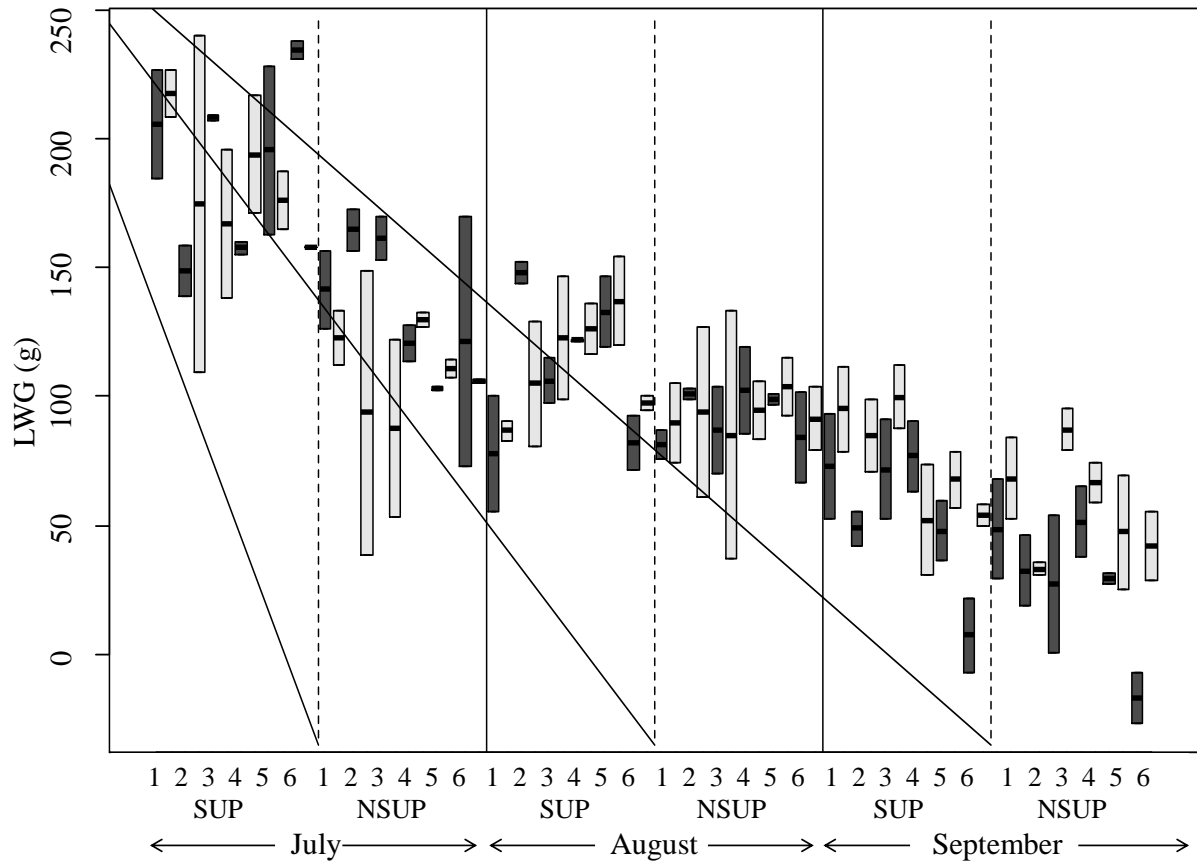
No significant fourfold interaction was observed.

Table 3.5 Digestibility of ingested organic matter (dOM), organic matter intake (OMI), digestible organic matter intake (DOMI), metabolizable energy intake (MEI), herbage organic matter intake (herbageOMI) per metabolic live weight ($LW^{0.75}$) as well as daily live weight gain (LWG) of supplemented (SUP) and non-supplemented (NSUP) sheep grazing the Inner Mongolian steppe during different experimental periods in 2010 (Arithmetic mean; n=24).

Parameter	July	August	September
Herbage mass on offer [kg DM/ha]	1233	1030	788
Stocking density [sheep/ha]	6.2	6.5	6.7
Live weight [kg/sheep]	34.2	36.9	38.2
Herbage allowance [kg DM/kg LW]	8.7	7.7	6.0
<u>dOM</u>			
SUP	0.563 ^{A,ab}	0.559 ^{A,a}	0.548 ^{A,b}
NSUP	0.542 ^{B,a}	0.539 ^{B,a}	0.517 ^{B,b}
<u>OMI [g/kg^{0.75}LW]</u>			
SUP	81.4 ^{A,a}	77.6 ^{A,a}	63.8 ^{A,b}
NSUP	74.8 ^{B,a}	70.6 ^{B,a}	57.3 ^{B,b}
<u>DOMI [g/kg^{0.75}LW]</u>			
SUP	46.0 ^{A,a}	43.5 ^{A,a}	34.9 ^{A,b}
NSUP	40.6 ^{B,a}	38.1 ^{B,a}	29.6 ^{B,b}
<u>MEI [MJ/kg^{0.75}LW]</u>			
SUP	0.71 ^{A,a}	0.67 ^{A,a}	0.54 ^{A,b}
NSUP	0.62 ^{B,a}	0.58 ^{B,a}	0.45 ^{B,b}
<u>herbageOMI [g/kg^{0.75}LW]</u>			
SUP	67.3 ^{A,a}	64.5 ^{A,a}	51.1 ^{A,b}
NSUP	74.8 ^{B,a}	70.6 ^{B,a}	57.3 ^{B,b}
<u>LWG [g]</u>			
SUP	186.0 ^{A,a}	112.0 ^{A,b}	65.0 ^{A,c}
NSUP	121.9 ^{B,a}	92.9 ^{B,b}	43.1 ^{B,c}

Different superscripts indicate significant differences ($P < 0.05$) between experimental periods (a, b; within rows) for SUP and NSUP sheep and between SUP and NSUP sheep (A, B; within columns). DM, dry matter; LW, live weight.

Figure 3.1 Daily live weight gain (LWG) of supplemented (SUP) and non-supplemented (NSUP) sheep grazing the Inner Mongolian steppe during July, August and September 2010 from herbage allowance class 1- 6 in continuous (dark grey box plots) and alternating grazing system (light grey box plots in 2010), bars indicate Median (n=2).



No differences were observed between HA classes for all measured parameters ($P \leq 0.075$). Differences in OMI, DOMI, herbageOMI, MEI, and LWG between sheep at individual HA classes were disparate in July, August, and September ($P < 0.001$). There were no significant relationships between SD and dOM, feed intake, or daily LWG of sheep according to the regression analyses ($R^2 \leq 0.008$; $P \leq 0.292$). Significant interactions between experimental period with grazing system or HA class for OMI, DOMI, herbageOMI and MEI and LWG were observed but considered to be of less relevance and therefore the latter parameters were not differentiated for each variable (see Table 3.3, 3.4 and 3.5). Across both grazing systems and all HA classes and irrespective of supplementation dOM, OMI, DOMI, herbageOMI and MEI were similar in July and August, but lower in September compared to the previous experimental periods. In contrast LWG constantly decreased from July to September (see Table 3.5).

A triple interaction between grazing system, HA classes, experimental period was

observed for LWG. In July differences in LWG between both grazing systems were higher in low HA classes whereas in September differences in LWG between both grazing systems were higher at higher HA classes. No significant fourfold interaction was found for any of the measured parameters.

3.5 Discussion

3.5.1 Effect of concentrate supplementation

Animal performance in pastoral livestock systems, in particular in semi-arid regions of the world, is largely determined by the quantity and quality of forage available on pasture. Offering concentrate feeds in addition to grazing may compensate for a low availability and/or nutritional value of forage i.e. in times of low rainfall or as a result of heavy grazing. It may thereby maintain nutrient and energy intakes and consequently, performance of animals. Our results show that already 250 g/d of a concentrate mixture (~ 18 % of their total OMI) increased dOM and thus OMIs and MEIs of sheep. Despite a lower herbageOMI this allowed for a higher LWG of SUP compared to NSUP animals. Hence, results on dOM, feed intake, and LWG are highly conclusive. The latter issue confirms findings of Rokomantu and Aregore (2006), who determined a higher LWG of SUP compared to NSUP sheep in hot and humid Fiji despite lower herbageOMI when offering either a concentrate mixture or wheat grain in addition to grazing. Similarly, LWG of grazing sheep in a study by Santra et al. (2002) in a semi-arid region of India was improved by feeding a barley-grain-based concentrate feed.

Across both grazing systems, all HA classes, and the entire grazing season, the mean difference in the MEIs of SUP and NSUP sheep was 1.43 MJ ME/d. According to the ME requirement of sheep for gain (MEg) of 23 kJ/g (Jeroch et al., 1996), this additional MEI would be sufficient for an additional LWG of SUP sheep in our study of approximately 60 g/d. In July, the measured difference in LWG between both treatment groups of 64 g/d was very similar to the expected increase in animal performance, suggesting that SUP sheep were able to convert the additional ME into body gain. However, in September, LWG of SUP sheep was only 22 g/d higher than of NSUP sheep. Since SUP and NSUP animals of both treatment groups were kept together in the same paddocks and sheep usually stay close together during grazing (Lin et al., 2011), differences in the grazing activity and walking

distances and hence, the ME requirements for physical activity are unlikely. Moreover, LW and hence, maintenance ME requirements of SUP (38.1 kg LW) and NSUP sheep (37.1 kg LW) were very similar during this month and can therefore not explain the inferior effect of concentrate feeding in September. However, fat content in gain increases with advancing maturity of animals (Jeroch et al., 1996). Hence, ME_g requirements (in kJ/g LWG) might have been higher in September than in July. This would at least partly explain the discrepancy between expected and measured LWG of SUP sheep. Moreover, factors other than MEI could have limited the animals' LWG towards the end of the grazing season i.e. the decrease in herbage nutrient contents with progressing vegetation period. Thus, results show that concentrate supplementation can considerably increase LWG of grazing livestock, but efficiency (i.e. g LWG/g concentrate) differs depending on the season, quality of the herbage, and/or the age of the animals.

In our study feeding 250 g/d of a corn-based concentrate mixture to sheep (equivalent to ~ 0.8 % of their mean LW) increased total OMI of sheep by on average 9 %, however, reduced their herbageOMI. Across both grazing systems, all HA classes, and experimental periods, the replacement rate was 0.26 MJ herbage ME per 1 MJ concentrate ME. On organic matter basis the mean decrease in herbageOMI was 0.41 g per 1 g of concentrate feed. This is similar to the replacement rate of 0.31 g herbage per 1 g of concentrate (on DM basis) reported by Bodine and Purvis (2003) who fed a corn-soybean-based concentrate feed to steers grazing a dormant tallgrass prairie in Oklahoma, U.S.A. at 1.0 % of their LW (326 kg). Moreover, Dickhoefer et al. (2011) reported a similar replacement rate of 0.47 g herbage per 1 g of green fodder offered to grazing goats (on DM basis) in semi-arid Northern Oman. The depressed herbageOMI in the latter investigations as well as in our study is most likely due the fact that rumen volume was limiting total feed intake of the animals (Van Soest, 1994). Although high quality concentrate feeds are rapidly fermented and may even increase forage degradability (Van Soest, 1994), part of the supplemental feed was consumed on behalf of the herbage. This relatively high replacement rate in our study might partly be due to the medium quality of the concentrate with 11.2 MJ ME/kg DM. Replacement rates were similar in July, August, and September despite a lower OMI of sheep towards the end of the grazing season which may contradict the assumption that rumen fill was the limiting factor. However, *in vitro* digestibility of herbage and dOM strongly declined from July to September due to increasing NDF concentrations. Moreover, the proportion of ADL in NDF was higher in September than in July. The lower degradability of the fibrous fraction at the end of grazing season and hence,

the prolonged rumen retention times could thus explain the similar substitution rates.

3.5.2 Effect of grazing system and grazing intensity

The effect of supplementation might differ between grazing systems and HA classes due to differences in the mass and nutritional quality of herbage on offer. Hence, feeding concentrate feedstuffs in addition to grazing may compensate for a lower feed intake and performance of grazing livestock at CON than at ALT due to an inferior HM and herbage quality. Contrary to our assumptions, the extent to which supplemental feeding increased animal feed intake and performance was independent of grazing system. This might be due to the fact that SDs were monthly adjusted to standing HM to achieve comparable HAs at both systems. Moreover, digestibility and nutrient concentrations of herbage on offer did not differ between ALT and CON neither in 2010 nor in any of the previous study years (Schönbach et al., 2009; Dickhoefer et al., submitted). This might have mitigated the negative effects of CON on feed intake and performance of individual sheep within the frame of this research project. Hence, grazing system did not influence LWG of sheep in the preceding study years 2005 – 2009 (Lin et al., 2012). Similarly, feed intake and LWG of sheep did not differ between the two grazing systems in 2009 (Dickhoefer et al., submitted) and our study year. Even total LWG per hectare, calculated by multiplying LWG of sheep by the SD in the respective plots, was very similar at ALT (633 g/ha) and CON (655 g/ha) in our study despite differences in HM between ALT and CON on offer at lowest HA classes (Dickhoefer et al., submitted). Moreover, Lin et al. (2011) who studied animal behavior within the frame of our research project did not find any differences in the daily trajectories or the duration of grazing periods between ALT and CON sheep. Altogether, the lack of differences between systems in herbage and animal parameters explains why no interactions between grazing system and concentrate supplementation were found.

Similarly, HA class had no impact on dOM, OMI, herbageOMI, and LWG of sheep. In contrast, decreases in OMI and/or LWG of sheep with decreasing HA were found in the preceding years 2005 – 2009 (Lin et al., 2012; Schönbach et al., 2012; Müller et al., 2012). These differences were related to the lower HM on offer and consequently, the lower feed intakes and/or higher energy expenditures of sheep for physical activity (Glindemann et al., 2009b; Lin et al., 2011; Dickhoefer et al., submitted; Müller et al., 2012).

Hence, in a pre-study in 2009 (not published), NSUP animals at HA class 6 lost weight towards the end of the grazing season, while NSUP sheep at HA class 5 were able to maintain or even increase their LW. The increase in LWG per g concentrate feed offered was greater at HA class 6 than at HA class 5 in this year. In contrast, it was almost identical at all HA classes in our study (27 g – 44 g), most likely due to the lacking differences in dOM, OMI, and LWG of sheep between HA classes. Even at HAs ≤ 1.8 kg DM/kg LW (HA class 6), the animals were able to maintain their MEI e.g. by consuming the whole plants and/or by slightly increasing their grazing times and bite frequencies (Lin et al., 2011).

Overall, this indicates that high inter- and intra- annual variability in precipitation and temperature might predominate the effects of grazing system and HA class on feed intake and LWG at least in the short term. Six study years with grazing seasons of only three months each might not have been sufficient to clearly establish the effects of management system and HA class on herbage and in particular animal parameters (Schönbach et al., 2009; Dickhoefer et al., submitted; Lin et al., 2012).

3.5.3 Economical and ecological relevance

At 250 g/d of concentrate feed offered, a total of 22.5 kg was fed to each animal during the 90 d-grazing season. According to the current price of the local concentrate feed used in our study of 2.30 ¥/kg, equivalent to about 0.28 €/kg (02.06.2010; 1 € = 8.35 ¥; www.bankenverband.de/service/waehrungsrechner), this sums up to feeding costs of about 6.30 €/animal. Across the entire grazing season, total LWG of SUP sheep exceeded that of NSUP sheep by 3.12 kg. Hence, the additional feeding cost of 2.02 €/kg LWG even exceeded the revenue from the sale of sheep of 1.78 €/kg LW for an animal of approximately 30 kg LW (mean prices during 2008 – 2010, derived from interviews with ten local farmers; Bösing, personal communication). From an economic point of view, a concentrate supplementation over the whole grazing season therefore does not appear to increase the profit for farmers. However, use efficiency of the concentrate offered was highest in July (see section 4.1) so that costs for supplemental feeding in this month were only 0.86 €/kg LWG which is 0.92 € lower than the mean price of sheep determined during farmers interviews (1.78 €/kg LW; Bösing, personal communication). Hence, neglecting other costs for labor, transport, and feeding equipment concentrate supplementation restricted to specific periods or to animals with a higher growth potential (i.e. younger or male animals) appears to be profitable.

Moreover, the increase in LWG of individual sheep due to concentrate feeding would allow for a similar total LWG per unit of land area when SDs were reduced from on average 7 – 10 sheep/ha at HA classes 4 – 6 to 6 sheep/ha at HA class 3. This reduction in herd sizes would reduce input of labor and veterinary care as well as expenses for feeding hay outside of the vegetation period. At current prices the latter sums up to ~ 19 €/animal and year (mean costs derived from interviews with ten local farmers; Bösing, personal communication) and thus by far exceed costs of a concentrate feeding during the 90 d-grazing season.

According to Christensen et al. (2003), a minimum HM of 51 % of the annual ANPP is needed to prevent long-term degradation of the semi-arid grasslands in Inner Mongolia. This equals to about 644 kg OM/ha in our study area (Schönbach et al., 2011). HM on HA class 4 – 6 plots in the beginning of August of 567, 538, and 367 kg OM/ha, respectively, were already below this threshold after one month of grazing. End-of-season standing biomass (ESSB) at these plots represented only 82 %, 45 %, and 24 % of this minimum HM, respectively, in September 2010. Instead, ESSBs at HA classes ≤ 3 (corresponding to ~ 6 sheep per ha) were 861 kg OM/ha and were thus sufficient to ensure long-term grassland productivity. In addition to the possible reduction in SD mentioned above concentrate supplementation decreased herbageOMI and therefore might increase ESSB. The latter could not be measured separately for a SUP or NSUP scenario in our study, because sheep of both treatment groups were kept together at the same plots. However, across both systems, all HA classes, and experimental periods, SUP sheep daily ingested 0.08 kg OM less herbage than NSUP sheep. At HA classes 4 – 6 this would sum up to a 66, 60, and 109 kg OM/ha lower herbage consumption during the 90 d-grazing season when all animals would have been supplemented (calculated by multiplying Δ herbageOMI by the SD in respective plots and 90 d). This is equivalent to 4.6, 4.2 and 7.7 % of the mean annual ANPP of the local grassland steppe (Schönbach et al., 2011). Hence, by reducing herbageOMI of individual animals concentrate supplementation can substantially alleviate ESSB above the critical threshold. It may thus be a useful measure to reduce grazing pressure in particular in dry years with low ANPP and might considerably contribute to maintain long-term grassland productivity.

3.6 Conclusions

In semi-arid and arid pastoral systems a moderate concentrate supplementation strongly increases feed intake and LWG of grazing livestock and appears sufficient to maintain output per area even at lower SDs. Efficiency of the use of concentrate feed was similar at ALT and CON grazing and over a wide range of SDs in our study, most likely due to a lack of differences in herbage and animal parameters between systems and HA classes and the adaptive feeding behavior of sheep. At current prices for feed and sheep, supplementation of almost fully grown animals over the entire grazing season does not appear profitable. Nevertheless, a concentrate feeding restricted to selected months and/or to animals with higher growth potential might be cost-effective. Furthermore, from an ecological point of view the effects of feeding regional by-products should be tested to limit the import of concentrate feed. The considerable reduction in herbageOMI of individual animals alleviates grazing pressure and thus can contribute to maintain long-term productivity of grasslands and similar environments.

3.7 References

- Aiple, K.P., Steingass, H., Menke, K.H., 1992. Suitability of a buffered fecal suspension as the inoculum in the Hohenheim Gas Test .1. Modification of the method and its ability in the prediction of organic-matter digestibility and metabolizable energy content of ruminant feeds compared with rumen fluid as inoculum. *Journal of Animal Physiology and Animal Nutrition* 67, 57-66.
- Akiyama, T., Kawamura, K., 2007. Grassland degradation in China: Methods of monitoring, management and restoration. *Grassland Science* 53, 1-17.
- Bai, Y.F., Han, X.G., Wu, J.G., Chen, Z.Z., Li, L.H., 2004. Ecosystem stability and compensatory effects in the Inner Mongolia grassland. *Nature* 431, 181-184.
- Bai, Y.F., Wu, J.G., Xing, Q., Pan, Q.M., Huang, J.H., Yang, D.L., Han, X.G., 2008. Primary production and rain use efficiency across a precipitation gradient on the Mongolia plateau. *Ecology* 89, 2140-2153.
- Bodine, T.N., Purvis, H.T., 2003. Effects of supplemental energy and/or degradable intake protein on performance, grazing behavior, intake, digestibility, and fecal and blood

- indices by beef steers grazed on dormant native tallgrass prairie. *Journal of Animal Science* 81, 304-317.
- Brandt, M., Allam, S.M., 1987. Analytik von Titandioxid im Darminhalt und Kot nach Kjeldahlaufschluß. *Archives of Animal Nutrition* 37, 453-454.
- Caton, J.S., Dhuyvetter, D.V., 1997. Influence of energy supplementation on grazing ruminants: Requirements and responses. *Journal of Animal Science* 75, 533-542.
- Christensen, L., Coughenour, M.B., Ellis, J.E., Chen, Z.Z., 2003. Sustainability of Inner Mongolian grasslands: Application of the Savanna model. *Journal of Range Management* 56, 319-327.
- Christensen, L., Coughenour, M.B., Ellis, J.E., Chen, Z.Z., 2004. Vulnerability of the Asian typical steppe to grazing and climate change. *Climatic Change* 63, 351-368.
- Dickhoefer, U., Hao, J., Bösing, B.M., Lin, L.J., Susenbeth, A., submitted. Diet digestibility, feed intake and live weight gain of grazing sheep as affected alternating and continuous grazing systems.
- Dickhoefer, U., Mahgoub, O., Schlecht, E., 2011. Adjusting homestead feeding to requirements and nutrient intake of grazing goats on semi-arid, subtropical highland pastures. *Animal* 5, 471-482.
- Fahmy, M.H., Boucher, J.M., Poste, L.M., Grégoire, R., Butler, G., Comeau, J.E., 1992. Feed efficiency, carcass characteristics, and sensory quality of lambs, with or without prolific ancestry, fed diets with different protein supplements. *Journal of Animal Science* 70, 1365-1374.
- Glindemann, T., Tas, B.M., Wang, C., Alvers, S., Susenbeth, A., 2009a. Evaluation of titanium dioxide as an inert marker for estimating fecal excretion in grazing sheep. *Animal Feed Science and Technology* 152, 186-197.
- Glindemann, T., Wang, C., Tas, B.M., Schiborra, A., Gierus, M., Taube, F., Susenbeth, A., 2009b. Impact of grazing intensity on herbage intake, composition, and digestibility and on live weight gain of sheep on the Inner Mongolian steppe. *Livestock Science* 124, 142-147.
- IUSS Working Group WRB, 2007. World reference base for soil resources 2006, 2nd edition. World Soil Resources Reports No. 103, First Update. FAO, Rome.

- Jeroch, H., Kirchgeßner, M., Pallauf, J., Pfeffer, E., Schulz, E., Staudacher, W., 1996. Mitteilungen des Ausschusses für Bedarfsnormen der Gesellschaft für Ernährungsphysiologie - Energie-Bedarf von Schafen. In: Giesecke, D. (Ed.), Proceedings of the Society of Nutrition Physiology DLG-Verlag, Frankfurt, Germany, pp. 149-151.
- Lin, L.J., Dickhoefer, U., Müller, K., Chenjie, W., Glindermann, T., Hao, J., Wan, H., Schönbach, P., Gierus, M., Taube, F., Susenbeth, A., 2012. Growth of sheep as affected by grazing system and grazing intensity in the steppe of Inner Mongolia, China. *Livestock Science* 144, 140-147.
- Lin, L.J., Dickhoefer, U., Muller, K., Wurina, Susenbeth, A., 2011. Grazing behavior of sheep at different stocking rates in the Inner Mongolian steppe, China. *Applied Animal Behaviour Science* 129, 36-42.
- Lourenco, A.L.G., Dias-da-Silva, A.A., Fonseca, A.J.M., Azevedo, J.T., 2000. Effects of live weight, maturity and genotype of sheep fed a hay-based diet, on intake, digestion and live weight gain. *Livestock Production Science* 63, 291-296.
- Menke, K.H., Steingass, H., 1987. Schätzung des energetischen Futterwertes aus der in-vitro mit Pansensaft bestimmten Gasbildung und der chemischen Analyse. 2. Mitteilung: Regressionsgleichung *Übersicht Tierernährung* 14, 53-94.
- Mortimore, M., 1993. Population growth and land degradation. *GeoJournal* 31, 15-21.
- Müller, K., Dickhoefer, U., Chenjie, W., Schönbach, P., Wan, H., Schiborra, A., Tas, B.M., Gierus, M., Taube, F., Susenbeth, A., submitted. Impact of grazing intensity or herbage quality, feed intake, and live weight gain of sheep grazing the steppe of Inner Mongolia, China.
- Müller, K., Lin, L., Wang, C., Glindemann, T., Schiborra, A., Schönbach, P., Wan, H., Dickhoefer, U., Susenbeth, A., 2012. Effect of continuous v. daytime grazing on feed intake and growth of sheep grazing in a semi-arid grassland steppe. *Animal* 6, 526-534.
- Naumann, K., Bassler, R., 2004. Bestimmung von Rohprotein Mittels Dumas-Verbrennungsmethode. In: Dieterle, P. (Ed.), *Methodenbuch, Band 3, Die chemische Untersuchung von Futtermitteln*. VDLUFA-Verlag, Bonn, pp. 1-5.

- Rokomatu, I., Aregheore, E.M., 2006. Effects of supplementation on voluntary dry matter intake, growth and nutrient digestibility of the Fiji Fantastic sheep on a basal diet of Guinea grass (*Panicum maximum*). *Livestock Science* 100, 132-141.
- Santra, A., Karim, S.A., Chaturvedi, O.H., 2002. Effect of concentrate supplementation on nutrient intake and performance of lambs of two genotypes grazing a semiarid rangeland. *Small Ruminant Research* 44, 37-45.
- Schönbach, P., Wan, H., Gierus, M., Müller, K., Lin, L., Bai, Y., Loges, R., Susenbeth, A., Taube, F., 2012. Effects of grazing intensity and precipitation on herbage accumulation, herbage quality and animal performance in a semi-arid grassland of Inner Mongolia. *Grass and Forage Science*, in press. DOI: 10.1111/j.1365-2494.2012.00874.x.
- Schönbach, P., Wan, H.W., Gierus, M., Bai, Y.F., Müller, K., Lin, L.J., Susenbeth, A., Taube, F., 2011. Grassland responses to grazing: effects of grazing intensity and management system in an Inner Mongolian steppe ecosystem. *Plant and Soil* 340, 103-115.
- Schönbach, P., Wan, H.W., Schiborra, A., Gierus, M., Bai, Y.F., Müller, K., Glindemann, T., Wang, C., Susenbeth, A., Taube, F., 2009. Short-term management and stocking rate effects of sheep grazing on herbage quality and productivity of Inner Mongolia steppe. *Crop and Pasture Science* 60, 1-12.
- Sollenberger, L.E., Moore, J.E., Allen, V.G., Pedreira, C.G.S., 2005. Reporting forage allowance in grazing experiments. *Crop Science* 45, 896-900.
- Southgate, J.R., Cook, G.L., Kempster, A.J., 1982. A comparison of the progeny of British Friesian dams and different sire breeds in 16- and 24-month beef production systems 1. Live-weight gain and efficiency of food utilization. *Animal Production* 34, 155-166.
- Van Soest, P.J. (Ed.), 1994. *Nutritional ecology of the ruminant*. Cornell University Press Ithaca, N.Y. [u.a.], USA.
- Van Soest, P.J., Robertson, J.B., Lewis, B.A., 1991. Methods for dietary fibre, neutral detergent fibre, and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science* 74, 3583-3597.
- Wang, C.J., Tas, B.M., Glindemann, T., Rave, G., Schmidt, L., Weissbach, F., Susenbeth, A., 2009. Fecal crude protein content as an estimate for the digestibility of forage in

grazing sheep. *Animal Feed Science and Technology* 149, 199-208.

Yu, M., Ellis, J.E., Epstein, H.E., 2004. Regional analysis of climate, primary production, and livestock density in Inner Mongolia. *Journal of Environmental Quality* 33, 1675-1681.

Zhao, H.L., Zhao, X.Y., Zhou, R.L., Zhang, T.H., Drake, S., 2005. Desertification processes due to heavy grazing in sandy rangeland, Inner Mongolia. *Journal of Arid Environments* 62, 309-319.

4 General discussion and conclusion

Over thousands of years, the grasslands of the Mongolian plateau were used by nomadic livestock farmers in a sustainable way (Douglas et al., 2006). They were non-materialistic, and avoided over-exploiting natural resources such as grassland and water. However, this pattern of land use in Inner Mongolia has changed dramatically due to political transformation, settlement policy, and a steadily increasing human population (see Chapter 1). Today, most of the grassland is overgrazed (Li et al., 2000; Xu et al., 2008; Li et al., 2012), with a number of negative ecological consequences having been documented: changes in plant community composition (Wan et al., 2011; Ren et al., in press) leading towards higher dominance of unpalatable and low digestible species (Li et al., 2012) and/or shifts from perennial to annual plant species, extensive land degradation through increased soil erosion (Tong et al., 2004; Hoffmann et al., 2008), desertification (Zhao et al., 2005), and increasing greenhouse gas emission (Chen et al., 2011; Schönbach et al., 2012). Since local livestock producers still strongly depend on the grassland resources (Douglas et al., 2006), it is necessary to conserve this ecosystem to ensure their future agricultural livelihoods (see Chapter 1). Meeting this challenge requires the development and implementation of new feeding strategies that conserve the natural resources of the grassland steppe while maintaining or even increase livestock productivity.

These new feeding strategies need to be tailored to the harsh environmental conditions, e.g. a more sophisticated grazing management system (e.g. able to increase biomass production with low precipitation rates), sustainable stocking densities and concentrate supplementation (e.g. restricted to selected months). Moreover, farmers need to combine knowledge about the inter- and intra-annual variability in climatic conditions, and hence, herbage production and quality, as well as animal behavior, performance, and feed intake. The stocking density (SD) for grazing livestock is the most important factor regulating herbage allowance (HA). In this study, comparisons are made between continuous and alternate grazing management systems for the optimization of grassland resources, and analyses are undertaken of concentrate supplementation as a potentially valuable contribution to maintaining output per area at lower SDs. These studies were conducted in the steppe region near Xilinhot, according to Li et al. (2012) one of the most representative areas of the Inner Mongolia steppe. Therefore, results of this study are

applicable to the whole region.

4.1 Feeding strategies

4.1.1 Grazing intensity

In order to avoid over-exploitation of the grassland, there is an urgent need to identify an optimum grazing pressure that maximizes economic output whilst avoiding negative ecological consequences in the long term. Optimizing grazing intensity is an important strategy for improving animal performance. In the present study (Chapter 2), data collected from an alternating grazing management system (ALT) during 2005–2010 were used to evaluate the sustainability of grassland use of six different HA classes. Feed intake and performance of individual sheep were expected to decline with increasing SD as a consequence of lower HA. Furthermore, it was assumed that there would be a cumulative negative effect of high grazing intensities on herbage mass over the six-year period, with consequent lower organic matter intake (OMI) and live weight gain (LWG) per animal and per ha, as a result of a negative shift in plant species composition, less herbage growth due to trampling damages, and a decreasing seed bank as the years pass.

In the first experiment, six different HA classes were tested: very light (HA class 1), light (HA class 2), light-moderate (HA class 3), moderate (HA class 4), heavy (HA class 5), and very heavy (HA class 6). The SD in these HA classes ranged from 1.7 ± 0.2 in HA class 1 to 9.5 ± 0.6 sheep/ha in HA class 6. According to the visual assessment of herbage mass and the number of animals per area of land in the Xilin River Basin, as well as a comparison with the experimental plots, actual stocking densities are equal to HA class 5 and 6. Tong et al. (2004) reported that SDs in the Xilin River Basin increased from 1.4 heads/ha of livestock in 1985 to 2.5 heads/ha in 1999, corresponding to a stocking density of 7.5 sheep/ha with a grazing season of 4 months (Stocking rate: 2.5 heads/ha \rightarrow Stocking density: 2.5 heads/ha \cdot 12 month/ 4 month grazing season = 7.5). Based on the recent and ongoing increase in local livestock populations (Chen et al., 2009; see Chapter 1) and personal communication with farmers in this region, actual SDs were probably even higher in 2005 – 2010.

In terms of the changes in vegetation at high SDs within the framework of the research project (Schönbach et al., 2009; Schönbach et al., 2011; Wan et al., 2011; Ren et

al., in press), there were observed a number of negative consequences of high SDs, both in the short-term and over a period of 6 years: decreasing end-of-season standing biomass (ESSB), decreasing litter and annual herbage accumulation, decreasing above-ground net primary production (ANPP), and decreasing herbage mass available for grazing sheep. But in terms of the animal parameters after six years of grazing at high and very high stocking densities (HA class 5 and 6), no decline in LW yield per unit of land area was observed for the alternating (Chapter 3) and continuous (Lin et al., 2012) grazing system. LWG of individual animals was only marginally influenced by high SDs. Moreover, in the short term, heavy grazing has the advantage that food selection by sheep is strongly limited, grazing pressure on the grassland resources is more evenly distributed, food wastage is limited, and hence forage use efficiency is increased. Consequently, from an economic point of view, in order to achieve a high LWG per ha, it is a reasonable option for farmers in this region to temporarily manage the grassland at very high SDs. Because the experimental treatment doesn't induce an accumulative effect over time of grazing intensity on herbage mass, there was no decline in LWG per ha at the highest stocking densities for 2005 – 2010. Grazing pressure was kept constant by the HA method, by which the number of animals was adjusted every month so that HA remained constant within the defined HA range of each HA class.

From an ecological point of view, the results for vegetation ground cover and ESSB at the end of the grazing season indicate that, in three of the six study years, it would have been necessary to use the grassland steppe at SDs about 50 % lower than those yielding the highest animal output per unit of land area. Furthermore, variation in LWG increased from low to high HA class (see Chapter 2), indicating that the resilience to variable climatic conditions of animals in different years decreased with increasing HA class. Moreover, animals at HA classes 5 and 6 had to be removed from the plots at the end of August 2006 because they showed a considerably high weight loss, highlighting that the maximum SD for sheep was exceeded in this year. Although the experimental design does not cause an accumulative negative effect of high SDs over time, and grassland can tolerate high SDs (7– 10 sheep/ha) over six years without significantly lowering the output per area of land unit, a SD above 6 sheep/ha leads to overgrazing, at least in dry years (2005, 2006), whereas the LWG/ha was highest at 4 and 6 sheep/ha. As also shown by Wilson and Macleod (1991), the results for dry years in my study confirm that heavily-grazed plots were overgrazed, because in these years there is no linear relationship between SD and

LWG/ha. They determined overgrazing as a loss of linear relationship between animal productivity and stocking rate with time (Wilson and Macleod, 1991). Results for other years, when the highest LWG/ha is achieved at lower SDs, indicate that vegetation production should also be considered in the evaluation of grassland status. To prevent soil erosion during winter months, and thus to maintain long-term grassland productivity, it is necessary to reduce SDs to $2.0 - 6.4$ sheep/ha, depending on climate conditions. According to the FAO (2012), a sheep unit is defined as one 40 kg ewe with lamb, and indeed farmers mainly keep ewes with their lambs in the herds. The currently practiced standard differs to the values in this experimental study in which a sheep unit is defined as one hogget (1.5 years old) with an initial live weight of about 32 kg. Nevertheless, the results of the experiments can be applied to farm animals with the same performance and to the grasslands that they utilize.

Furthermore, the results indicate that in the long-term a reduction of SD to achieve a sustainable grassland use would not reduce the economic profit of farmers because of limited increase in output per area in some years as well as higher costs (e.g. vet, winter feed) at greater herd sizes.

4.1.2 Concentrate supplementation

The effect of concentrate supplementation on OMI and LWG of grazing sheep, and its potential contribution to steppe conservation, was analyzed. The effects of a concentrate supplementation across all HA classes and with alternating and continuous grassland use were tested in 2010. It was hypothesized that concentrate supplementation would increase LWG of sheep and that the efficiency of concentrate feeding may differ between grazing systems, HA classes, and different periods of the grazing season. Total feed intake and LWG of sheep increased with concentrate feeding, however, in contrast to the hypotheses, the effect was independent of grazing system and HA class. This was most likely due to a lack of differences in herbage and animal parameters between the two grazing management systems and the six HA classes, and/or selective feeding of sheep. Due to the fact that at high HAs animals have the capability of selecting plant species or plant parts of higher nutritional quality, and at low HAs standing herbage quality is higher than at high HA, digestibility of ingested organic matter (dOM) did not vary between different SDs.

The interaction between SUP and experimental period (EP) shows that the effect of

concentrate supplementation on sheep performance decreases as the vegetation period progressed. Mean additional LWG in supplemented (SUP) compared to non-supplemented (NSUP) animals over the whole grazing season was 35 g/d, equivalent to 41 % of the mean LWG of NSUP animals (see Chapter 3.4). It was greatest in July (65 g/d) and lowest in September (only 22 g/d). Mean efficiency was low and ranged from 0.32 to 0.11 g LWG per g concentrate. This low gain efficiency could be due to the medium quality of concentrate feed used in the present study. As a consequence, 1 kg of additional LWG in July realized by a daily supplementation of 250 g of concentrate feed would cost 1.15 euro (3.8 g concentrate/g LWG) compared to the average feeding costs across the whole grazing season of 6.03 euro/kg LWG (based on 7.1 g concentrate/g LWG). Furthermore, absolute growth rates of NSUP and SUP sheep were greatest in July, suggesting that, on the one hand, a concentrate supplementation limited to the beginning of grazing season was more profitable for farmers. Regarding the ecological parameters of vegetation ground cover and ESSB at the end of the grazing season, which can be used to evaluate grassland performance, it might be more profitable for farmers to sell marketable sheep at the end of July and save the grassland for the rest of vegetation period. In general, farmers sell their animals in this region a month later at the end of August to achieve more LW. But this study showed that by using concentrate feed farmers will achieve more profit and can conserve their grassland one month earlier. Furthermore, concentrate feeding to animals with high growth potential and therefore higher concentrate feed efficiency might be more cost-effective.

As the experimental period progressed, a decreasing available herbage mass and dOM were recorded, with consequent reduction in digestible organic matter (DOMI) and intakes of metabolizable energy (MEI). This also explains the decrease in LWG in SUP as well as NSUP. LWG of NSUP and SUP in July is much higher than that in September. On the basis of MEI, maintenance requirements of metabolizable energy (ME_m) and growth requirements of metabolizable energy (ME_g), calculated LWG in July was 55 g/d, rising to 67 g/d in September. The difference between calculated and measured LWG (mean value from July to September = 27g) increases from 0 g (no difference) in July to 45 g in September. The animals have probably reached close to their full growth capacity by July, and in August and September the animals may have already reached mature body size. According to Yang Lian (2011), the compensatory growth in July increases LWG. He reported that in the grasslands of Inner Mongolia, animals lose a substantial amount of

weight in the spring because of low HA, but then show a high compensatory LWG at the beginning of summer (June and July) when herbage grows again.

Across all experimental periods in 2010, total LWG/ha with 10.3 sheep/ha (HA class 6) was 20 kg/ha in NSUP and very similar (22 kg/ha) with 5.9 sheep/ha (HA class 3). Consequently, concentrate supplementation resulted in higher total LWG/ha allowing the reduction of stocking densities and attainment of the same LWG/ha with a reduction in SD of about 4.4 sheep/ha. Additionally, concentrate supplementation reduced herbage organic matter intake (OMI) by 10 %. Therefore, ESSB on grasslands grazed by animals supplemented with concentrate is about 10 % higher than without concentrate supplementation (Figure 4.1). Putting aside the high inter-annual climatic variability and differences in herbage and animal parameters, the maximum SD across all years (2005 – 2010) to remain below the recommended ecological threshold of 656 kg OM/ha ESSB, was 3.5 sheep/ha. With concentrate supplementation and a reduction of herbage OMI by about 10 %, this maximum SD will shift to 3.9 sheep/ha. Consequently a moderate concentrate supplementation enables farmers to keep 0.4 sheep more per ha.

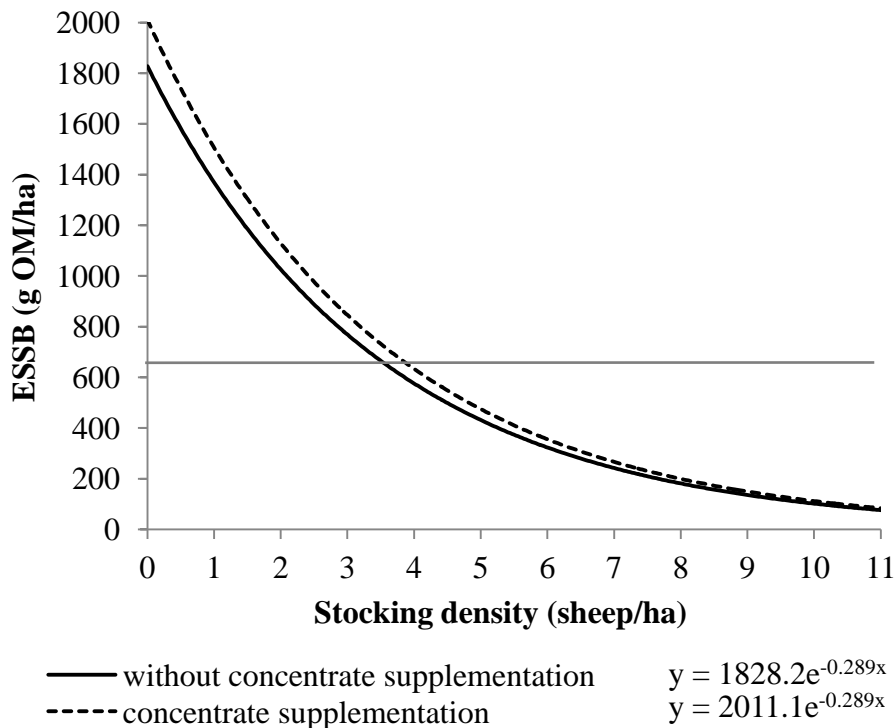


Figure 4.1 Regression equations ($y = a \cdot e^{bx}$) between the end-of-season standing biomass (ESSB) and stocking density (x) during the grazing season of 2005 – 2010 with and without concentrate supplementation ($n=12$ per year). Grey line indicates for the ESSB threshold of 656 g OM/ha (for details see chapter 3).

This calculation does not take into account the cumulative effect of high SD on herbage in the long term, and neither the trampling impacts on herbage, but it does illustrate that concentrate supplementation is an appropriate tool for conservation of the grassland ecosystem at a regional scale. It is also a valuable feeding strategy to compensate for farmers' economic losses caused by the recent de-stocking policies of the local government.

4.1.3 Grazing system

Sophisticated grazing systems are considered an important tool to maintain long-term grassland productivity. Grazing management systems can modify the effects of other feeding strategies such as grazing intensity modification and concentrate supplementation. The study of the effects of grazing systems on herbage and animal parameters produced inconsistent results, but ones that indicate that it is important to consider animal performance as well as herbage quality and productivity to evaluate grazing management strategies (Schönbach et al., 2011; Wan et al., 2011; Lin et al., 2012; Dickhoefer et al.,

submitted). In the context of the MAGIM-project, several studies analyzed the effects of different grazing management systems on dOM, OMI, LWG, and MEI per individual animal and per land unit. One of the major objectives was to test the effects of the alternating grazing (ALT) system on the sustainability of the grassland ecosystem in Inner Mongolia. Schönbach et al. (2011) found that grassland managed with ALT is more resilient to heavy grazing than with continuous grazing (CON) system after four years. The authors found a higher ANPP and ground cover with ALT compared to CON at the end of the grazing season, contributing to the prevention of soil erosion – and thus land degradation – during the non-grazing season. Wan et al. (2011) found no decline in total above-ground biomass (\triangle vegetation ground cover; Schönbach et al., 2011) of plant communities with increasing SD in ALT, whereas in CON total above-ground biomass was reduced, particularly at high SDs, indicating that ALT is a more sustainable land-use system.

Grazing system effects, however, were less pronounced on animal parameters. ALT didn't lead to higher OMI or LWG in animals in this study and furthermore, contrary to first-held assumptions, the extent to which supplemental feeding increased animal feed intake and performance was independent of grazing system. This might be due to the fact that the SDs were adjusted monthly to standing HM in order to achieve comparable HAs for both systems. Moreover, digestibility and nutrient concentrations of available herbage were similar in ALT and CON in 2010 and any of the previous study years (Schönbach et al., 2009; Hao et al., 2012). Dickhoefer et al. (submitted) concluded that in terms of dOM, OMI and LWG, ALT is neither superior nor inferior to CON. They concluded that the short study duration, the high variability in climatic conditions, and the adaptive capacity of grazing livestock, might explain the lack of differences between the two grazing systems. Besides ALT and CON, other grazing management systems (e.g. rotational grazing system (ROT) and day-time grazing) were evaluated within the framework of the MAGIM-project. Wang et al. (2009) and Hao et al. (2013) evaluated the effects of a ROT in 2005–2008. The latter study found that ROT does not improve herbage growth, feed intake and performance of sheep, probably due to the lack of herbage re-growth during grazing seasons and the animals' selective feeding behavior. Müller et al. (2012) compared day-time grazing with day-and-night grazing using data collected within the MAGIM-project during 2005 – 2007. In this study, it was observed that additional time on the pasture at night does not increase feed intake or animal performance. Moreover, Müller et al. (2012)

concluded that there were no positive effects of additional night grazing on grassland productivity and herbage quality, because of sheep crowding together during darkness, and fecal and urinary excretions being unevenly distributed across the entire pasture. Local farmers in Inner Mongolia keep their animals in corrals during the night to collect their manure for heating and cooking. Keeping sheep in corrals at night seems to be a reasonable strategy for farmers in the Inner Mongolian steppe (Müller et al., 2012).

The present study did not observe any effects of grazing management system on animal parameters in the short term. However, Wan et al. (2011) reported a negative vegetation shift within a grazing system at the species level (unpalatable species and low digestible species) in the long term. Likewise in our study system (ALT and CON), a perceivable effect of grazing system, on the effect of concentrate supplementation, and on animal performance can be assumed in the long-term.

4.2 Practical implications

The increased grazing pressure on the grasslands of Inner Mongolia is caused by changes to political governance and land property rights over the last decades. It is essential that farmers manage grasslands sustainably in order to maintain profitable pastoralism in the long-term. Extended farm lease periods can be an important tool for dealing with overgrazing. In a semi-arid region, such as the Inner Mongolian grassland steppe, it is not possible to define a fixed optimum stocking density (SD). High climatic variations (e.g. in precipitation) within and between years, together with non-predictable vegetation productivity and animal performance means that a specific optimum SD varies according to region and year.

Individual animals are only marginally influenced by high SDs in terms of DOM, OMI and LWG, despite a very low HA (herbage allowance). LWG per unit land area is usually highest under very high SDs (9.5 ± 0.6 sheep/ha), indicating that in the short term farmers act properly from an economic point of view. However, ground cover and ESSB at the end of the grazing season indicate that high SDs in most of the study years exceed the threshold values seen as critical for a sustainable long-term grassland use. In order, to analyze grazing effects, animal and herbage parameters should be considered together, at least in the long term. To prevent soil erosion during winter months and thus, to maintain long-term grassland productivity, it is necessary to reduce SDs to no more than 2.0 –

6.4 sheep/ha, depending on climate conditions. Therefore, it is necessary from an ecological point of view to use the grassland steppe at SDs 14 – 73% lower than the currently practiced SD of ~ 7.4 sheep/ha. As a consequence of overgrazing the predicted negative changes in herbage composition will decrease LWG/ha in the future.

Thus, I conclude that the ecological compatible maximum SD for the highest vegetation ground cover and biomass at the end of grazing season, and the economic optimum SD with the highest LWG/ha, will converge in future. This is evident in my experiment, which was inter alia carried out in a dry year and in which the economic maximum SD of 4 sheep/ha is close to the ecological maximum SD of 3 sheep/ha for this particular year.

A moderate amount of concentrate supplementation restricted to selected months, and/or to animals with higher growth potential, positively affects growth and can therefore improve farmers' income. The considerable reduction in herbage intake of animals by concentrate supplementation alleviates grazing pressure independent of SD and grazing management system. It is an efficient tool to reduce SDs while maintaining live weight yield per ha and the income of farmers on marginal grazing lands, thus contributing to the long-term maintenance of grassland ecosystems productivity.

4.3 References

- Chen, W., Wolf, B., Brüggemann, N., Butterbach-Bahl, K., Zheng, X., 2011. Annual emissions of greenhouse gases from sheepfolds in Inner Mongolia. *Plant and Soil* 340, 291-301.
- Dickhoefer, U., Hao, J., Bösing, B.M., Lin, L.J., Susenbeth, A., submitted. Diet digestibility, feed intake and live weight gain of grazing sheep as affected alternating and continuous grazing systems.
- Douglas, A.J., Dennis, P.S., Daniel, M., Daalkhaijav, D., 2006. Mongolian rangelands in transition. *Secheresse* 17, 133-141.
- FAO, 2012. Country Pasture/Forage Resource Profiles, China. In: Degang, P.H.Z.a.D.Z. (Ed.), 6. Opportunities for improvement of fodder resources. Food and Agricultural Organization of the United Nations. Rome.
- Hao, J., Dickhoefer, U., Lin, L., Müller, K., Glindemann, T., Schönbach, P., Schiborra, A.,

- Wang, C., Susenbeth, A., 2013. Effects of rotational and continuous grazing on herbage quality, feed intake and performance of sheep on a semi-arid grassland steppe. *Archives of Animal Nutrition* 67, 62-76.
- Hoffmann, C., Funk, R., Wieland, R., Li, Y., Sommer, M., 2008. Effects of grazing and topography on dust flux and deposition in the Xilingele grassland, Inner Mongolia. *Journal of Arid Environments* 72, 792-807.
- Li, S., Verburg, P., Lv, S., Wu, J., Li, X., 2012. Spatial analysis of the driving factors of grassland degradation under conditions of climate change and intensive use in Inner Mongolia, China. *Regional Environmental Change* 12, 461-474.
- Li, S.G., Harazono, Y., Oikawa, T., Zhao, H.L., He, Z.Y., Chang, X.L., 2000. Grassland desertification by grazing and the resulting micrometeorological changes in Inner Mongolia. *Agricultural and Forest Meteorology* 102, 125-137.
- Lin, L.J., Dickhoefer, U., Müller, K., Chenjie, W., Glindermann, T., Hao, J., Wan, H., Schönbach, P., Gierus, M., Taube, F., Susenbeth, A., 2012. Growth of sheep as affected by grazing system and grazing intensity in the steppe of Inner Mongolia, China. *Livestock Science* 144, 140-147.
- Müller, K., Lin, L., Wang, C., Glindemann, T., Schiborra, A., Schönbach, P., Wan, H., Dickhoefer, U., Susenbeth, A., 2012. Effect of continuous v. daytime grazing on feed intake and growth of sheep grazing in a semi-arid grassland steppe. *Animal* 6, 526-534.
- Ren, H., Schönbach, P., Wan, H., Gierus, M., Taube, F., in press. Effects of grazing intensity and environmental factors on species composition and diversity in typical steppe of Inner Mongolia, China. DOI: 10.1371/journal.pone.0052180.
- Schönbach, P., Wan, H.W., Gierus, M., Bai, Y.F., Müller, K., Lin, L.J., Susenbeth, A., Taube, F., 2011. Grassland responses to grazing: effects of grazing intensity and management system in an Inner Mongolian steppe ecosystem. *Plant and Soil* 340, 103-115.
- Schönbach, P., Wan, H.W., Schiborra, A., Gierus, M., Bai, Y.F., Müller, K., Glindemann, T., Wang, C., Susenbeth, A., Taube, F., 2009. Short-term management and stocking rate effects of sheep grazing on herbage quality and productivity of Inner Mongolia

- steppe. *Crop and Pasture Science* 60, 1-12.
- Schönbach, P., Wolf, B., Dickhoefer, U., Wiesmeier, M., Chen, W.W., Wan, H.W., Gierus, M., Butterbach-Bahl, K., Kogel-Knabner, I., Susenbeth, A., Zheng, X.H., Taube, F., 2012. Grazing effects on the greenhouse gas balance of a temperate steppe ecosystem. *Nutrient Cycling in Agroecosystems* 93, 357-371.
- Tong, C., Wu, J., Yong, S., Yang, J., Yong, W., 2004. A landscape-scale assessment of steppe degradation in the Xilin River Basin, Inner Mongolia, China. *Journal of Arid Environments* 59, 133-149.
- Wan, H.W., Bai, Y.F., Schönbach, P., Gierus, M., Taube, F., 2011. Effects of grazing management system on plant community structure and functioning in a semiarid steppe: scaling from species to community. *Plant and Soil* 340, 215-226.
- Wang, C.J., Tas, B.M., Glindemann, T., Mueller, K., Schiborra, A., Schoenbach, P., Gierus, M., Taube, F., Susenbeth, A., 2009. Rotational and continuous grazing of sheep in the Inner Mongolian steppe of China. *Journal of Animal Physiology and Animal Nutrition* 93, 245-252.
- Wilson, A.D., Macleod, N.D., 1991. Overgrazing - Present or Absent. *Journal of Range Management* 44, 475-482.
- Xu, Y., Wan, S., Cheng, W., Li, L., 2008. Impacts of grazing intensity on denitrification and N₂O production in a semi-arid grassland ecosystem. *Biogeochemistry* 88, 103-115.
- Yang Lian, W.J., Randall Jones, David Kemp, Ma Zhifeng and Taro Takahashi (Ed.), 2011. Changing livestock and grassland management to improve the sustainability and profitability of alpine grasslands in Sunan county, Gansu province. Australian Centre for International Agricultural Research, Canberra.
- Zhao, H.L., Zhao, X.Y., Zhou, R.L., Zhang, T.H., Drake, S., 2005. Desertification processes due to heavy grazing in sandy rangeland, Inner Mongolia. *Journal of Arid Environments* 62, 309-319.

5 Summary

The present study was conducted within the framework of the Sino-German MAGIM-project (“Matter fluxes of Grasslands in Inner Mongolia as influenced by stocking rate”, 2004 – 2010) and the LOTGras-project (“Long-term strategies towards improved grassland productivity in semi-arid environments”, 2010 – 2013) funded by the Deutsche Forschungsgemeinschaft DFG (German Research Foundation). In the MAGIM-project, biological aspects (e.g. grazing intensity, grazing management system, vegetation productivity and species composition, and soil parameters) of the Inner Mongolian steppe ecosystem were studied with the aim of reducing the ecological problems mainly associated with overgrazing in this region. LOTGras focused on precise feed supplementation to improve sustainable animal productivity and avoid degradation of the plant community. The objectives of this study were to evaluate the effects of different feeding strategies, in particular looking at the impact of grazing intensity, grazing management system and concentrate supplementation on feed intake, digestibility of organic matter intake and live weight gain of grazing sheep and on grassland condition in a semi-arid and arid pastoral system.

A grazing experiment in the Xilin River Basin (northeast Inner Mongolia) was conducted during the grazing seasons of 2005 – 2010, with two management regimes and six different grazing intensities (Very light – very heavy) and with ~ 300 female non-lactating Mongolian fat-tailed sheep. A continuous grazing management system, in which plots for grazing and hay-making were used continuously, and an alternating grazing management system, in which plots for grazing and hay-making alternated annually, were established. The first study analyzed results (2005 – 2010) of the alternating grazing system, to evaluate the impact of grazing intensity on digestibility, feed intake and live weight gain of grazing sheep. The second study in 2010 the effects of a moderate concentrate supplementation on sheep and the grassland in both grazing management systems and six different grazing intensities were analyzed.

Results of the first study shows that individual animals are only marginal influenced by high grazing intensities regarding digestibility of organic matter intake, organic matter intake, metabolizable energy intake and live weight gain despite a very low herbage allowance. In contrast parameters measured per unit of land area, organic matter intake per ha, metabolizable energy intake per ha and live weight gain per ha increases with increasing

grazing intensity during all years. All parameters are strongly influenced by year and significant interaction between grazing intensity and year are observed for live weight gain per animal and live weight gain per ha. Live weight gain per area of land unit is highest in very high stocking densities (9.5 ± 0.6 sheep/ha) in most years, indicating that in short term farmers act properly from an economical point of view. Whereas, vegetation ground cover and end-of-season-standing biomass at the end of the grazing season indicate that high stocking densities in most of the study years exceed the threshold values seen as critical for a sustainable long-term grassland use. To prevent soil erosion during winter months and thus, to maintain long-term grassland productivity, it is necessary to reduce stocking densities to $<2.0 - 6.4$ sheep/ha, depending on climatic conditions. The ecological optimum is not congruent with the economic stocking density, but they will converge due to predicted negative changes in herbage composition in the future.

Results of the second study show that concentrate supplementation strongly increases feed intake and live weight gain of grazing livestock and appears sufficient to maintain output per area even with lower stocking densities. Efficiency in the use of concentrate feed was similar for both grazing systems and over a wide range of stocking densities in our study, most likely due to a lack of differences in herbage and animal parameters between systems and grazing intensities and the adaptive feeding behavior (e.g. selection of herbage and expanded grazing time) of sheep. Concentrate supplementation restricted to selected months with high efficiency (i.e. g live weight gain/g concentrate) can be cost-effective. The considerable reduction in the herbage organic matter intake of individual animals alleviates grazing pressure and can thus contribute to maintaining long-term productivity of grasslands and similar environments.

6 Zusammenfassung

Die vorliegende Dissertation wurde im Rahmen des Deutsch-Chinesischen MAGIM-Projektes (“Matter fluxes of Grasslands in Inner Mongolia as influenced by stocking rate”, 2004 – 2010) und des LOTGras-Projektes (“Long-term strategies towards improved grassland productivity in semi-arid environments”, 2010 – 2013), gefördert durch die Deutsche Forschungsgemeinschaft (DFG), durchgeführt. Dieses Projekt untersucht die biologischen Aspekte (z.B. Beweidungsintensität, Beweidungs-Management-System, Produktivität und Artenzusammensetzung der Vegetation und Bodenparameter) im Steppen-Ökosystem der Inneren Mongolei, die zur Reduktion der hauptsächlich durch Überweidung hervorgerufenen ökologischen Probleme in dieser Region beitragen. Ziel dieser Arbeit war es die Auswirkungen von verschiedenen Fütterungsstrategien wie dem Beweidungssystem, der Beweidungsintensität und der Supplementierung von Kraftfutter auf die Futteraufnahme, Verdaulichkeit der aufgenommenen organischen Masse und die Lebendgewichtszunahmen von weidenden Schafen und auf das Grünland in semi-ariden und ariden Gebieten zu bewerten.

Während der Vegetationsperioden in 2005 bis 2010 wurde ein Beweidungsexperiment mit weiblichen nicht laktierenden mongolischen Fettschwanzschafen in zwei Beweidungssystemen mit jeweils sechs verschiedenen Beweidungsintensitäten (von sehr gering bis sehr stark) im Flussgebiet des Xilin im Nordosten der Inneren Mongolei durchgeführt. Im ersten Beweidungssystem erfolgte die Nutzung der Flächen kontinuierlich, entweder wurden sie dauerhaft beweidet oder für den Heuschnitt genutzt. Im zweiten alternierenden Beweidungssystem wechselte die Nutzung der Flächen als Weideland oder für den Heuschnitt jährlich.

In der ersten Studie wurden für die Bewertung von Effekten der Beweidungsintensität auf die Futteraufnahme sowie die Lebendgewichtszunahme bei weidenden Schafen Daten des alternierenden Beweidungssystems analysiert (2005 – 2010). In einer zweiten Studie im Jahr 2010, wurden die Auswirkungen einer moderaten Kraftfutter Supplementierung in beiden Beweidungssystemen und sechs verschiedenen Beweidungsintensitäten analysiert.

Ergebnisse der ersten Studie zeigen, dass einzelne Tiere durch hohe Beweidungsintensitäten hinsichtlich der Verdaulichkeit der organischen Masse, Aufnahme der organischen Masse, Aufnahme der umsetzbaren Energie und folglich der Lebendgewichtszunahme trotz eines sehr niedrigen Grünfutterangebots nur

marginalbeeinflusst sind. Wohingegen diese Parameter gemessen pro Landflächeneinheit (Aufnahme der organischen Masse pro ha, Aufnahme der umsetzbaren Energie pro ha und Lebendgewichtszunahme pro ha) mit zunehmender Beweidungsintensität in allen Jahren ansteigen. Das Jahr hat auf alle Parameter einen starken Einfluss und für Lebendgewichtszunahme pro Tier und Lebendgewichtszunahme pro ha gibt es zwischen Beweidungsintensität und Jahr signifikante Wechselwirkungen. Die Lebendgewichtszunahme pro Landflächeneinheit ist in sehr hohen Beweidungsintensitäten ($9,5 \pm 0,6$ Schafe/ha) am höchsten, was kurzfristig gesehen darauf hindeutet, dass die Farmer aus wirtschaftlicher Sicht in den meisten Jahren richtig handeln. Allerdings zeigen die geringe Bodenbedeckung und Biomasse der Vegetation am Ende der Beweidungssaison, dass in den meisten Jahren der für eine langfristige und nachhaltige Nutzung des Graslandes kritische Schwellenwert unterschritten wird. Zur Vermeidung der Bodenerosion in den Wintermonaten und damit einer langfristigen Erhaltung der Grünlandproduktivität ist es notwendig, abhängig von den klimatischen Bedingungen, die Beweidungsintensität auf unter 2,0 – 6,4 Schafe/ha zu reduzieren. Kurzfristig betrachtet weicht die höchste ermittelte ökologisch vertretbare Beweidungsintensität stark von der Beweidungsintensität mit dem höchsten wirtschaftlichen Ertrag (Lebendgewichtszunahmen pro Fläche) ab. Langfristig jedoch werden sie sich, aufgrund der prognostizierten negativen Veränderungen in der Grünfutterzusammensetzung bei hoher Beweidungsintensität, annähern.

Weiterhin zeigen Ergebnisse der zweiten Studie, dass bei moderater Supplementierung von Kraftfutter sich die Futteraufnahme erhöht und die daraus resultierenden zusätzlichen Lebendgewichtszunahmen der Schafe ausreichend scheinen, die Leistung pro Fläche auch bei niedrigeren Beweidungsintensitäten aufrecht zu erhalten. Der Futteraufwand bei Kraftfuttereinsatz in unserer Studie war ähnlich, sowohl in beiden Beweidungssystemen als auch über alle Beweidungsintensitäten hinweg. Dies ist möglicherweise auf den mangelnden Unterschied in Futter- und Tier-Parametern und auf das adaptive Fressverhalten der Schafe (z.B. Selektion des Grünfutters, verlängerte Fressdauer) zurückzuführen. Eine Kraftfuttersupplementierung beschränkt auf Monate mit den höchsten Lebendgewichtszunahmen kann profitabel sein. Der deutliche Rückgang in der Grundfutteraufnahme einzelner Tiere verringert den Beweidungsdruck und kann somit dazu beitragen, die langfristige Produktivität des Grünlandes in diesem und auch ähnlichen semi-ariden Ökosystemen zu erhalten.

Curriculum Vitae

Persönliche Daten

Name	Britta Mareike Bösing
Geburtsdatum, -ort	22.05.1983 in Heilbronn-Neckargartach, Baden-Württemberg
Familienstand	ledig
Staatsangehörigkeit	deutsch

Schulbildung

08/1989 – 1994	Spitalschule Leonberg
08/1993 – 1999	Johannes- Kepler- Gymnasium Leonberg
02/1999 – 2003	Mariengymnasium Papenburg

Hochschulausbildung

10/2003 – 09/2006	Studium der Biologie an der Universität Osnabrück Fachrichtung: Biologie/ Diplom, Bachelorstudiengang „Biologie der Organismen“
10/2006 – 03/2009	Studium der Biologie an der Universität Hamburg Hauptfach: Zoologie Nebenfächer: Naturschutz, Angewandte Botanik
09/2006	Bachelor of Science der Biologie. Thema: Vergleichende Untersuchung zum Individual- und Sozialverhalten von Wisenten <i>Bison bonasus</i> in einem Gehege und in einem Semiwaldreservat der Nordwestdeutschen Tiefebene („gut“)
03/2009	Diplom Biologin. Thema: Interactions between wildlife and vegetation under different grazing intensities and habitat types in the Knersvlakte, South Africa („sehr gut“)

Berufliche Tätigkeit/ Praktische Erfahrungen

03/2010 – 03/2013	Wissenschaftliche Mitarbeiterin am Institut für Tierernährung und Stoffwechselphysiologie mit dem Ziel der Promotion, Christian-Albrechts-Universität zu Kiel. Thema der Dissertation: Feeding strategies of sheep grazing the Inner Mongolian steppe, China
-------------------	--

-
- 08/2009 – 03/2010 Tätigkeit als selbstständige Biologin bei BIOLA (Biologisch-landschaftsökologische Arbeitsgemeinschaft), Gotenstraße 4, 20097 Hamburg (Erfassung von See- und Zugvogelaktivitäten auf einem Forschungsschiff auf der Nordsee)
- 06/2007 – 02/2008 Tätigkeit als studentische Hilfskraft in der AG Systematik, Biozentrum Klein Flottbek, Prof. Dr. Jürgens (Dateneingabe mittels BIOTABase, bodenanalytische Arbeiten im Labor), Universität Hamburg

Danksagung

Es ist mir ein besonderes Anliegen mich bei all denjenigen zu bedanken die zu dieser Arbeit beigetragen haben und mich bei der Arbeit unterstützt haben.

Besonders möchte ich mich bei meinem Doktorvater Prof. Dr. Andreas Susenbeth bedanken, für die Bereitstellung des Themas und vor allem für die fachlichen Diskussionen und Inspirationen. Ich fand bei ihm stets eine offene Tür und ein offenes Ohr für meine Fragen.

Meiner Betreuerin Jun. Prof. Dr. Uta Dickhöfer danke ich für die vielen fachlichen Gespräche und Anregungen. Sie hat mich erfolgreich motiviert, mir immer wieder neue Denkanstöße gegeben und sorgte mit wertvollen Ratschlägen für das Gelingen dieser Arbeit.

Hao Jun, Magdalena Ohm, Diana Cordes, Niels Moritz, Shiming Tang und Miguel-Angel Velazquez und den Farmern Han, Fang, Bauschi, Xiomu, Goa, Dongming und Guanyhe Tian danke ich für die tatkräftige Unterstützung bei der Erhebung der Daten und die Bereicherung der praktischen Arbeit in der Inneren Mongolei.

Für die sehr geduldige Unterstützung bei den statistischen Auswertungen danke ich Dr. Mario Hasler. Mario hat sich viel Zeit für die ausführlichen Erklärungen meiner nicht enden wollenden Fragen genommen.

Den Mitarbeitern des Instituts für Tierernährung und Stoffwechselphysiologie und meinen Kollegen Prof. Dr. Wolfram, Dr. Silvia Wein, Sandra Ahnert, Zein Abbas, Dr. Max Holstermann, Dr. Carsten Diez, Dr. Laura Berger, Birgit Beyer, Anika Henke, Simon Klatt, Faras Ansari und Dr. Philipp Schönbach danke ich für die vielen Diskussionen und Anregungen während des Seminars und die kleinen praktischen Hilfestellungen bei der Auswertung und beim Schreiben.

Den technischen Assistentinnen Anette Hollmann und Monika Paschke-Beese danke ich für die Unterstützung bei den Laboranalysen an der Universität Kiel.