

The Institute for Plant Nutrition and Soil Science
of the Christian-Albrechts-Universität Kiel

**Effects of different grazing intensities on soil water and
thermal regimes under *Leymus chinensis* and *Stipa grandis*
vegetation types in Inner Mongolia grassland, China**

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TABLE OF CONTENTS

TABLE OF CONTENTS	I
LIST OF FIGURES	IV
LIST OF TABLES	VI
LIST OF ABBREVIATIONS	VIII
LIST OF SYMBOLS	X
1 INTRODUCTION	1
1.1 Background	1
1.2 State of the art	2
1.2.1 Soil basic properties	2
1.2.2 Soil water regime	3
1.2.3 Soil thermal regime	4
1.2.4 Evapotranspiration	5
1.2.5 Vegetation effect	6
1.2.6 Model application	7
1.3 Research objectives	8
1.4 References	9
2 EFFECTS OF GRAZING INTENSITY ON SOIL WATER REGIME AND FLUX IN INNER MONGOLIA GRASSLAND, CHINA	19
2.1 Abstract	19
2.2 Introduction	21
2.3 Materials and methods	23
2.3.1 Site description	23
2.3.2 Soil sampling and analyses	24
2.4 Results	28
2.4.1 Soil properties	28
2.4.2 Soil water regime	30
2.4.3 Soil matric potential	32

2.4.4	Plant available water.....	33
2.4.5	Water flux	34
2.5	Discussion.....	36
2.5.1	Effect of grazing on soil structure	36
2.5.2	Soil water regime.....	36
2.5.3	Water flux	38
2.6	Conclusions	39
2.7	Acknowledgements	40
2.8	References	40
3	EFFECTS OF GRAZING INTENSITY ON SOIL THERMAL PROPERTIES AND HEAT FLUX UNDER LEYMUS CHINENSIS AND STIPA GRANDIS VEGETAION IN INNER MONGOLIA, CHINA	45
3.1	Abstract.....	45
3.2	Introduction	47
3.3	Materials and methods.....	49
3.3.1	Study site description.....	49
3.3.2	Soil sampling and analyses.....	50
3.4	Results	55
3.4.1	Climate conditions and basic soil properties	55
3.4.2	Soil water content and soil temperature	55
3.4.3	Soil volumetric heat capacity	57
3.4.4	Soil thermal conductivity.....	59
3.4.5	Heat flux	60
3.5	Discussion.....	64
3.5.1	Effect of vegetation type on soil thermal properties.....	64
3.5.2	Effect of grazing intensity on thermal properties	64
3.5.3	Effect of soil properties on thermal properties	65
3.5.4	Effect of vegetation type on heat flux.....	66
3.5.5	Effect of grazing intensity on heat flux	67
3.5.6	Management implication.....	68
3.6	Conclusions	69
3.7	Acknowledgements	70
3.8	References	70
4	MODELING GRAZING EFFECTS ON SOIL WATER BUDGET UNDER LEYMUS CHINENSIS AND STIPA GRANDIS VEGETATION IN INNER	

MONGOLIA, CHINA	76
4.1 Abstract.....	76
4.2 Introduction	78
4.3 Materials and methods.....	80
4.3.1 Study site description.....	80
4.3.2 Soil sampling and analyses.....	81
4.3.3 Numerical modeling	82
4.4 Results	86
4.4.1 Basic soil properties and van Genuchten parameters	86
4.4.2 Model calibration and validation.....	87
4.4.3 Water budget.....	89
4.4.4 Simulation of soil water content in 2010.....	92
4.5 Discussion.....	94
4.5.1 Model parameterization and validation	94
4.5.2 Effect of grazing on pore size distribution and saturated hydraulic conductivity	95
4.5.3 Effect of grazing on modeling soil water budget under different vegetation types	96
4.5.4 Simulation and land management implication	98
4.6 Conclusions	99
4.7 Acknowledgements	100
4.8 References	100
5 GENERAL DISCUSSION AND CONCLUSIONS	107
6 SUMMARY	117
7 ZUSAMMENFASSUNG	119
8 ACKNOWLEDGEMENTS	121
9 REFERENCES	122
10 CURRICULUM VITAE	129

LIST OF FIGURES

- Figure 2-1: Soil water retention curves at different depths at the SGCG and the LCHG sites (S: simulated value by RETC, M: measured value, SGCG: continuous grazing site, LCHG: heavy grazing site)..... 28
- Figure 2-2: Pore size distribution at different depths at the SGCG and the LCHG sites (SGCG: continuous grazing site, LCHG: heavy grazing site; Sparse: macropores >50 μm ; White: mesopores, 0.2-50 μm ; Black: micropores, <0.2 μm) 29
- Figure 2-3: The rainfall and soil temperature at 2 cm depth at the SGCG and the LCHG sites (SGCG: continuous grazing site, LCHG: heavy grazing site)..... 30
- Figure 2-4: The daily change of soil water content at the SGCG and the LCHG sites at different soil depths (SGCG: continuous grazing site, LCHG: heavy grazing site).... 31
- Figure 2-5: The daily change of soil matric potential at different soil depths at the SGCG and the LCHG sites (SGCG: continuous grazing site, LCHG: heavy grazing site) 33
- Figure 2-6: The dynamics of plant available water at the SGCG and the LCHG sites at different soil depths (SGCG: continuous grazing site, LCHG: heavy grazing site).... 34
- Figure 2-7: The daily change of net water flux at the SGCG and the LCHG sites in 5 to 20 cm and 20 to 40 cm layers from May to September in 2008, respectively (SGCG: continuous grazing site, LCHG: heavy grazing site)..... 35
- Figure 3-1: Air temperature and rainfall during the growing season in 2008 and in 2009..... 53
- Figure 3-2: Daily changes in soil water content with different grazing intensities at 5 sites during the growing season in 2008 and in 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively) 56
- Figure 3-3: Daily changes in soil temperature with different grazing intensities at 5 sites during the growing season in 2008 and in 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively) 57
- Figure 3-4: Daily changes in soil volumetric heat capacity with different grazing intensities at 5 sites during the growing season in 2008 and in 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively) 58
- Figure 3-5: Daily changes in soil thermal conductivity with different grazing intensities at 5 sites during the growing season in 2008 and in 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively) 59
- Figure 3-6: Daily changes in net soil heat flux with different grazing intensities at 5 sites during the growing season in 2008 and in 2009 (LCUG79, LCWG and LCHG are

un-grazed since 1979, winter grazed and heavily grazed under <i>Leymus chinensis</i> vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under <i>Stipa grandis</i> vegetation, respectively)	61
Figure 3-7: Changes in soil heat flux, rainfall and air temperature during a single day with different grazing intensities under rainfall and no-rainfall conditions (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under <i>Leymus chinensis</i> vegetation, respectively).....	62
Figure 3-8: Changes in soil heat flux, rainfall and air temperature during a single day at un-grazed sites under rainfall and no-rainfall conditions for both vegetation types (LCUG79: un-grazed since 1979 under <i>Leymus chinensis</i> vegetation; SGUG79: un-grazed since 1979 under <i>Stipa grandis</i> vegetation).....	63
Figure 4-1: Modeling calibration for the hydraulic parameters at the SGCG site in May 2008 (SGCG: continuously grazed under <i>Stipa grandis</i> vegetation).....	88
Figure 4-2: Comparison between monitored and modeled soil temperature at the SGCG site in 2008 and 2009 (SGCG: continuously grazed under <i>Stipa grandis</i> vegetation).....	88
Figure 4-3: Comparison between monitored and modeled soil water content at the SGCG site in 2008 and 2009 (SGCG: continuously grazed under <i>Stipa grandis</i> vegetation).....	89
Figure 4-4: Comparison between potential and actual evapotranspiration at the SGCG site in 2008 and 2009 (SGCG: continuously grazed under <i>Stipa grandis</i> vegetation).....	91
Figure 4-5: Comparison between monitored and simulated soil water content at the SGCG site in 2010 (SGCG: continuously grazed under <i>Stipa grandis</i> vegetation)	93

LIST OF TABLES

- Table 2-1: Soil texture, bulk density (BD), organic carbon (OC), saturated hydraulic conductivity (K_s) and van Genuchten parameters at the CG and the HG sites (SGCG: continuous grazing site, LCHG: heavy grazing site, θ_r is fixed to $0.02 \text{ cm}^3 \text{ cm}^{-3}$)..... 27
- Table 2-2: The net, upward and downward water flux and rainfall during the growing season in 2008 at the SGCG and the LCHG sites (SGCG: continuous grazing site, LCHG: heavy grazing site)..... 27
- Table 3-1: Leaf area index (LAI), soil texture, bulk density (BD), total porosity (TP), soil organic matter (SOM) and saturated hydraulic conductivity (K_s) at 5 sites (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)..... 54
- Table 3-2: Summary of total net heat flux at 5 sites during the growing season 2008 and 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively; negative value: downward flux; nd=not determined) 60
- Table 4-1: Soil texture, bulk density (BD), total porosity (TP), soil organic matter (SOM) and saturated hydraulic conductivity (K_s) at 5 sites (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively) 85
- Table 4-2: van Genuchten parameters (θ_r : residual water content; θ_s : saturated water content; α : reciprocal value of air entry pressure; n : the smoothness of pore size distribution and $m=1-1/n$) fitted by RETC software (R^2 : determination coefficient) from the laboratory-derived hydraulic parameters in soil cores at 5 sites (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)..... 86
- Table 4-3: Root mean square errors ($RMSE$) at 5 sites during growing season in 2008 and 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively; nd=not determined) 87
- Table 4-4: Estimated water budget components (R : rainfall; I : interception; T_p : transpiration; E_s : evaporation; FD : free drainage; SR : surface runoff; ΔS : water storage change; Error: model water balance errors) at 5 sites during growing seasons in 2008 and 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively; nd=not determined) 90
- Table 4-5: Potential evapotranspiration (ET_0) and actual evapotranspiration (ET) at 5 sites during growing season in 2008 and 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis*

vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under <i>Stipa grandis</i> vegetation, respectively; nd=not determined)	92
Table 4-6: Root mean square errors (<i>RMSE</i>) of simulation at 3 sites in 2010 (LCUG79 is un-grazed since 1979 under <i>Leymus chinensis</i> vegetation; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under <i>Stipa grandis</i> vegetation, respectively)	92
Table 4-7: Simulated water budget components (<i>R</i> : rainfall; <i>I</i> : interception; <i>T_p</i> : transpiration; <i>E_s</i> : evaporation; <i>FD</i> : free drainage; <i>SR</i> : surface runoff; ΔS : water storage change; Error: model water balance errors) at 5 sites during growing seasons in 2010 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under <i>Leymus chinensis</i> vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under <i>Stipa grandis</i> vegetation, respectively)	93

LIST OF ABBREVIATIONS

<i>A</i>	Soil dependent coefficient in Equation 3.3
<i>B</i>	Soil dependent coefficient in Equation 3.4
<i>b₁</i>	Empirical parameter in Equation 4.5
<i>b₂</i>	Empirical parameter in Equation 4.5
<i>b₃</i>	Empirical parameter in Equation 4.5
<i>BD</i>	Bulk density (g cm ⁻³)
<i>C</i>	Soil dependent coefficient in Equation 3.5
<i>C_L</i>	Volumetric heat capacity of liquid water (J m ⁻³ K ⁻¹)
<i>C_p</i>	Volumetric heat capacity of bulk soil (J m ⁻³ K ⁻¹)
<i>C_v</i>	Volumetric heat capacity of vapor (J m ⁻³ K ⁻¹)
<i>D</i>	Soil dependent coefficient in Equation 3.6
<i>d</i>	Diameter of pore (μm)
<i>dT</i>	Differences in temperature (K)
<i>dZ</i>	Differences in distance (cm)
<i>E</i>	Soil dependent coefficient in Equation 3.7
<i>E_s</i>	Evaporation (mm)
<i>ET</i>	Evapotranspiration (mm)
<i>ET₀</i>	Potential evapotranspiration (mm)
<i>FD</i>	Free drainage (mm)
<i>LAI</i>	Leaf area index
<i>LC</i>	<i>Leymus chinensis</i>
<i>LCHG</i>	Heavily r grazed under <i>Leymus chinensis</i>
<i>LCUG79</i>	Un-grazed since 1979 under <i>Leymus chinensis</i>
<i>LCWG</i>	Winter grazed under <i>Leymus chinensis</i>
<i>h</i>	Water pressure head (cm)
<i>I</i>	Interception (mm)
<i>K_L</i>	Isothermal hydraulic conductivity of liquid phase (cm day ⁻¹)
<i>K_{LT}</i>	Thermal hydraulic conductivity of liquid phase (cm ² K ⁻¹ day ⁻¹)
<i>K_s</i>	Saturated hydraulic conductivity (cm day ⁻¹)
<i>K_v</i>	Isothermal water vapor hydraulic conductivity (cm day ⁻¹)
<i>K_{vT}</i>	Thermal water vapor hydraulic conductivity (cm K ⁻¹ day ⁻¹)
<i>l</i>	Pore connectivity parameter
<i>L₀</i>	Volumetric latent heat of vaporization of liquid water (e.g., J m ⁻³)
<i>m</i>	van Genuchten parameter (-)
<i>m_c</i>	Clay fraction (%)
<i>m_o</i>	Organic matter fraction (%)
<i>N</i>	Number of observations
<i>n</i>	van Genuchten parameter (-)
<i>O_i</i>	Monitored value
<i>OC</i>	Organic carbon (g kg ⁻¹)
<i>P_i</i>	Modeled value
<i>q</i>	Water flux (mm s ⁻¹)
<i>q_L</i>	Liquid water flux density (cm day ⁻¹)
<i>q_v</i>	Water vapor flux density (cm day ⁻¹)
<i>RMSE</i>	Root mean square errors
<i>R</i>	Rainfall (mm)
<i>S</i>	Sink term (cm ³ cm ⁻³ day ⁻¹)
<i>S_e</i>	Effective saturation
<i>SG</i>	<i>Stipa grandis</i>
<i>SGCG</i>	Continuously grazed under <i>Stipa grandis</i>
<i>SGUG79</i>	Un-grazed since 1979 under <i>Stipa grandis</i>
<i>SOM</i>	Soil organic matter (g kg ⁻¹)

<i>SR</i>	Surface runoff (mm)
<i>T</i>	Temperature (K)
<i>t</i>	Time (day)
<i>T_P</i>	Transpiration (mm)
<i>TP</i>	Total porosity (%)
<i>t₂-t₁</i>	Time between two measurements (s)
<i>z</i>	Spatial coordinate (cm)
<i>Z₁</i>	Thickness of first soil layer (cm)
<i>Z₂</i>	Thickness of second soil layer (cm)

LIST OF SYMBOLS

α	van Genuchten parameter (-)
$C_s(\theta)$	Soil volumetric heat capacity ($\text{cal cm}^{-3} \text{ }^\circ\text{C}^{-1}$)
$J(\theta, T)$	Soil heat flux (W m^{-2})
θ	Soil volumetric water content ($\text{cm}^3 \text{ cm}^{-3}$)
θ_{fc}	Water content at Field capacity ($\text{cm}^3 \text{ cm}^{-3}$)
θ_L	Volumetric liquid water content ($\text{cm}^3 \text{ cm}^{-3}$)
θ_{pwp}	Water content at permanent wilting point ($\text{cm}^3 \text{ cm}^{-3}$)
θ_{paw}	Plant available water (mm)
θ_r	Residual water content ($\text{cm}^3 \text{ cm}^{-3}$)
θ_s	Saturated water content ($\text{cm}^3 \text{ cm}^{-3}$)
θ_v	Volumetric water vapor content ($\text{cm}^3 \text{ cm}^{-3}$)
$\lambda(\theta)$	Thermal conductivity ($\text{W m}^{-1} \text{ K}^{-1}$ or $\text{J m}^{-3} \text{ K}^{-1} \text{ day}^{-1}$)
$\lambda(\theta)_1$	Thermal conductivity of first soil layer ($\text{W m}^{-1} \text{ K}^{-1}$)
$\lambda(\theta)_2$	Thermal conductivity of second soil layer ($\text{W m}^{-1} \text{ K}^{-1}$)
$\lambda(\theta)_{eq}$	Equivalent thermal conductivity ($\text{W m}^{-1} \text{ K}^{-1}$)
ϕ	Total porosity (%)
ψ	Soil matric potential (kPa)
ψ_T	Soil water potential (the sum of matric and gravitational potential, kPa)
ρ_b	Soil bulk density (g cm^{-3})
β	Angle between flow direction and vertical axis ($^\circ$)
ΔS	Water storage change (mm)
ΔL	Distance of two points (cm)
$\overline{\Delta\theta}$	Water content difference ($\text{cm}^3 \text{ cm}^{-3}$)
$\Delta\psi_T$	Difference in soil water potential (kPa)
$\overline{grad\psi_T}$	Hydraulic gradient (kPa cm^{-1})

1 INTRODUCTION

1.1 Background

China is one of the most severely desertified countries in the world (Zha and Gao, 1997; Decai, 1998; Zhong and Qu, 2003). In recent years, desertification has become a major environmental problem, attracting widespread attention in China, especially, in the arid, semi-arid climatic zones (Huang et al., 2007). Inner Mongolia region dominantly covered by grassland and barren deserts is the world's largest extra-tropical semiarid and arid land (Lu et al., 2011), which has experienced intensive land use practices with grazing as the representative disturbance type on the natural steppe during recent decades (Pei et al., 2008; Li et al., 2011). The traditional extensive, semi-nomadic sheep grazing system changed to a dramatically intensified stationary livestock farming, which resulted in over-grazing and over-cropping in this region inducing 31% desertified area in the northern China (Zhao and Masayuki, 1997). Numerous studies have indicated that over-grazing on pasture as the major factor led to desertification (Zhu and Chen, 1994; Pei et al., 2008), resulted in a destructive change in soil hydraulic, mechanical, thermal and biological properties, dramatic changes in vegetation and modifications in nutrient cycling (Bauer et al., 1987; Dormaar et al., 1994; Kurz et al., 2005; Hoshino et al., 2009). Furthermore, we can define a permanent destruction of the agricultural productivity and results also in an increased vulnerability of the soils due to soil erosion by sand storms especially in the spring (Su et al., 2004; Zhang et al., 2004). To enable a sustainable agricultural system, grazing management practices must ensure adequate soil water for plant growth (Chanasyk et al., 2004). Although it is well known that the grazing management is the major factor to change the soil water and thermal regimes in Inner Mongolia, the interactions among them are not fully understood. Therefore it is necessary to figure out the site adjusted grazing intensity for the sustainable development of Inner Mongolia grassland.

1.2 State of the art

1.2.1 Soil basic properties

Soils play an important role in ecosystem productivity and stability as a source of plants' nutrients and water. As the livestock trample the soil hydraulic and mechanical properties, e. g. saturated hydraulic conductivity, bulk density and total porosity are changed (Drewry et al., 1999; Hayashi et al., 2006; Krümmelbein et al., 2009). The increases in bulk density with increased grazing intensity led to reduce macropore space and infiltration (Warren et al., 1986; Naeth and Chanasyk, 1995; Drewry et al., 1999), and reduce the saturated soil water content, finally modify the retention curve derived from a change of the inflection point to a lower matric potential (Garnier et al., 2004; Rachman et al., 2004; Hayashi et al., 2006). Most previous studies focused on the land management effects on soil mechanical properties in agriculture and also had evaluated the influence of soil structural changes on soil hydraulic properties (Willat and Pullar, 1983; Singleton et al., 2000; Garnier et al., 2004; Krümmelbein et al., 2009). Grazing impact on hydrological changes commonly have negative effects on the productivity of grassland soils and their ecological functioning (Greenwood and McKenzie, 2001), because the reduction of macropores results in a reduced water infiltration into soil, altered pore size distribution, and soil water retention characteristics (Singleton et al., 2000; Martinez and Zinck, 2004; Tuli et al., 2005; Kutilek et al., 2006), and water and air conductivity (Willat and Pullar, 1983; Gebhardt et al., 2006). Meanwhile, compaction and structure degradation of the topsoil caused by increasing intensities of sheep and goat grazing have left the soils vulnerable to wind and water erosion in Inner Mongolia grassland (Li et al., 2000; Gao et al., 2002). However, numerous studies have indicated that grazing exclosure in degraded land has a high potential to restore soil conditions, and reduce erosion (Hiernaux et al., 1999; Su et al., 2005; Mekuria et al., 2007; Steffens et al., 2008). It presented the soil physical and chemical properties generally could improve after

long-term grazing enclosure in Inner Mongolia grassland (Krümmelbein et al., 2009; Li et al., 2011). In addition, given the social and economic aspects the grassland can not be fenced for such long time because the grazing is the major support of life and therefore requests the establishment of an appropriate grazing management in this region.

1.2.2 Soil water regime

Soil water content is an important environmental indicator for the energy-water balance, and of a soil's ability to regulate the hydrologic cycle (Sheppard et al., 2009; Weber and Gokhale, 2011). In semi-arid rangelands, soil water content is the most limiting factor for primary productivity (LeHouerou et al., 1988; Knapp et al., 2007). While the hydrological function defined as the ability of pasture to capture, store, and release water (Pellant et al., 2000), is essential for a good understanding of the soil water regime and the ecosystem functioning (Tongway and Ludwig, 2003). In semi-arid areas water fluxes are strongly influenced by rainfall and grazing (Jamiyansharav et al., 2011), which can provide an insight into the water supply for plants during the growing season (Bréda et al., 1995). While the plant available water, as a very important source for plant growth (de Jong and Bootsma, 1996; An et al., 2003; Hoshino et al., 2009), is always affected by soil properties, e. g. bulk density, soil pores (Kay and VandenBygaart, 2002; Pagliai et al., 2004) and also the different utilizing on the landscape by grazing (Zhao et al., 2007; Gan et al., 2012a). As the consequence, the effect of grazing management on water-related mechanisms is urgently needed to be understood in the studied area (Fitzjohn et al., 1998; Chen and Wang, 2000).

The retention capacity of soil water depends on soil type (Singer and Munns, 1991; Weber et al., 2011), vegetation cover (Snyman, 2009), and land-use (White et al., 2000; Betts, 2001). The effects of all factors and their interactions on soil water are variable and complex (Singh et al., 2003). In this context, quantification of the

stored water and its distribution requires a more complete understanding of knowledge in soil water content and its movement in a soil layer, which is fundamental to analyze biological reactions, plant growth, and material transports (Pinder and Jones, 1969; Sklash and Farvolden, 1979). So we focused on the effect of different grazing intensities on the soil water regime to define whether a site adjusted grazing intensity could improve the soil water condition.

1.2.3 Soil thermal regime

Soil temperature is an important property influencing the uptake of water and nutrients by roots, plant growth as well as the decomposition of organic matter, and flux processes (Bachmann, 1997; Clough et al., 1998; Hillel 1998; Bristow et al., 2001), as it is a primary factor in determining the rates and directions of soil physical processes and of energy and mass exchanges with the atmosphere (Noborio et al., 1996; Lipiec et al., 2007). Soil thermal properties like the volumetric heat capacity and the thermal conductivity play an important part in the surface-energy partitioning and temperature distribution (Horton and Chung, 1991; Tyson et al., 2001), which all are driven by soil moisture distribution, and are also influenced by soil composition, soil structure, and vegetation cover (shading, root influence on soil moisture content) (de Vries, 1966; Dec et al., 2009; Ju et al., 2010). These impact factors of soil properties and structure on soil thermal properties can be arranged into two groups (Abu-Hamdeh, 2003): those which are inherent to the soil itself, e. g. the mineralogical composition (Campbell, 1985), and those which can be managed or controlled externally to a certain extent involving soil water content and bulk density (Campbell, 1985; Abu-Hamdeh, 2003). The published papers related to soil thermal properties provide valuable information, especially about the change of thermal conductivity as a function of soil water content and bulk density (Ghuman and Lal, 1985; Hopmans and Dane, 1986; Ochsner et al., 2001; Dec et al., 2009). With increasing bulk density as a result of particle contact enhancement as porosity decreases the thermal conductivity could increase (Abu-Hamdeh, 2000, 2003; Lipiec

and Hatano, 2003). All practices causing soil compaction increase the bulk density and decrease the porosity, which in turn have a significant effect on heat capacity (Abu-Hamdeh, 2003). In addition to compaction, land management on soil heat flux has been the subject of several studies (Enz et al., 1988; Azooz et al., 1997; Richard and Cellier, 1998; Sauer et al., 1998), which can influence soil water content and other physical characteristics which have also an impact on soil thermal conductivity (Fritton et al., 1974; Dec et al., 2009). Furthermore the partial surface mulch and clustering of the vegetation cover also have the effects on soil heat flux (Bristow and Horton, 1996; Kustas et al., 2000). However, such information on thermal properties and heat flux for Inner Mongolia grassland are not sufficient. Our research focused on the interactions of different grazing intensities and vegetation types on the thermal regime assumes to find out whether and how these factors change the thermal regime in Inner Mongolia grassland.

1.2.4 Evapotranspiration

Evapotranspiration (*ET*) is the link between water and energy budgets, which is the major component of the terrestrial hydrological budget (Brutsaert, 1982). In water-limited region, like Inner Mongolia grassland, *ET* depends on two processes concerning water loss to the atmosphere by evaporation from soil and snow cover, and transpiration from plants (Miao et al., 2009; Sun et al., 2010). Variability in *ET* in semi-arid environments is therefore important to be quantified as it affects not only energy balance but also productivity of the region (Lu et al., 2011). In arid regions, *ET* is always limited by the availability of soil water (Sala et al., 1992; Kurc and Small, 2007; Wilske et al., 2010), therefore the dynamic interactions between *ET* and soil water are essential to understand soil–plant–atmosphere relations and the regional water balance (Brutsaert and Chen, 1995; Granier et al., 2000a, 2000b). However *ET* is also controlled by canopy architecture and development, soil characteristics, and land management (Kelliher et al., 1995; Frank, 2003; Li et al., 2007), which is well known by the change of *ET* with land management associated disturbances on soil

water status (Grayson and Western, 1998; Zhang and Schilling, 2006), herbivores by removing aboveground biomass thus altering microclimate (Frank, 2003; Jamiyansharav et al., 2011), and plant species and grassland ecosystem (Baldocchi et al., 2004). It is therefore crucial to obtain that information about grazing management on soil water budget, especially its impact on *ET*, in order to improve understanding soil water and thermal regimes in Inner Mongolia grassland.

1.2.5 Vegetation effect

The perennial rhizome grass *Leymus chinensis* and bunch grass *Stipa grandis* (Tong et al., 2004; Chen et al., 2005) cover about 60% of the total land area in the Xilin River catchment in Inner Mongolia grassland (Li et al., 1988). It is well known that there are distinct differences in the morphology and photosynthetic physiology between these species *Leymus chinensis* and *Stipa grandis* (Du and Yang, 1988; Du et al., 1999; Cui et al., 2001), which may affect the water use and heat transport of these two species in the semi-arid grassland and may result in different strategies to overcome mechanical and hydraulic stresses under those climatic conditions. It is also understood that many arid and semi-arid types of grassland have experienced a shift in dominant vegetative composition from perennial grasses to shrubs and bare soil, a change which coincides with desertification (Scheffer et al., 2001; Jackson et al., 2002) and which are caused by stationary livestock farming and the increase of livestock in Inner Mongolia grassland in the past four decades (Cao and Yang, 1999). Taking into account the effects of different vegetations on soil water use (Bird, et al., 2004; Burba and Verma, 2005), heat flux (Tuzet et al., 1997; Kustas et al., 2000), evapotranspiration (Twerdoff et al., 1999), and also the interactions among these factors which are reported that the impact of soil water content on soil heat flux and evapotranspiration should be considered with the effect of vegetation and the residues cover together (Kustas et al., 2000; Wilske et al., 2010), our research chose the typical species *Leymus chinensis* and *Stipa grandis* in Inner Mongolia grassland to define what differences in soil water and thermal regimes can be derived from the different

characteristics between these vegetation types.

1.2.6 Model application

The different land managements affect the water movement in the unsaturated soil through shifting the plant architecture and soil functions (Flerchinger et al., 2003). Although many quantitative studies of management effects on soil properties have been noted (Hill, 1990; Cresswell et al., 1993; van Es et al., 1999; Green et al., 2003), few researches dealt with their consequences on water flux and the quantification of water within the various compartments (Chung and Horton, 1987; Drewry, 2006). The various soil water models ranging from simple water balance calculation to complex ones based on Richards' equation provide the opportunity to simulate the water flow. The numerical solutions of Richards' equation usually need two essential hydraulic functions including water retention characteristics and hydraulic conductivity (Butters and Duchateau, 2002; Ghanbarian-Alavijeh et al., 2011). Very often these parameterized retention curve data together with the saturated hydraulic conductivity data of soils are used to derive the van Genuchten-Mualem parameters as an alternative for a direct measured dataset (Budiman et al., 1999; Rajkai et al., 2004), which is one of the most widely used approach (Han et al., 2010) to precisely describe water retention characteristics for a broad range of soils, including disturbed and undisturbed soils (Leech et al., 2006), and even peat and composted pine bark (Naasz et al., 2005). The mathematical code is included in the HYDRUS-1D program which is valid for the one-dimensional water flow in variably-saturated soils (Šimůnek et al., 2009). Considering the intensive extremity weather, labour requirements, and expensive maintenance of instrument, it is not easy to compile the long-term soil water data sets in such desolate district of most Inner Mongolia grassland. Our study was designed to find out whether it is acceptable to simulate the soil water information by HYDRUS-1D with the annually averaged parameters of initial and boundary conditions in soil, and plant functions avoiding the long-term repeated samplings and monitoring.

1.3 Research objectives

The present work is a part of the MAGIM project (Matter fluxes in grasslands of Inner Mongolia as influenced by stocking rate) carried out in the Xilin River catchment in Inner Mongolia grassland and aimed to understand how sheep grazing affects water, carbon and nitrogen fluxes at various spatial and temporal scales. In the following the effect of grazing on soil water and thermal regimes, and modeled soil water budget as affected by different grazing intensities and vegetation covers (*Leymus chinensis* and *Stipa grandis*) controlled in situ conditions will be described based on the following hypotheses:

1. **Will a site-adjusted grazing intensity improve the soil water regime? Will soil water content be significantly different under *Leymus chinensis* and *Stipa grandis*?** The objectives are (i) to characterize the temporal distribution of the soil water along soil profile by grazing intensity and vegetation cover (ii) to quantify water fluxes between different soil layers as affected by grazing intensity in Inner Mongolia grassland, China.
2. **Will a site-adjusted grazing intensity improve the soil thermal regime? Will soil thermal properties and heat flux be significantly different under *Leymus chinensis* and *Stipa grandis*?** The objectives are: (i) to characterize the spatial and temporal distribution of soil thermal properties within the soil profiles and (ii) to quantify soil heat flux as affected by different grazing intensities and vegetation types in Inner Mongolia grassland, China.
3. **Could soil water content and budget be simulated using HYDRUS-1D program with the annually averaged soil and vegetation information when the long-term monitor and repeated soil and plant samplings are not available? Will the partitions of soil water budget be changed by different grazing intensities under *Leymus chinensis* and *Stipa grandis*?** The objectives were: (i) to identify the grazing effect on soil functions and quantify the water budget by different grazing intensities and vegetation types

using HYDRUS-1D program, and (ii) to model soil water content and budget using annually averaged parameters by HYDRUS-1D program.

1.4 Reference

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2 EFFECTS OF GRAZING INTENSITY ON SOIL WATER REGIME AND FLUX IN INNER MONGOLIA GRASSLAND, CHINA

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2.1 Abstract

In the past few decades, the increase in grazing intensity has led to soil degradation and desertification in Inner Mongolia grassland, China, due to population growth and shift in the socio-economic system. We investigated two sites with different grazing intensities: continuous grazing site (SGCG) and heavy grazing site (LCHG). The objectives were i) to characterize the temporal distribution of soil water content along soil profile and ii) to quantify the water fluxes as affected by grazing intensity. Soil water content was monitored by Theta-probes. Soil water retention curves were determined by pressure membrane extractor, furthermore processed by RETC (REtention Curve) software. Soil matric potential, plant available water and water flux were calculated using these data. Both sites showed an identical seasonal soil water dynamic within four defined hydraulic periods: (1) wetting transition coincided with a dramatic water increase due to snow and frozen soil thawing from March to April, (2) wet summer, rainfall in accordance with plant growth from May to September, (3) drying transition, a decrease of soil water from October to November due to rainfall limit, (4) dry winter, freezing from December to next February. Heavy grazing largely reduced soil water content by 43–48% and plant available water by 46–61% as compared to the SGCG site. During growing season net water flux was nearly similar between LCHG (242 mm) and SGCG (223 mm) sites between 5 and 20 cm depths. However, between 20 and 40 cm depths, the upward flux was more pronounced at LCHG site than at SGCG site, indicating water was depleted by root

uptake at LCHG site but stored at SGCG site. In semi-arid grassland ecosystem, grazing intensity can affect soil water regime and flux, particularly in the growing season.

Key Words: heavy grazing, Plant available water, semi-arid grassland, soil matric potential, soil water content

2.2 Introduction

Inner Mongolia grassland is one of the most seriously desertified regions in the world. For centuries grazing and trampling of sheep is a major stress faced by grassland in this region. In the past few decades, due to an increase in population and a shift in the socio-economic system, it is subject to an increased grazing pressure, causing soil degradation and a risk of severe soil erosion, nutrient depletion and desertification in Inner Mongolia grassland (Li et al., 2000; Su et al., 2005). Striking evidence for this process is given by numerous sandstorms attributed to the grazing management attacking, e.g., Beijing with an increasing frequency.

Soil plays an important role in ecosystem productivity and stability as a source of plants' nutrients and water. In grassland, livestock affects soil properties via two main mechanisms: trampling compacts the soil and increases bulk density (Van Haveren, 1983; Warren et al., 1986; Trimble and Mendel, 1995); and herbivory reduces plant cover (Weltz and Wood, 1986; Coughenour, 1991). Heavy grazing accompanied with animal trampling normally has detrimental effects on soil hydraulic and mechanical properties (Greenwood and McKenzie, 2001; Zhao et al., 2007). Especially in the topsoil, soil deformation is characterized by a decrease of pore volume and as a result it alters pore size distribution, soil water retention characteristics (Martínez and Zinck, 2004; Kutílek et al., 2006), water and air fluxes (Willat and Pullar, 1983; Krümmelbein et al., 2006). Meanwhile, heavy grazing destroys the vegetation coverage over large areas of grassland in Inner Mongolia, leaving the soils vulnerable to wind and water erosion (Li et al., 2000; Gao et al., 2002). These processes decrease water storage capacity, soil fertility, and grassland productivity (Christensen et al., 2004).

Soil water content is the most limiting factor for primary productivity in semi-arid rangelands (LeHouerou et al., 1988). A good understanding of the soil water

regime associated with the various types of cover is important for the understanding of ecosystem functioning (Tongway and Ludwig, 2003). The soil water retention curve, which defines the relationship between soil water content and matric potential, is an important physical soil property. The water retention curves as well as the hydraulic conductivity curves of soils are either directly determined or derived from given databases and further processed with the van Genuchten function (Budiman et al., 1999; Rajkai et al., 2004). The availability and movement of soil water are essential especially in arid or semi-arid regions, which can provide an insight into the water supply for plants during the growing season (e.g. Bréda et al., 1995). Plant available water is often regarded as a very essential water regime for plant growth. (Feddes et al., 1988; de Jong and Bootsma, 1996; An et al., 2003; Saito et al., 2006 ; Hoshino et al., 2009). Under the prevailing semi-arid climatic condition in Inner Mongolia, plant available water plays a key role in the sustainable development of steppe ecosystems. Considering plant available water as one of the most limiting factors for sustainable grassland development, the effects of grazing on water-related mechanisms is urgently needed to be understood in the studied area (Chen and Wang, 2000).

Many arid and semi-arid grasslands throughout the world have experienced a shift in dominant vegetative composition from perennial grasses to shrubs and bare soil, a change which coincides with desertification (Daily, 1995; Van Auken, 2000; Scheffer et al., 2001; Jackson et al., 2002). In the past four decades, the replacement of nomadic and semi-nomadic grazing by stationary livestock farming and the increase of livestock (more than 8×10^8 ungulates) resulted in extensive degradation amounting for 80% (moderate) and 42% (heavily affected) of the total Inner Mongolia area (Cao and Yang, 1999; Xie and Wittig, 2004; Zhang et al., 2004). Both studied sites are typical grasslands in Inner Mongolia. The continuous grazing site (SGCG) dominated by the bunch grass, endurable drought *Stipa grandis* represents the most statuses in Inner Mongolia grassland which may transform to the heavy grazing site (LCHG) and suffer from a shift to a bare soil. Therefore, it is important to understand

the soil water regime and flux under these two different grazing intensities. Although many quantitative studies showed grazing intensity had an effect on soil physical properties (Krümmelbein et al., 2006; Zhao et al., 2007) and vegetation coverage (Gao et al., 2002), few researches demonstrated its consequence on water flux (Zhao et al., 2010). Therefore, in this study our objectives were i) to characterize the temporal distribution of the soil water along soil profile at the two grazing sites and ii) to quantify water fluxes between different soil layers as affected by grazing intensity in Inner Mongolia grassland. We hypothesized that the soil water regime and water flux depended closely on the grazing intensity.

2.3 Materials and methods

2.3.1 Site description

The research was carried out on a long-term experiment established at the Inner Mongolia Grassland Ecosystem Research Station (IMGERS; 43°37'50"N, 116°42'18"E) situated in the Xilin River catchment, Northern China. The experiment evaluates the effect of grazing intensity on mass flux in the continental semi-arid grasslands of the Central Asian steppe ecosystem, with a dry and cold middle latitude climate (Kawamura et al., 2005). In the last two decades, the annual mean air temperature was 0.7 °C with the annual mean minimum temperatures around -20 °C in January. Annual precipitation was 343 mm included less 5% of snow. More than 85% of the annual precipitation is concentrated during the growing period (May to September) through rainfall. The vegetation is characterized by the perennial rhizome grass *Leymus chinensis* in areas with relatively wet soil conditions while bunch grass *Stipa grandis* dominates in drier regions (Tong et al., 2004; Chen et al., 2005), respectively. These two kinds of steppe vegetation cover about 60% of the land area in the Xilin River catchment (Li et al., 1988). Soils are classified as Calcic Chernozems (IUSS Working Group WRB, 2006), which were developed from aeolian sediments

deposited on a pleistocene basalt plateau (Wiesmeier et al., 2009). In this case study, two representative sites were investigated. One site is the heavy grazing site (LCHG) with 2.0 sheep units ha⁻¹ year⁻¹, where the vegetation is composed of herbaceous species such as *Artemisia frigida*, *Salsola collina* Pall and *Chenopodium glaucum* L. The other one is the continuous grazing site (SGCG) with 1.2 sheep units ha⁻¹ year⁻¹, which is dominated by *Stipa grandis*. Each site is around 100 ha, with about 10 km distance between them.

2.3.2 Soil sampling and analyses

At each site three replicate profiles within a distance of 15 m were installed and connected to one solar powered automatic data-logger, which recorded soil water content, soil temperature and precipitation at 30-min intervals. In each soil profile, soil moisture was measured using horizontally inserted Theta-probes (Type ML2x, Delta-T Devices, Cambridge, UK) at 5, 20, and 40 cm depths. Theta-probes were calibrated for the site-specific soil using the gravimetric method. The technical specifications of Theta-probe only defined the accuracy above 0 to 70 °C (Delta-T Devices Ltd., 1999). In winter the top soil was almost frozen in study sites, thus the limitation of Theta-probe might induce the errors of soil water content in winter. The soil water content was averaged arithmetically from three profiles at a given depth. The top soil temperature at 2 cm depth was monitored by Platinum ground temperature probes (Pt-100). The rainfall was measured by rain gauges (DECAGON DEVICES ECRN-100). The study period lasted 551 days, from 15th of August 2007 to 15th of February 2009.

Before the installation of the probes, undisturbed soil samples (cylinder 100 cm³, n=7) were taken from three layers of 4–8, 18–22, and 40–44 cm for the laboratory measurements. The basic soil physical and chemical properties including soil texture, bulk density and organic carbon were measured. Saturated hydraulic conductivity K_s was measured with a falling head method in laboratory (Hartge and Horn, 1992).

Water retention characteristics were determined with a ceramic pressure plate assembly at equilibrium matric potentials of -1 , -3 , -6 , -15 , -30 kPa and -1500 kPa in a pressure chamber. The obtained data were used to obtain the soil water retention curves and to derive the van Genuchten parameters by RETC (REtention Curve) software (van Genuchten, 1980).

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha\psi)^n]^m} \quad (2.1)$$

where θ is the soil water content ($\text{cm}^3 \text{cm}^{-3}$), θ_s and θ_r are the saturated and residual water contents ($\text{cm}^3 \text{cm}^{-3}$), respectively. θ_r was fixed to $0.02 \text{ cm}^3 \text{cm}^{-3}$. ψ is the matric potential (kPa) as indicated by pressure head, the parameters of α , n , and $m=1-1/n$ are dimensionless. Based on the van Genuchten equation 2.1 the matric potential in the field can be calculated with measured soil water content. The arithmetical mean of matric potential of three profiles at each site was presented in this study. The soil water content lower than the fixed θ_r ($0.02 \text{ cm}^3 \text{cm}^{-3}$) resulted in the calculation error was not considered because of the freezing in winter.

According to capillary rise theory, the pore size can be simply calculated by Equation 2.2 (Kutílek and Nielsen, 1994) when the soil is hydrophilic at 20°C of water.

$$d = \frac{3000}{|\psi|} \quad (2.2)$$

where d is the diameter of pore (μm), ψ is the matric potential (kPa) as indicated by pressure head. Thus, macropores ($>50 \mu\text{m}$), mesopores ($0.2\text{--}50 \mu\text{m}$) and micropores ($<0.2 \mu\text{m}$) correspond to the matric potentials of >-6 , from -6 to -1500 , and <-1500 kPa, respectively.

The soil water available for plants is generally estimated as the difference of the water content between field capacity (θ_{fc}) and plant wilting point (θ_{pwp}). The matric potential of -6 kPa is defined as the upper boundary of water field capacity for sandy soil, while the plant wilting point is related to the matric potential of -1500 kPa.

During the monitoring period, the recorded soil water content was always lower than the field capacity. Thus, the plant available water in each soil layer was calculated as follows:

$$\theta_{\text{paw}} = (\theta - \theta_{\text{pwp}}) \times |\Delta L| \quad (2.3)$$

where θ_{paw} is the plant available water (mm), ΔL is the distance of two points (cm) which was the thickness of the layer in this study. Three layers, *i. e.*, 0–10, 10–30, and 30–50 cm, were determined, which were based on the soil depth at 5, 20, and 40 cm, respectively.

In order to investigate how water flows throughout the growing season, the soil water flux was calculated by following equations (Becher, 1971). The absolute value of water flux was calculated by formulation 2.4 and its direction was confirmed by equation 2.5.

$$|q| = \left| \overline{\Delta\theta} \right| \cdot \frac{|\Delta L|}{t_2 - t_1} \quad (2.4)$$

where q is the water flux (mm s^{-1}), $\overline{\Delta\theta}$ is the water content difference between two points ($\text{cm}^3 \text{cm}^{-3}$), $t_2 - t_1$ is the time between two measurements (s). The direction of water flux can be confirmed by the following equation:

$$\overline{\text{grad}\psi_{\text{T}}} = \frac{\Delta\psi_{\text{T}}}{\Delta L} \quad (2.5)$$

where $\overline{\text{grad}\psi_{\text{T}}}$ is hydraulic gradient between two points (kPa cm^{-1}), $\Delta\psi_{\text{T}}$ (kPa) is the difference in soil water potential between two points, ψ_{T} (kPa) is the sum of soil matric potential and gravitational potential. The upward flow is positive. The following analyses are based on half hourly ($t_1 - t_2$) quantified differences between arithmetical mean values of soil water content and soil water potential in both layers: 5 to 20 cm and 20 to 40 cm layers. They were then summed up to the daily water flux (mm day^{-1}).

Table 2-1: Soil texture, bulk density (*BD*), organic carbon (*OC*), saturated hydraulic conductivity (K_s) and van Genuchten parameters at the SGCG and the LCHG sites (SGCG: continuous grazing site, LCHG: heavy grazing site, θ_s : saturated water content, α , n , and m : empirical shape parameters)

Site	Depth cm	Sand %	Silt %	Clay %	BD g cm ⁻³	OC g kg ⁻¹	K_s cm day ⁻¹	θ_s cm ³ cm ⁻³	α	n	m	R^2
SGCG	4–8	65.5	21.4	13.1	1.36	14.3	132.9	0.49	0.017	1.63	0.39	0.96
	18–22	62.3	24.1	13.6	1.35	12.2	130.4	0.49	0.031	1.45	0.31	0.94
	40–44	58.1	27.9	14.0	1.44	8.8	112.4	0.46	0.040	1.29	0.22	0.97
LCHG	4–8	67.9	20.6	11.5	1.30	11.6	93.0	0.51	0.016	1.57	0.36	0.97
	18–22	75.1	14.6	10.3	1.42	6.0	92.7	0.46	0.014	1.83	0.45	0.96
	40–44	71.6	17.1	11.3	1.45	3.7	79.4	0.45	0.015	1.86	0.46	0.96

Table 2-2: The net, upward and downward water flux and rainfall during the growing season in 2008 at the SGCG and the LCHG sites (SGCG: continuous grazing site, LCHG: heavy grazing site)

Site	Date	Rainfall mm	Between 5 and 20 cm depth			Between 20 and 40 cm depth		
			Upward mm	Downward mm	Net mm	Upward mm	Downward mm	Net mm
SGCG	May	52	34	-17	17	0	-38	-38
	June	73	64	-25	39	0	-50	-50
	July	91	44	-23	21	0	-67	-67
	August	101	78	0	78	0	-51	-51
	September	9	68	0	68	0	-31	-31
	Summary	326	288	-65	223	0	-237	-237
LCHG	May	40	58	-8	50	20	-26	-24
	June	104	76	-47	29	18	-38	-20
	July	107	76	-22	54	38	-24	14
	August	113	69	-5	64	40	0	40
	September	9	45	0	45	22	0	22
	Summary	373	324	-82	242	120	-88	32

2.4 Results

2.4.1 Soil properties

The Paired-Samples T Test was used to analyze the differences in soil water content, matric potential, and the available water between sites and depths by SPSS software, vs.13.0 (SPSS Inc., Chicago).

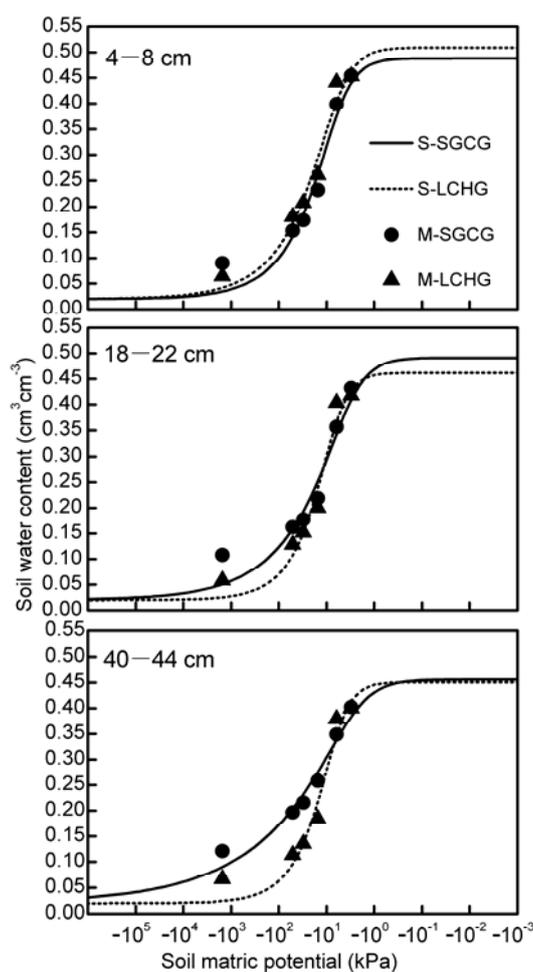


Figure 2-1: Soil water retention curves at different depths at the SGCG and the LCHG sites (S: simulated value by RETC (REtention Curve) software, M: measured value, SGCG: continuous grazing site, LCHG: heavy grazing site)

Some basic soil physical and chemical properties are listed in Table 2-1. The soil texture from both sites is sandy loam, although it is slightly coarser at the LCHG site than at the SGCG site in the subsoil layer. The bulk density in topsoil is slightly

greater at the SGCG site than at the LCHG site, while for deeper soil horizons it is contrary. The saturated hydraulic conductivity K_s and the organic carbon content are greater at the SGCG site than at the LCHG site at all three depths.

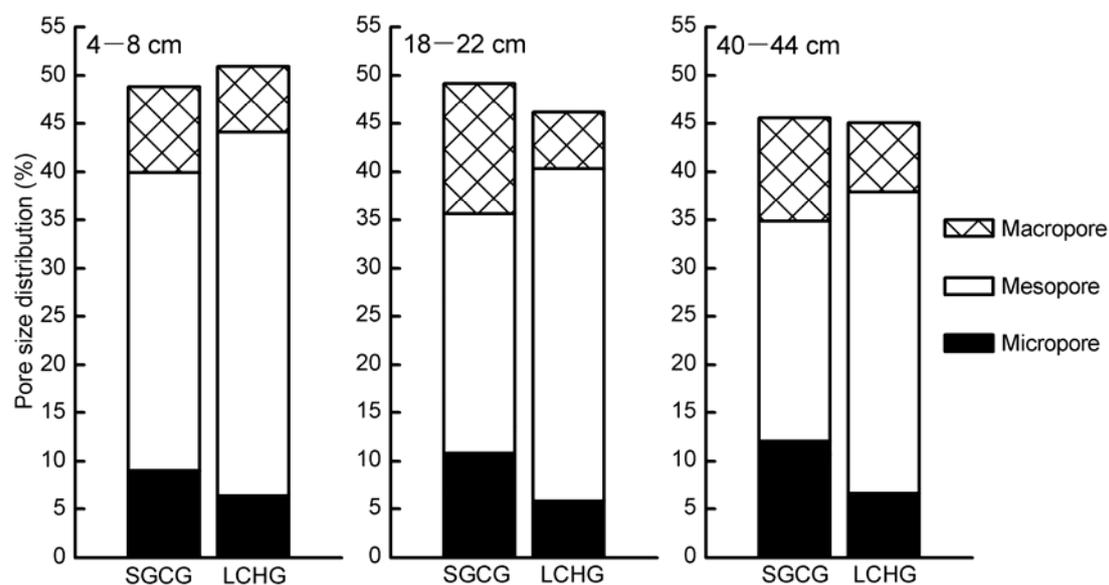


Figure 2-2: Pore size distribution at different depths at the SGCG and the LCHG sites (SGCG: continuous grazing site, LCHG: heavy grazing site; Sparse: macropores $>50 \mu\text{m}$; White: mesopores, $0.2-50 \mu\text{m}$; Black: micropores, $<0.2 \mu\text{m}$)

Figure 2-1 shows the fitted soil water retention curves with van Genuchten model and their parameters as listed in Table 2-1. The fitted data agreed well with the measured values ($R^2 > 0.93$, $p < 0.05$). Among the investigated soil profiles, water retention curves at the LCHG site showed a sharp slope as compared to the SGCG site except for the surface soil. The total pore volume generally decreased from the topsoil layer to the subsoil at the LCHG site, whereas such phenomenon was not evident at the SGCG site (Figure 2-2). However, the micropore volume ($<0.2 \mu\text{m}$) increased with depth at the SGCG site compared with the nearly similar values (5.8%–6.7%) at the LCHG site. The mesopore volume ($0.2-50 \mu\text{m}$) decreased from topsoil to deeper layers at both sites. The amount of $>50 \mu\text{m}$ macropores (8.9–13.5%) and micropores (9.0–12.1%) were greater at the SGCG site than at the LCHG site which showed the 5.9–7.1% macropores and the 5.8–6.8% micropores. While the mesopores at SGCG site (22.8–30.9%) was smaller than that at LCHG site (31.3–37.7%). In the topsoil,

the total pore volume was slightly smaller at the SGCG site than at the LCHG site, but the micropore volume was greater at the SGCG site due to finer texture.

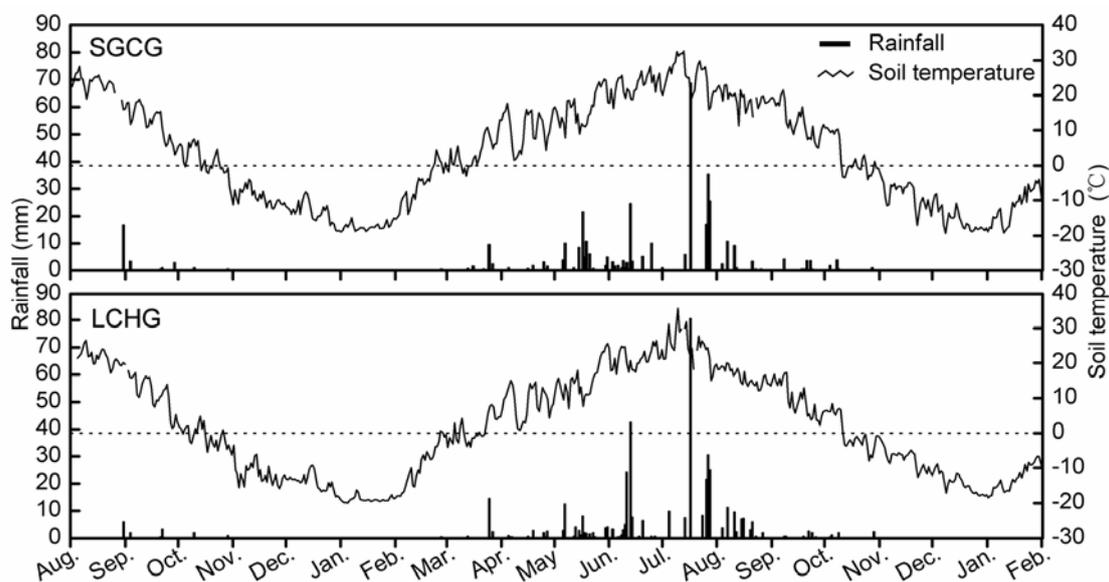


Figure 2-3: The rainfall and soil temperature at 2 cm depth at the SGCG and the LCHG sites (SGCG: continuous grazing site, LCHG: heavy grazing site)

2.4.2 Soil water regime

The rainfall from August 2007 to February 2009 was 389 and 426 mm at the SGCG and the LCHG sites, respectively (Figure 2-3). From May to September, 2008, the rainfall accounted for 90.1% and 91.4% of the annual amount at the SGCG and LCHG sites, respectively, while soil temperature at 2 cm depth was always above zero. Sufficient plant available water during the rainy season and warm temperature are beneficial for plant growth. We defined this period as growing season. From November to next February top soil temperature was generally below zero in coincidence with no rainfall. This period is dry with the lowest soil water content in the year as shown in Figure 2-4. The daily soil water content varied throughout the year, depending largely on rainfall and temperature. Thus, four different soil hydrological phases could be clearly defined at the two sites.

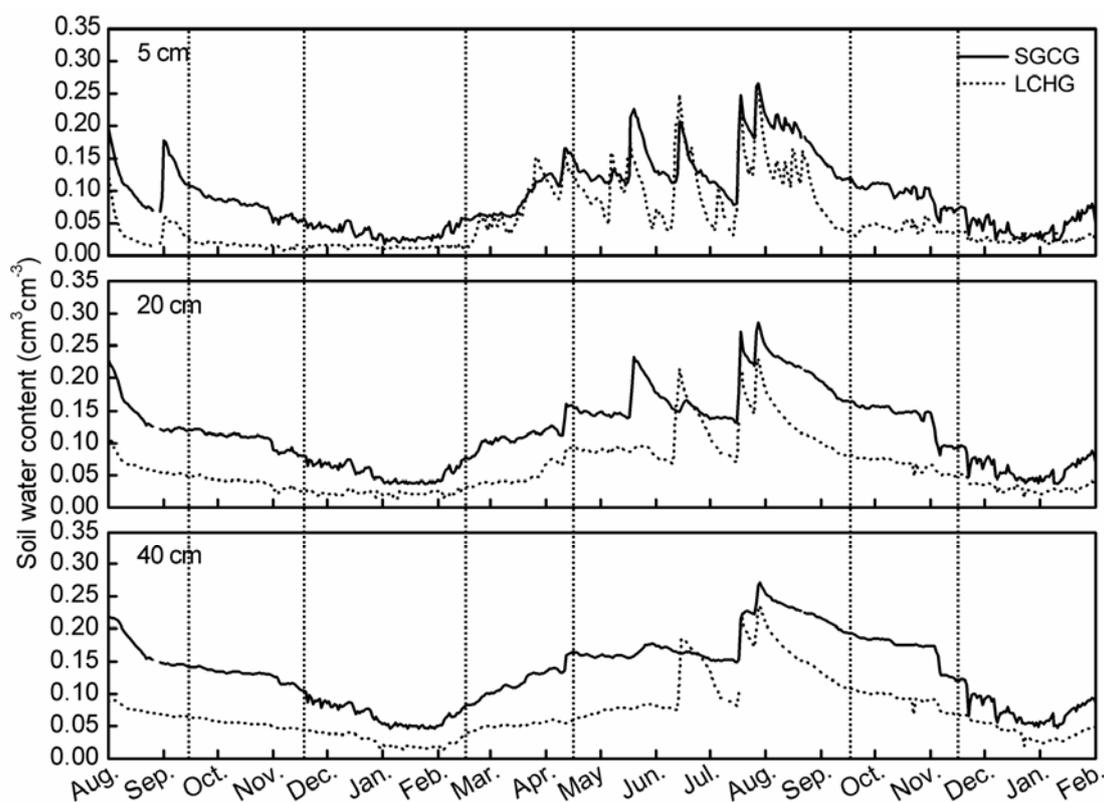


Figure 2-4: The daily change of soil water content at the SGCG and the LCHG sites at different soil depths (SGCG: continuous grazing site, LCHG: heavy grazing site)

The first phase was the dry winter from December to next February, when the soil water content was lowest with no rainfall and frozen soil conditions. From March to April the soil temperature increased, the soil water content changed from dry to relative moist due to snow and frozen soil thawing, which was defined as the wetting transition phase. From May to September, the soil water content remained relatively high due to rainfall. This period was the key season for plant growth in the studied area. We defined this phase as wet summer. From October to November, soil moisture started from relative humid to relatively dry due to limited rainfall, which was defined as drying transition. The lengths of both transition phases were generally much shorter than the dry winter or wet summer. During the monitoring period of August 2007 to February 2009, soil water content was generally lowest at the top soil layer of 5 cm, and increased with soil depth. The difference in soil water content between both sites was also smallest during the growing season. Whatever it was on rainfall days or on dry days the fluctuation of soil water content in top soil layer was greater than that in deeper soil horizons.

As the main difference between both sites, the soil water content was significantly higher ($P < 0.05$) under SGCG condition through all the seasons at a given soil depth. The averaged soil water content during the observed period was 0.09, 0.12 and 0.13 $\text{cm}^3 \text{cm}^{-3}$ at the SGCG site while that was 0.05, 0.06 and 0.07 $\text{cm}^3 \text{cm}^{-3}$ at the LCHG site at 5, 20 and 40 cm depths, respectively. Only in the growing season some peak values of soil water content were occasionally higher at the LCHG site than at the SGCG site due to rainfall events. At the LCHG site the soil water content was more sensitive, which showed that it decreased quicker after rainy events, compared with that at the SGCG site. In the winter time, it was always lower at the LCHG site than at the SGCG site, but the frozen water cannot be correctly registered by Theta-probe.

2.4.3 Soil matric potential

The daily change of soil matric potential at the two sites showed remarkable difference (Figure 2-5). Because of the limitations in the Theta-probe technique to register frozen water the soil matric potential in both winter periods of 2008 and 2009 were always lower than the wilting point in the complete profile of the SGCG and LCHG sites. We did not consider the winter season here. During the growing season soil matric potential was the highest, ranging mainly between -6 to -100 kPa at both sites. Nevertheless, during the two transitional phases either from dry to humid or vice versa the soil matric potential ranged mainly from -100 to -1500 kPa at both sites in which greater change occurred at the LCHG site than at the SGCG site. The soil matric potential in the topsoil was more negative ($P < 0.05$) at the LCHG site than at the SGCG site but faded off at 20 cm depth. On the contrary, at 40 cm depth the soil matric potential was more negative at the SGCG site than at the LCHG site. The soil matric potential depended strongly on rainfall, which was more obvious for the top layer at the LCHG site than at the SGCG site. The consistency between soil matric potential and rainfall was less evident with increasing of soil depth, which is in agreement with Bréda et al. (1995) and Casas and Ninot (2007) who documented that

the variations of soil water potential weakened as increasing soil depth.

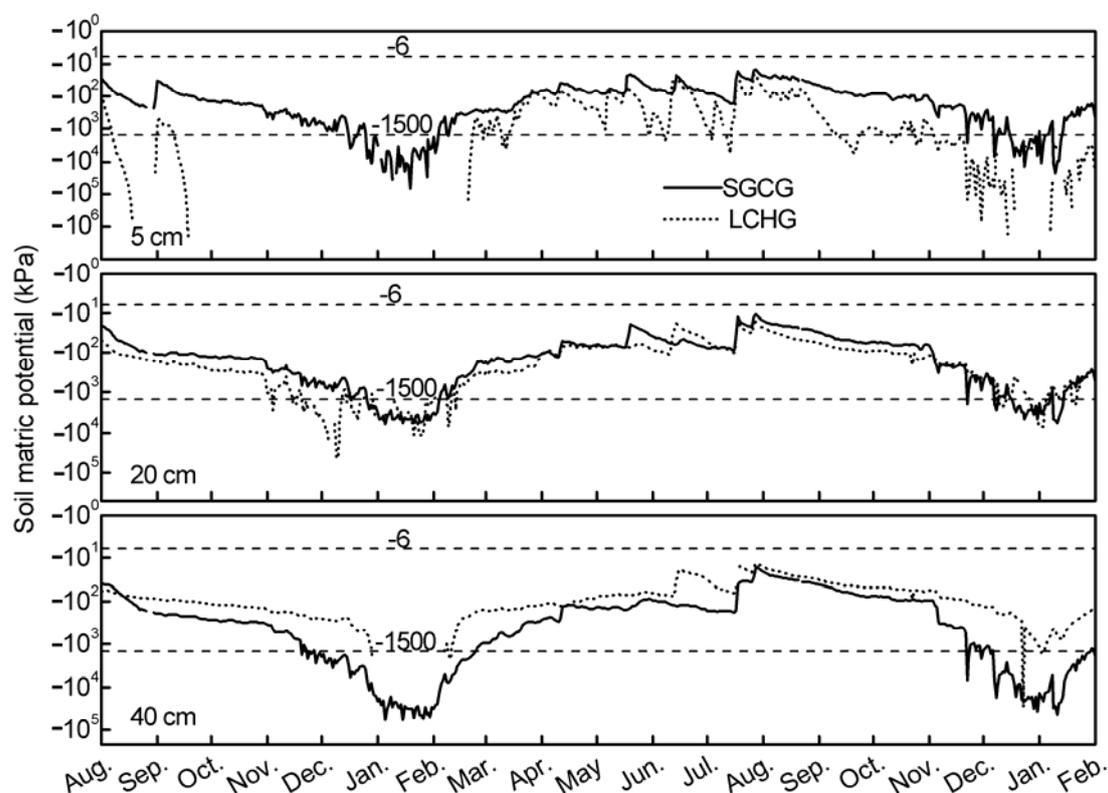


Figure 2-5: The daily change of soil matric potential at different soil depths at the SGCG and the LCHG sites (SGCG: continuous grazing site, LCHG: heavy grazing site)

2.4.4 Plant available water

Figure 2-6 shows the dynamics of plant available water at the two sites at different soil depths. During the whole period, the averaged plant available water at 5 and 20 cm depth was 6 and 14 mm at the SGCG site while that was 2 and 8 mm at the LCHG site, respectively. But the difference became negligible at 40 cm depth. The absolute and highest values of the plant available water were in line with growing season, and they were lower at the LCHG site than at the SGCG site. The different plant available water may result from the root length density besides the soil water regime. The root length density was 5.2 cm cm^{-3} and 1.9 cm cm^{-3} in 0–20 cm and 20–40 cm layer at the SGCG site, respectively, which were corresponding to 4.7 cm cm^{-3} and 0.39 cm cm^{-3} at the LCHG site in 2008.

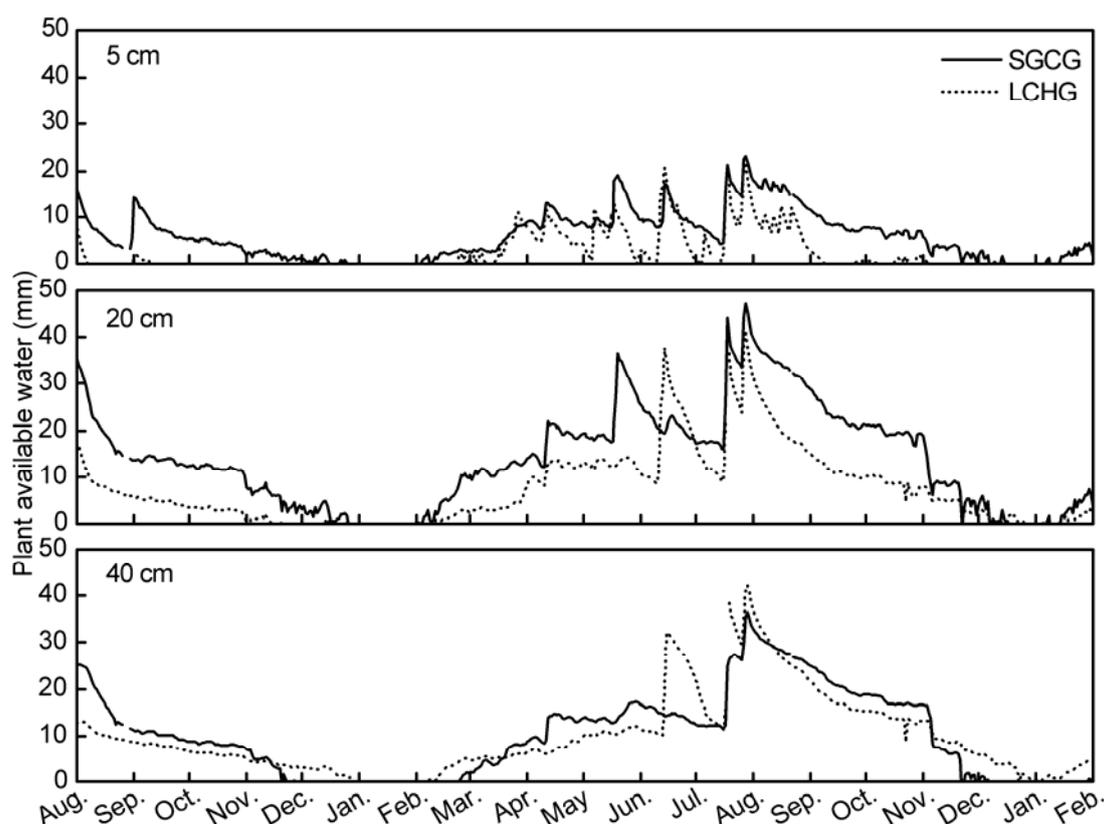


Figure 2-6: The dynamics of plant available water at the SGCG and the LCHG sites at different soil depths (SGCG: continuous grazing site, LCHG: heavy grazing site)

2.4.5 Water flux

Soil temperature below 0 °C from November to next February results in frozen soil water and is assumed to no flux conditions. In addition, during the two transition periods water flux was also very low due to low temperature and little rainfall. Therefore we focus only on the plant growing season from May to September, because the rainfall accounts for over 90% of annual amount. According to the gradients of the soil water content and the water potential throughout the complete soil profiles, the daily net water flux was calculated between 5 and 20 cm depth and between 20 and 40 cm depth in 2008 (Figure 2-7). Positive values indicate upward and negative values show the downward water movement. The soil water movement showed the fluctuations of upward and downward flux in growing season, relying largely on rainfall and evapotranspiration (*ET*). It was relatively stable when rainfall

was marginal.

At both sites the responses of soil water movement were generally consistent with the rainfall. The upward flux generally took place during the whole growing season in 5–20 cm layer. Usually once the heavy rain event (>20 mm) happened the downward flux took place in this layer, followed by a sharp increase of upward flux, e.g. on 31st May (21 mm), 25th June (24 mm), 31st July (69 mm). However, the downward flux took place in 20–40 cm layer at the SGCG site during the whole growing season, furthermore the rainfall increased it. After the heavy rain events, the downward flux was evidently observed in 20–40 cm layer at the LCHG site, however, the net water flux always behaved upward.

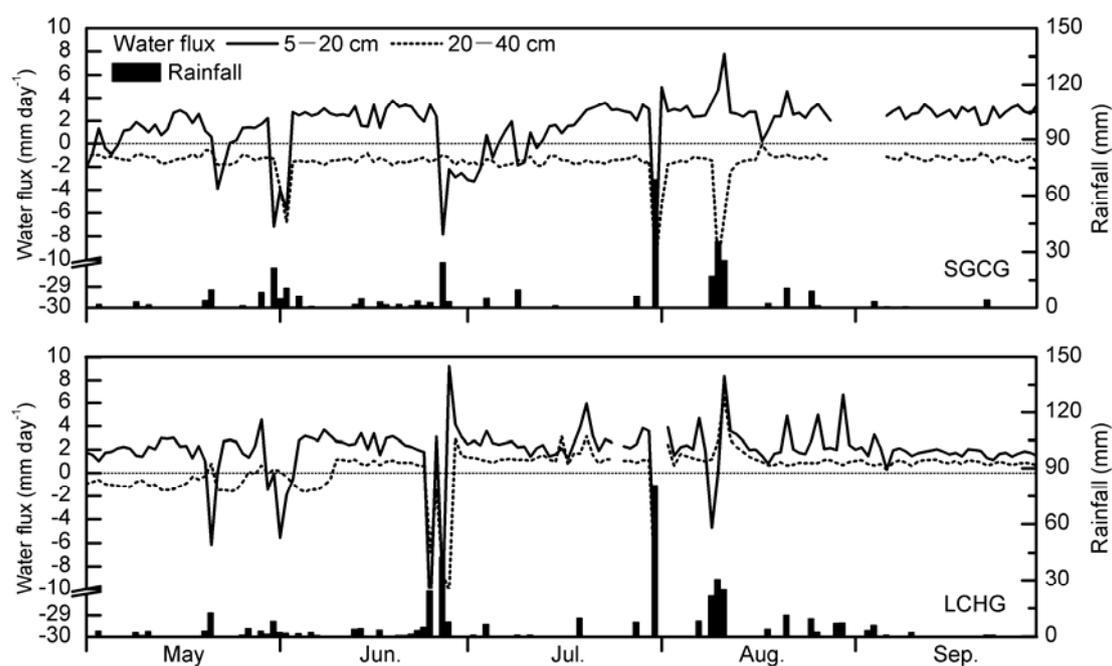


Figure 2-7: The daily change of net water flux at the SGCG and the LCHG sites in 5 to 20 cm and 20 to 40 cm layers from May to September in 2008, respectively (SGCG: continuous grazing site, LCHG: heavy grazing site)

Table 2-2 summarizes the net water flux, the upward and the downward fluxes during the growing season from May to September in 2008. The upward flux was larger in 5–20 cm layer than in 20–40 cm layer in both sites while the downward flux was smaller. Furthermore, the net water flux at the SGCG site (223 mm) was a bit

smaller than that at the LCHG site (242 mm) in 5–20 cm layer, but much less than at the LCHG in 20–40 cm layer (–237 mm at the SGCG site and 32 mm at the LCHG site). Only downward flux occurred in 20–40 cm layer at the SGCG site.

2.5 Discussion

2.5.1 Effect of grazing on soil structure

Soil deformation due to animal trampling results in a change of the pore structure and pore functioning on plant water and nutrient uptake. These effects can be also proofed at both sites which show not only a different pore system between the LCHG and the SGCG sites, but which also includes an alteration of the pore size distribution. The more mesopores at the LCHG site may result from animal tramples at the cost of macropores. Zhao et al. (2010) showed an increase of the mesopore volume as a result of grazing, which is in agreement with Peth and Horn (2006) who reported that the matric potential was more negative at a given soil water content at the trampled sites than at the undisturbed site. The coarse texture also induces the less amount of fine pore volume at the LCHG site. Meanwhile, the higher soil organic carbon at the SGCG site may improve the ability of water retention, because soil organic materials generally have a high capacity to retain water (Casas and Ninot, 2007).

2.5.2 Soil water regime

Change of pore structure by grazing as a consequence influences water retention and movement in the soil. The increase of grazing intensity from SGCG to LCHG caused a decrease of soil water content at all depths (Figure 2-4). The reasons may come from two aspects. One is that the increase of grazing intensity may reduce water infiltration as resulted from the animal trampling at the LCHG site. The finer soil texture at the SGCG site may remain more water than at the LCHG site, which can be

proofed by that the soil water content decreased quicker at the LCHG site than at the SGCG site once rainfall stopped (Figure 2-4). On the other hand, soil water loss is mainly through evaporation and transpiration in semi-arid region (Miao et al., 2009). During the growing season, the larger area of bare land resulting from heavy grazing at the LCHG site caused a higher evaporation but a less transpiration. However, we could not separate them in this study. If coupling them together as an *ET*, it can be defined as the upward water flux. The soil water loss was a little greater at the LCHG site than at the SGCG site (Table 2-2). Therefore, the soil water regime in the study region depends more on the water infiltration rate and retention capacity than on the water loss. Zhao et al. (2007, 2010) also documented that the heavy grazing resulted in a drier soil water regime and reduced the soil water storage capacity in Xilin River catchment in Inner Mongolia grassland. If we compare these data between different soil depths, the water content of top soil was more sensitive to rainfall than that of deeper soil, which may also attributes to strong evaporation that reduces the infiltration and recharge of soil profile.

The changing of soil water content further depends on snow and frozen soil thawing with the increasing soil temperature. In the period of March and April the amount of thawing snow accumulated in winter and frozen soil were important to determine the soil water content. Being consistent with the increase of soil temperature before the growing season, the water loss may be mainly from evaporation and runoff during snow and frozen soil thawing. The data showed (Figure 2-4) the small amount of liquid water in the soil and was furthermore affected by soil temperature. This change was more evident at the SGCG site than at the LCHG site, because the latter was subject to more severe compaction resulting in the lower water infiltration from animal trampling. This has been proofed in previous work by Zhao (2008) who found that a smaller amount of thawing snow infiltrated into the soil at the LCHG site than other un-grazing and continuous grazing sites. From October to November, the soil water content decreased due to a little supplement of water and partially to the soil freezing.

The plant available water was lower at the LCHG site than at the SGCG site in the top 20 cm depth, but the difference at 40 cm layer was minimal, indicating that in the growing season plants at the LCHG site suffered more serious water stress than at the SGCG site. In the other words, heavy grazing could induce lower biomass production as confirmed by Gao et al. (2008) who reported that heavy grazing significantly decreased live root biomass and belowground net primary productivity compared to un-grazing sites.

2.5.3 Water flux

The ratio of evapotranspiration/precipitation which is greater than 1.0 in Xilinhot confirms that all of the precipitation was lost by *ET* and the water supply limited *ET* in steppe ecosystems (Wever et al., 2002; Frank, 2003; Miao et al., 2009). The much greater upward than the downward water flux between 5 and 20 cm depths at both sites indicates the water loss is mainly driven by the *ET* in the root horizon. Certainly, the total rainfall is not enough to support the *ET* at the two sites, which is more serious at the LCHG site than at the SGCG site as proofed by Figures 2-4 and 2-6. The greater daily net water flux in the late growing season (August–September) at the SGCG site than at the LCHG site as showed in Figure 2-7 and Table 2-2 may result from more roots and higher soil water content at the SGCG site. Lower root length density at the LCHG site contributed less soil water movement than at the SGCG site. Secondly, higher water retention capacity at the SGCG site may provide a water source of upward flux. Although the soil water was consumed by the *ET*, it was still available for plant uptake, which was greater at the SGCG site than at the LCHG site as shown Figure 2-6. Interestingly, after most of rainfalls, especially the slight rainy events, higher upward net flux in 5–20 cm layer at both sites suggests that the rainfall-derived increase of soil water content can enhance the *ET*. In summer the water entering into the soil was probably to a large extent immediately lost by soil surface with the strong evaporation in Inner Mongolia. Li et al. (2007) pointed out that the *ET* in a Mongolian stepper under grazing was highly dependent on the

variability in soil water content caused by rainfall. In other words, the root uptake water or upward flux in semi-arid grasslands depends much on the soil water content and the gradient of the total water potential between soil-plant-air continuum (SPAC) even if the potential evapotranspiration may decrease as resulted from rainfall-derived temperature reduction. Meanwhile, at the LCHG site the evident upward flow was observed in 20–40 cm layer during growing season implying that the capillary rise of water from this layer could supply to plant growing. On the contrary, the flux at the SGCG site was always downward in this layer because the matric potential at 40 cm layer was always more negative than at 20 cm layer as shown in Figure 2-5. This difference between the two sites may result from the difference of their water retention capacities. At the SGCG site the water can be retained in the top 20 cm due to finer texture, however, for the coarse texture at the LCHG site water is more easily driven by the gravitational force. In addition, at the SGCG site a gentle slope of soil water retention curve at 40–44 cm depth (Figure 2-1) indicates that a slight decrease in the soil water content at this layer can result in a large decrease of the matric potential, inducing a downward flow from 20 cm to 40 cm depth. Such phenomenon was also observed by Schwärzel et al. (2009) who found water flux could be driven by a large decrease in the matric potential resulting from even a slight decrease of soil water. It also implies that this layer does not play an important role in water supply of plant growth at the SGCG site and partial water could be stored in this layer.

2.6 Conclusions

Heavy grazing reduced the soil water content largely at all the depths compared to continuous grazing, especially in 5 cm depth. The pattern and intensity of rainfall played a key role in the soil water content in Inner Mongolia grassland, which was more evident at the LCHG site than at the SGCG site. The soil water flux was a little greater at the LCHG site than at the SGCG site in 5–20 cm layer. Heavy grazing induced the water to flow upwards along the top 40 cm soil profile whereas the water

flowed upwards only in 5–20 cm layer at the SGCG site in the growing season. Most rainy events could directly increase the upward flux in top 20 cm layer but heavy rainfall events (>20 mm) generally resulted in an obvious downward water flux following by a great upward flux. During the growing season the evapotranspiration was the main driver for soil water loss. At the LCHG site the soil water supply for plant growth also came from the 20–40 cm layer, whereas the downward flux at the SGCG site throughout the whole growing season contributed to the soil water storage in deeper soil.

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3 EFFECTS OF GRAZING INTENSITY ON SOIL THERMAL PROPERTIES AND HEAT FLUX UNDER LEYMUS CHINENSIS AND STIPA GRANDIS VEGETATION IN INNER MONGOLIA, CHINA

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3.1 Abstract

The increase of grazing intensity may alter the fluxes of mass and energy in grassland ecosystem due to fast population growth and distinct land-use change. To understand effects of different grazing intensities on soil thermal properties and heat flux, 5 sites under two representative vegetation types: *Leymus chinensis* (LC) and *Stipa grandis* (SG) in Inner Mongolia, China were investigated: two un-grazed sites since 1979 (LCUG79 and SGUG79), two moderately grazed sites which are winter grazed in LC (LCWG, 0.5 sheep units ha⁻¹ year⁻¹) and continuously grazed in SG (SGCG, 1.2 sheep units ha⁻¹ year⁻¹), and one heavily grazed site (LCHG, 2.0 sheep units ha⁻¹ year⁻¹). Soil water content and temperature were registered in the growing seasons: 2008 and 2009. The results in the more sensitive top 20 cm layer showed that heavy grazing induced the lowest soil water content, followed by winter grazing in the LC region. Continuous grazing caused higher soil moisture compared with un-grazed in SG region, which can be explained by the on site adjusted grazing intensity. For all sites, soil volumetric heat capacity and thermal conductivity increased with depths, which was in accordance with soil moisture. In LC region, the thermal conductivity was greater at the LCHG site than at the LCUG79 and LCWG sites, but the volumetric heat capacity was not significantly different between them. In SG region, these properties were greater at SGCG site than at SGUG79 site. Net soil heat flux

generally moved downwards during the growing season. The greatest value was at LCHG site but lowest at LCUG79 site in LC region. On the contrary, a lower value was observed at SGCG site because of higher soil water content compared with SGUG79. For two un-grazed sites, heat flux was greater under SG vegetation than under LC vegetation. The long-term rainfall induced upward heat flux, but short-term rainfall caused a sharply downward increase. Without raining, the daily maximum and minimum of heat flux concurred with those of air temperature at LCHG site, but delayed at other sites. In conclusion, we can state that grazing intensity affects the soil thermal properties and heat flux, but vegetation type was only verified to impact heat flux. An appropriate grazing intensity improves soil water and thermal regimes compared with the long-term un-grazed sites.

Key Words: grazing intensity; semi-arid grassland; soil thermal properties; soil heat flux

3.2 Introduction

In Inner Mongolia grassland, China, both population growth and a quick land-use change enhanced over the past decades. The traditional extensive, semi-nomadic sheep grazing system changed to a dramatically intensified stationary livestock farming, which resulted in over-grazing and over-cropping in some areas. It is estimated by the UNEP (United Nations Environment Programme) that 60–70% of the grasslands in China are affected by deterioration and desertification mainly due to heavy grazing (Graetz, 1994). Heavy grazing accompanied with animal trampling has detrimental effects on soil hydraulic and mechanical properties especially if soils are either too wet and therefore susceptible to homogenization by puddling or mostly too dry with therefore reduced cohesive forces (Greenwood and McKenzie, 2001; Reszkowska et al., 2011a). Especially in the topsoil, soil deformation results in a decrease of pore volume and an increase in finer pores, i.e. changed soil water retention characteristics (Martínez and Zinck, 2004; Kutílek et al., 2006), and is even more important to the changes in water and air fluxes (Willat and Pullar, 1983; Krümmelbein et al., 2006; Reszkowska et al., 2011b). Heavy grazing also can lead to changes in vegetation cover (Paruelo et al., 2001) and plant community composition in grasslands (Li, 2001; Oba et al., 2001; Zhang and Skarpe, 1996).

An often neglected property concerning plant growth, evapotranspiration and even flux processes is the soil temperature, as it is a primary factor in determining the rates and directions of soil physical processes and of energy and mass exchanges with the atmosphere. It varies in response to changes in radiant, thermal, and latent energy exchanges taking place primarily through the soil surface (Tyagi and Satyanarayana, 2010). Soil thermal properties like thermal conductivity and volumetric heat capacity play an important role in the surface-energy partitioning and temperature distribution (de Vries, 1987; Horton and Chung, 1991; Noborio et al., 1996; Tyson et al., 2001), which all are driven by soil moisture distribution and absolute values, and are also

influenced by soil composition, soil structure, and vegetation cover (shading, root influence on soil moisture content) (de Vries, 1966; Dec et al., 2009; Ju et al., 2010). Any practice or process which causes changes of the bulk density, porosity as well as pore size distribution and arrangement of particles within aggregates at a given water content have a significant effect on thermal conductivity. Abu-Hamdeh (2000) stated that the thermal conductivity increased with increasing bulk density as a result of particle contact enhancement as porosity decreased. In addition to compaction, tillage can influence soil water content and other physical characteristics which have also an impact on soil thermal conductivity (Al Nakshabandi and Kohnke, 1965; Cochran et al., 1967; Fritton et al., 1974; Dec et al., 2009). Bristow and Horton (1996) and Kustas et al. (2000) demonstrated the effects of partial surface mulch and clustering of the vegetation cover on soil heat flux. Reduced soil disturbance due to long-term no-tillage induced changes in soil organic matter, aggregate size distribution and water storage capacity compared with a conventional tillage system thereby, altering above various factors affecting heat conduction (Arshad et al., 1990; Chang and Lindwall, 1992; Azooz et al., 1997; O' Donnell et al., 2009).

The perennial rhizome grass *Leymus chinensis* and bunch grass *Stipa grandis* (Tong et al., 2004; Chen et al., 2005) cover about 60% of the total land area in the Xilin River catchment in Inner Mongolia grassland (Li et al., 1988). Livestock grazing is however recognized as one of the main causes of soil and vegetation degradation in Inner Mongolia grassland. Grazing associated with animal activity alters soil hydraulic and mechanical properties (Greenwood and McKenzie, 2001) and heat flux by the variety of plant height and vegetation cover which contribute into the change in surface temperature (Li et al., 2000). It is also well known that many arid and semi-arid types of grassland have experienced a shift in dominant vegetative composition from perennial grasses to shrubs and bare soil, a change which coincides with desertification (Daily, 1995; Van Auken, 2000; Scheffer et al., 2001; Jackson et al., 2002). Such extensive shift in vegetation and desertification are caused by stationary livestock farming and the increase of livestock in Inner Mongolia grassland

in the past four decades (Cao and Yang, 1999). Some studies have also shown that there are distinct differences in the morphology and photosynthetic physiology between two species *Leymus chinensis* and *Stipa grandis* (Du and Yang, 1988; Du et al., 1999; Cui et al., 2001) which also may affect the water use and heat transport of these two species in the semi-arid grassland and may result in different strategies to overcome mechanical and hydraulic stresses under those climatic conditions.

The MAGIM project (Matter fluxes in grasslands of Inner Mongolia as influenced by stocking rate) carried out in Inner Mongolia grassland aims to understand how sheep grazing affects water, carbon and nitrogen fluxes at various spatial and temporal scales (Reszkowska et al., 2011a, 2011b; Wiesmeie et al., 2010; Wittmer et al., 2010). In the following the effect of grazing on soil thermal properties and heat flux as affected by grazing intensity and vegetation cover (*Leymus chinensis* or *Stipa grandis*) more controlled in situ conditions will be described based on the hypotheses: grazing will enhance the heat flux compared with un-grazed sites and that soils under *Stipa grandis* and *Leymus chinensis* vegetation have different thermal properties and result in different heat fluxes

Therefore, our objectives were: (i) to characterize the spatial and temporal distribution of soil thermal properties within the soil profiles and (ii) to quantify soil heat flux as affected by different grazing intensities and vegetation type in Inner Mongolia grassland, China.

3.3 Materials and methods

3.3.1 Study site description

The research was carried out on a long-term experiment established at the Inner Mongolia Grassland Ecosystem Research Station (IMGERS; 43°37'50"N,

116°42'18"E) situated in the Xilin River catchment, Northern China. The experiment evaluated the effect of grazing intensity on mass flux in the continental semi-arid grasslands of the Central Asian steppe ecosystem, with a dry and cold middle latitude climate (Kawamura et al., 2005). In the last two decades, the annual mean air temperature was 0.7 °C and the annual mean minimum temperature was approx -20 °C. Annual precipitation was 343 mm in which less than 5% fell as snow for the period 1982–2003. More than 85% of the annual precipitation is concentrated during the growing season (May to September). The vegetation is characterized by the perennial rhizome grass *Leymus chinensis* (LC) and bunch grass *Stipa grandis* (SG) (Tong et al., 2004; Chen et al., 2005), which cover about 60% of the land area in the Xilin River catchment (Li et al., 1988). Soils were classified as Calcic Chernozems (IUSS Working Group WRB, 2006) developed from aeolian sediments deposited on a pleistocene basalt plateau (Wiesmeier et al., 2009).

In this case study, both representative vegetation types: *Leymus chinensis* (LC) and *Stipa grandis* (SG) under different grazing intensities were investigated. In the LC region the following sites were investigated: un-grazed since 1979 (LCUG79, 24 ha), grazed in winter (LCWG, 40 ha) with 0.5 sheep units ha⁻¹ year⁻¹, and heavily grazed (LCHG, 100 ha) with 2.0 sheep units ha⁻¹ year⁻¹. In the SG region the following sites were investigated: un-grazed since 1979 (SGUG79, 24 ha), and continuously grazed (SGCG, 100 ha) with 1.2 sheep units ha⁻¹ year⁻¹. Both LCWG and SGCG were defined as moderate grazing intensity. The distance between LC and SG regions is about 10 km.

3.3.2 Soil sampling and analyses

At each site three replicate profiles within a distance of 15 m Theta-probes (Type ML2x, Delta-T Devices, Cambridge, UK) were installed at 5, 20 and 40 cm depths to monitor soil moisture and platinum ground temperature probes (Pt-100) within the measurement error of ±0.30 °C at the same depths measured soil temperature. All

sensors were connected to one solar powered automatic data-logger, which recorded soil water content and soil temperature at 30-min intervals. The Theta-probes were calibrated for the site-specific soil using the gravimetric method. The technical specification of the Theta-probe has a measurement error of $\pm 0.01 \text{ cm}^3 \text{ cm}^{-3}$ from 0 to 40 °C (Delta-T Devices Ltd., 1999.). In winter the top soil was almost frozen at all sites, thus the limitation of Theta-probe might induce the errors of soil water content so that only the data of the growing season were further analyzed and presented in this study. Rainfall was measured by rain gauges (DECAGON DEVICES ECRN-100). The whole study period lasted from 1st of May 2008 to 30th of September 2009, however, some probes and/or data loggers were out of order for 8 weeks at the LCWG site in 2008 and 12 weeks at the LCHG site in 2009, respectively. Thus, we compared the effect of grazing intensity on soil thermal properties and heat flux under LC vegetation using the data of 2008 and under SG vegetation using the data of 2009, respectively. The effect of vegetation type on two un-grazed soil thermal regimes was analyzed using the data of 2009. The daily values of soil water content, soil temperature and soil thermal properties were averaged from every 30-min data registered in the field. The net soil heat flux was then summed up for one day or for one growing season in order to also include the scale effects as a differentiation between the sites.

The basic soil properties including soil texture, bulk density, total porosity, organic matter and saturated hydraulic conductivity (K_s) of each layer: 4–8, 18–22 and 40–44 cm were measured in the laboratory (for more detailed information about the methods, please see Hartge and Horn, 2009). The leaf area index (LAI) was measured monthly during the growing season in 2008 with the leaf-area meter LI-3050 (LI-COR, Nebraska, USA).

Soil thermal properties were estimated according to de Vries (1966) and Campbell (1985). Volumetric heat capacity of soil was calculated as follows:

$$C_s(\theta) = \theta + 0.46(1 - \phi - m_o) + 0.6m_o \quad (3.1)$$

where $C_s(\theta)$ is soil volumetric heat capacity ($\text{cal cm}^{-3} \text{ }^\circ\text{C}^{-1}$), θ is soil water content ($\text{cm}^3 \text{ cm}^{-3}$), ϕ is total porosity, m_o is the organic matter fraction, 0.46 and 0.6 are the volumetric heat capacity of minerals and soil organic matter, respectively ($\text{cal cm}^{-3} \text{ }^\circ\text{C}^{-1}$). Both ϕ and m_o are the constants in Equation 3.1.

Thermal conductivity $\lambda(\theta)$ ($\text{W m}^{-1} \text{ K}^{-1}$) can be calculated with Equation 3.2 (Campbell, 1985),

$$\lambda(\theta) = A + B\theta - (A - D)\exp[-(C\theta)^E] \quad (3.2)$$

where A , B , C , D and E are soil dependent coefficients which have been related to soil properties. These relationships are:

$$A = 0.65 - 0.78\rho_b + 0.60\rho_b^2 \quad (3.3)$$

$$B = 1.06\rho_b \quad (3.4)$$

$$C = 1 + \frac{2.6}{m_c^{0.5}} \quad (3.5)$$

$$D = 0.03 + 0.10\rho_b^2 \quad (3.6)$$

$$E = 4 \quad (3.7)$$

where ρ_b is the soil bulk density (g cm^{-3}), and m_c is the clay fraction. Both ρ_b and m_c are the constants in above equations.

Soil heat flux in between two depths: 5–20 cm and 20–40 cm, was calculated with the following equation:

$$J(\theta, T) = -\lambda(\theta)_{\text{eq}} \frac{dT}{dZ} \quad (3.8)$$

where $J(\theta, T)$ is the soil heat flux (W m^{-2}), and dT and dZ are the differences in temperature (measured variable) and distance (constant) between two different depths, respectively. $\lambda(\theta)_{\text{eq}}$ (calculated variable) is the equivalent thermal conductivity between two depths, which was calculated by Equation 3.9 (Jury and Horton, 2004).

$$\frac{Z_1 + Z_2}{\lambda(\theta)_{eq}} = \frac{Z_1}{\lambda(\theta)_1} + \frac{Z_2}{\lambda(\theta)_2} \quad (3.9)$$

where Z_1 and Z_2 are the thicknesses of the soil layers, and $\lambda(\theta)_1$ and $\lambda(\theta)_2$ are soil thermal conductivity values in different depths, respectively. Water vapor is particularly effective in transporting latent heat from the soil to the atmosphere in summer. However, such non-conductive heat transfer mechanism was not considered in our study. In our study soil heat flux is more appropriate to refer to apparent soil heat flux as pointed out by Hinkel (1997).

The effect of grazing intensity on all analyzed parameters was tested using a one-way analysis of variance (ANOVA) and the Paired-Samples T Test was used to analyze the significant difference ($p < 0.05$) in soil water content, soil temperature and soil thermal properties among sites and depths by SPSS software, vs.13.0 (SPSS Inc., Chicago).

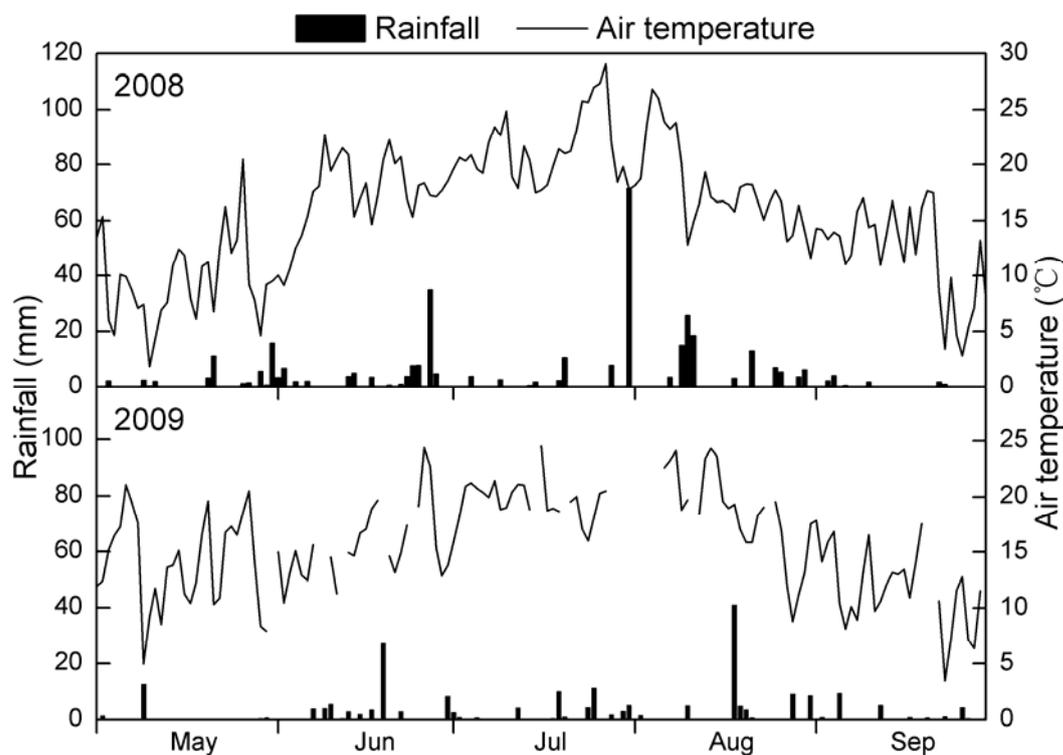


Figure 3-1: Air temperature and rainfall during the growing season in 2008 and in 2009

Table 3-1: Leaf area index (*LAI*), soil texture, bulk density (*BD*), total porosity (*TP*), soil organic matter (*SOM*) and saturated hydraulic conductivity (K_s) at 5 sites (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)

Site	<i>LAI</i>	Depth cm	Sand %	Silt %	Clay %	<i>BD</i> g cm ⁻³	<i>TP</i> %	<i>SOM</i> %	K_s cm day ⁻¹
LCUG79	0.91(±0.33)a	4-8	60.9(±2.7)b	24.9(±3.7)a	14.2(±1.0)b	1.14(±0.02)c	56.9(±0.8)a	3.3	165(±113)ab
		18-22	64.4(±2.8)b	21.8(±1.2)a	13.8(±3.9)bc	1.39(±0.04)ab	47.6(±1.5)cd	1.5	133(±67)b
		40-44	78.0(±0.3)a	13.5(±1.4)c	8.5(±1.1)c	1.43(±0.03)ab	45.9(±1.2)b	1.1	72(±23)b
LCWG	0.43(±0.11)bc	4-8	51.6(±2.5)c	30.2(±2.8)a	18.2(±0.3)a	1.18(±0.02)c	55.6(±0.8)a	3.1	55(±13)b
		18-22	55.9(±2.4)b	27.1(±1.3)a	17.0(±0.1)a	1.29(±0.01)c	51.4(±0.5)a	1.6	70(±36)b
		40-44	56.2(±1.9)b	27.7(±0.3)ab	16.1(±1.6)a	1.34(±0.04)b	50.4(±0.9)a	0.8	61(±5)b
LCHG	0.16(±0.07)b	4-8	67.9(±3.5)a	20.6(±2.9)a	11.5(±1.0)c	1.30(±0.02)b	51.0(±0.6)b	2.1	93(±18)b
		18-22	75.1(±3.6)a	14.6(±2.2)b	10.3(±1.4)c	1.42(±0.03)a	46.2(±1.3)d	1.0	93(±22)b
		40-44	71.6(±2.3)a	17.1(±1.8)bc	11.3(±0.7)c	1.45(±0.03)a	45.1(±1.2)b	0.6	79(±16)ab
SGUG79	0.73(±0.25)ac	4-8	62.3(±2.6)b	25.1(±1.9)a	12.6(±1.3)c	1.27(±0.04)b	52.0(±1.4)b	3.0	216(±62)a
		18-22	60.0(±3.2)b	26.0(±2.4)a	14.0(±0.9)b	1.33(±0.03)bc	49.8(±1.3)ab	2.2	268(±44)a
		40-44	55.6(±0.5)b	28.7(±1.5)a	15.7(±1.4)ab	1.37(±0.04)b	48.5(±1.6)a	1.6	143(±32)a
SGCG	0.35(±0.12)b	4-8	65.5(±1.9)ab	21.4(±1.4)a	13.1(±0.5)bc	1.36(±0.01)a	48.8(±0.5)c	2.5	133(±37)ab
		18-22	62.3(±3.0)b	24.1(±3.0)a	13.6(±0.1)bc	1.35(±0.03)b	49.2(±1.1)bc	2.1	130(±31)b
		40-44	58.1(±3.8)b	27.9(±3.3)a	14.0(±0.6)b	1.44(±0.04)a	45.6(±1.5)b	1.4	112(±24)a

Different lowercase letters indicate the significant difference between sites at the same depth ($p < 0.05$)

3.4 Results

3.4.1 Climate conditions and basic soil properties

Based on the data from IMGERS the mean air temperature was 15.7 and 15.8 °C during the growing season in 2008 and 2009, respectively, while the accumulative rainfall was 355 and 227 mm, respectively (Figure 3-1).

Some basic soil properties including soil texture, bulk density, total porosity, soil organic matter and saturated hydraulic conductivity are listed in Table 3-1. Soil texture was coarser at the LCHG site compared with the others, except for 40–44 cm depth at the LCUG79 site where the high sand fraction results from a slightly coarser parent material. Bulk density increases with soil depth, while soil organic matter and total porosity decreased. Soil organic matter and saturated hydraulic conductivity was generally higher at the un-grazed sites than at the grazed sites. Moreover, the saturated hydraulic conductivity was greater in the SG region comparing corresponding sites in the LC region. The leaf area index (*LAI*) declined with increasing grazing intensity from the un-grazed to the grazed sites in both the LC and SG regions (Table 3-1) while the lowest values were determined at the LCHG site.

3.4.2 Soil water content and soil temperature

The daily changes in soil water content affected by grazing intensity under *Leymus chinensis* and *Stipa grandis* vegetations are shown in Figure 3-2. Soil water content increased generally with increasing soil depth at all sites except for the LCWG site. A fluctuation of soil water content was obviously observed at 5 cm depth but it faded off with increasing soil depth at all sites under both vegetation types. In the LC region, soil water content was highest significantly at the LCUG79, but lowest at the LCHG ($p < 0.05$) during the growing season in 2008. In the SG region, it was always significantly greater at the SGCG site than at the SGUG79 site at a given soil depth ($p < 0.05$) during the growing season in 2009. For the two un-grazed sites but under different vegetation covers the soil water content was significantly greater ($p < 0.05$) at the SGUG79 site than at the LCUG79 in the top 20 cm in 2009.

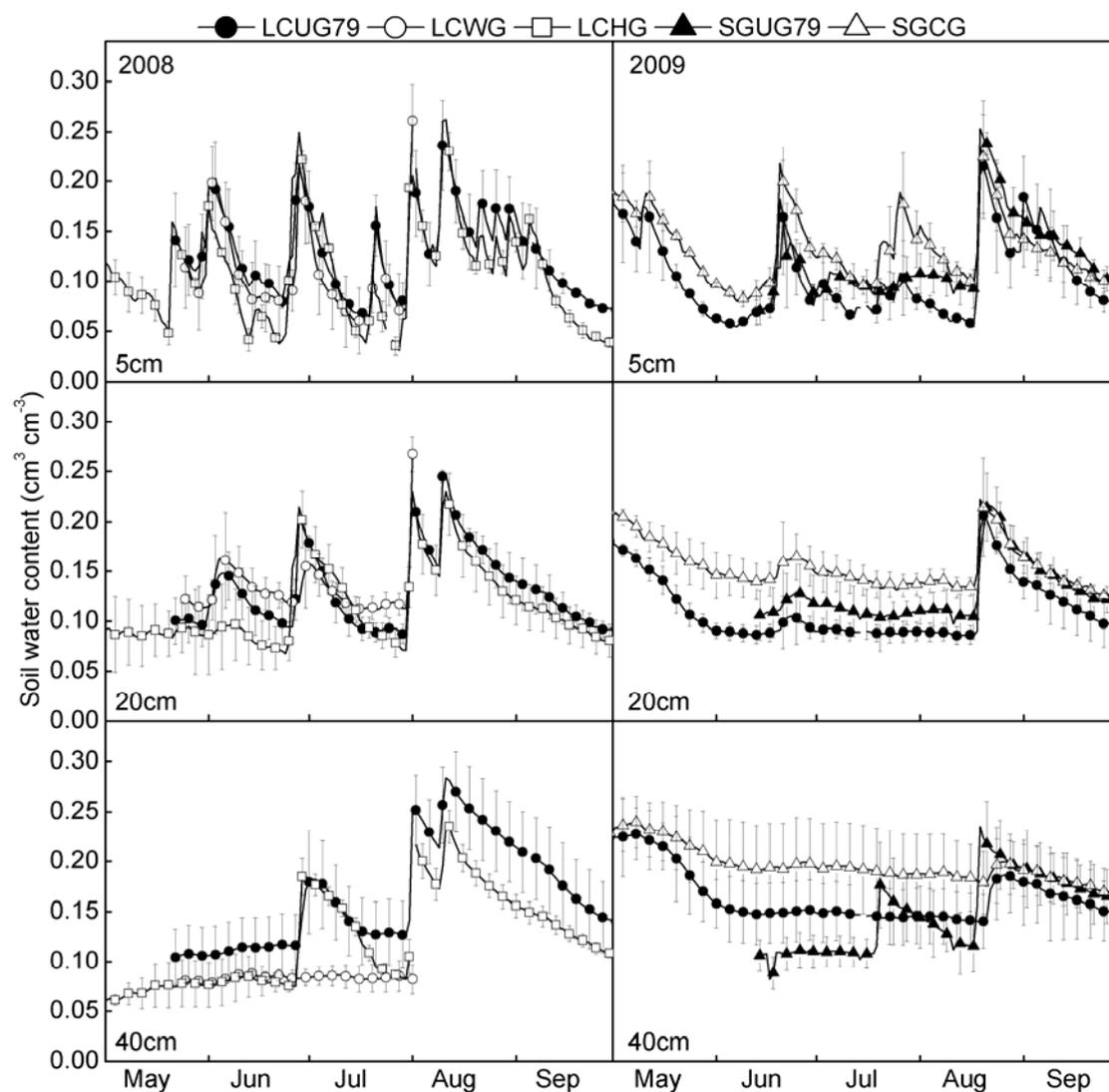


Figure 3-2: Daily changes in soil water content with different grazing intensities at 5 sites during the growing season in 2008 and in 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)

Soil temperature, similar to soil water content, decreased generally with increasing soil depth at all sites (Figure 3-3). It also presented a clear variation in the top 5 cm layer which vanished with increasing soil depth. In the LC region soil temperature was significantly higher at the LCHG site than at the LCWG site, followed by the LCUG79 site at 5 cm depth ($p < 0.05$) in 2008. However, it was not significantly different between the LCUG79 and LCWG sites at 20 cm depth, but was lowest at the LCHG site ($p < 0.05$). In the SG region a significantly higher soil temperature was observed at the SGCG site than at the SGUG79 site from 5 to 40 cm

depths in 2009 ($p < 0.05$). For the two un-grazed sites, it was always significantly higher at the SGUG79 site than at the LCUG79 site ($p < 0.05$) in 2009.

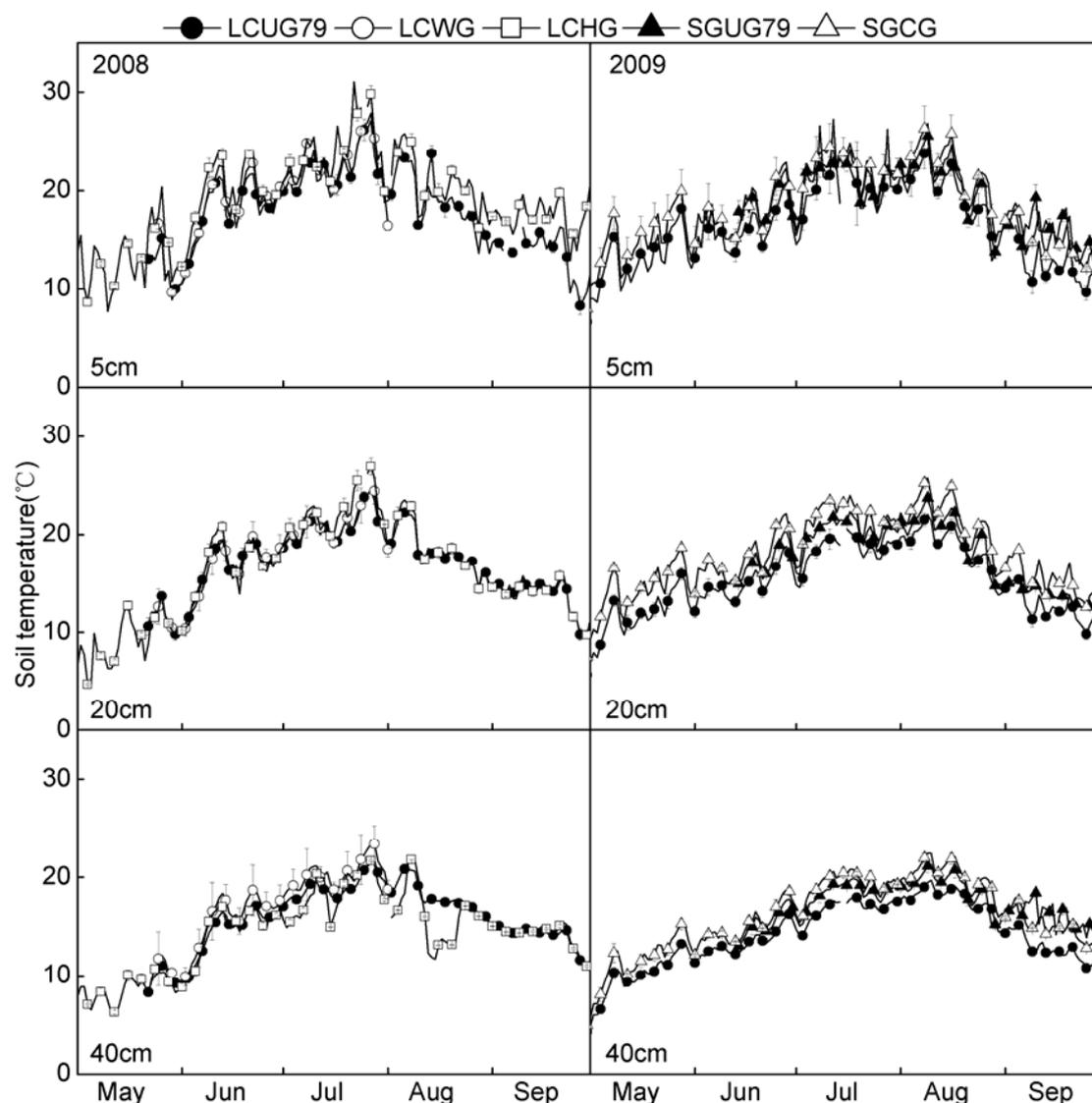


Figure 3-3: Daily changes in soil temperature with different grazing intensities at 5 sites during the growing season in 2008 and in 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)

3.4.3 Soil volumetric heat capacity

Figure 3-4 shows the daily change in soil volumetric heat capacity with different grazing intensities under *Leymus chinensis* and *Stipa grandis* vegetation. All sites showed that soil volumetric heat capacity increased generally with increasing soil depth except for LCWG, but its variation decreased. In the LC region soil volumetric

heat capacity was not significantly different between the LCUG79, LCWG and LCHG sites at the top 20 cm depth. At 40 cm depth, however, it was significantly greater at the LCUG79 site than at the LCHG site, followed by the LCWG site ($p < 0.05$) in 2008. In the SG region soil volumetric heat capacity was always significantly higher at the SGCG site than at the SGUG79 site at a given soil depth ($p < 0.05$) in 2009. Within different vegetation types, the two un-grazed sites showed greater values of soil volumetric heat capacity for the SGUG79 site than for the LCUG79 site except for 40 cm depth in 2009.

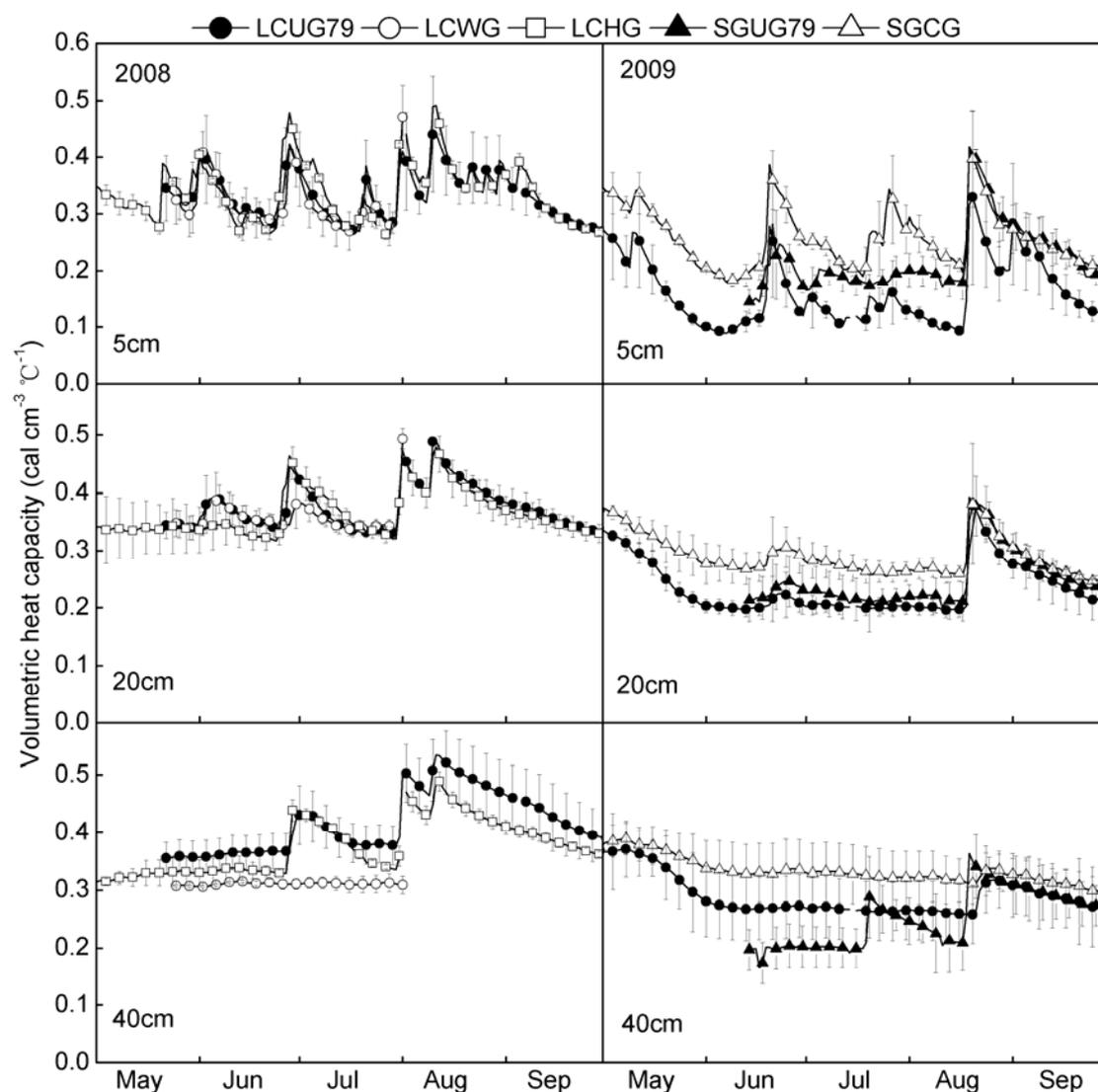


Figure 3-4: Daily changes in soil volumetric heat capacity with different grazing intensities at 5 sites during the growing season in 2008 and in 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)

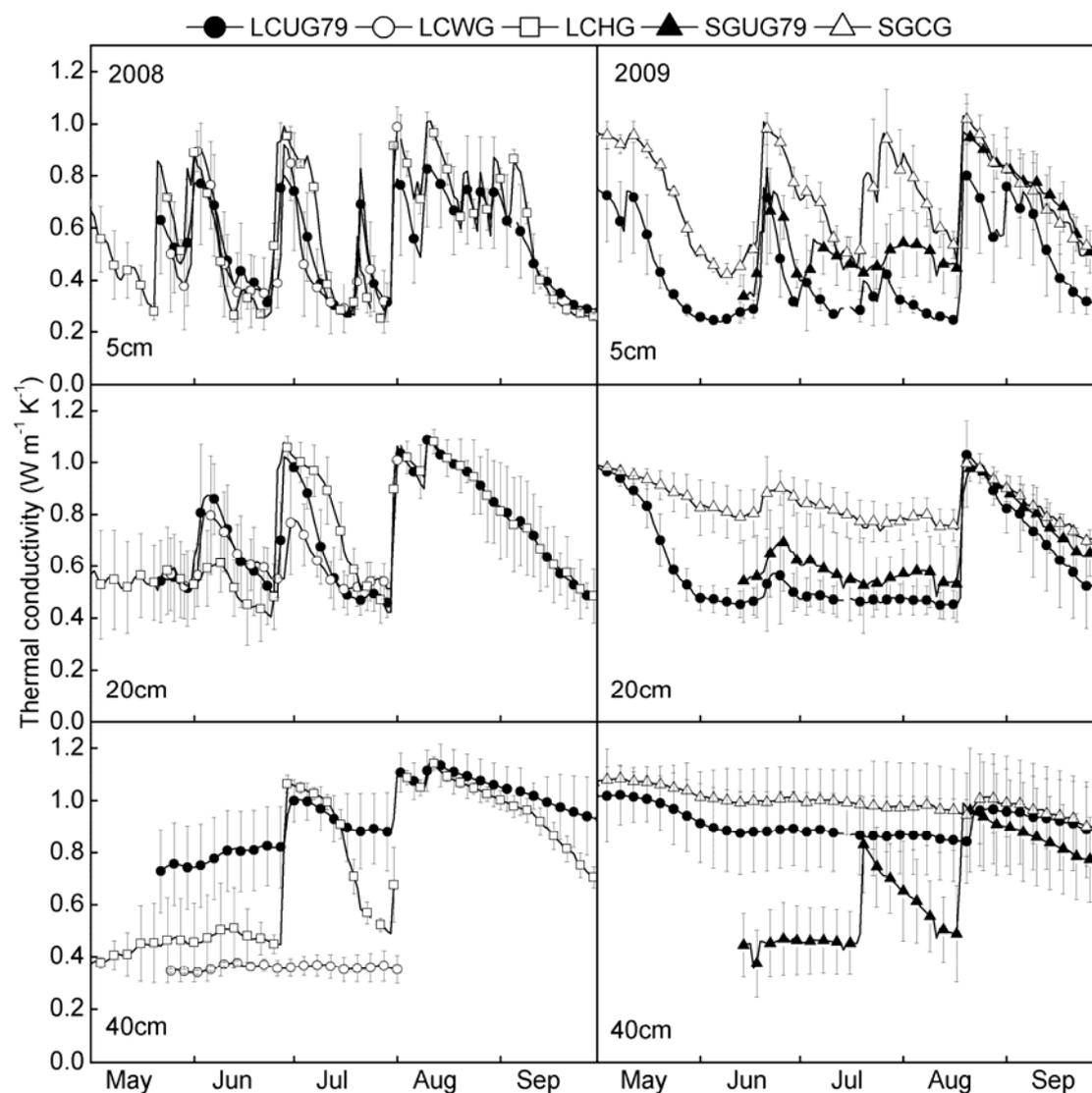


Figure 3-5: Daily changes in soil thermal conductivity with different grazing intensities at 5 sites during the growing season in 2008 and in 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)

3.4.4 Soil thermal conductivity

The daily changes in soil thermal conductivity affected by different grazing intensities under *Leymus chinensis* and *Stipa grandis* vegetations had a similar trend with soil volumetric heat capacity (Figure 3-5). The soil thermal conductivity increased generally with increasing soil depth at all sites except for the LCWG site. The variation of soil thermal conductivity was greater at 5 cm depth but decreased with increasing soil depth under both vegetations. In the LC region soil thermal conductivity was significantly greater ($p < 0.05$) at the LCHG site than at the LCUG79

and LCWG sites at 5 cm depth in 2008, but not at 20 and 40 cm depths. However, for the latter two sites, it was significantly greater ($p < 0.05$) at the LCUG79 site than at the LCWG site at 20 and 40 cm depths, whereas such obvious difference was not observed at 5 cm depth ($p > 0.05$). In the SG region soil thermal conductivity was significantly greater ($p < 0.05$) at the SGCG site than at the SGUG79 site at a given soil depth in 2009. For the two un-grazed sites soil thermal conductivity was significantly greater ($p < 0.05$) at the SGUG79 site than at the LCUG79 site for the top 20 cm, but an obviously inverse trend ($p < 0.05$) was detected at 40 cm depth in 2009.

3.4.5 Heat flux

Figure 3-6 shows the daily changes in net soil heat flux as a function of grazing intensity under *Leymus chinensis* and *Stipa grandis* vegetations for 2 depth intervals: 5–20 and 20–40 cm. A positive value indicates soil heat flux upwards while negative is downwards. In both regions the net soil heat flux generally was directed downwards

Table 3-2: Summary of total net heat flux at 5 sites during the growing season 2008 and 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively; negative value: downward flux; nd=not determined)

Year	Layer	LCUG79 W m ⁻²	LCWG W m ⁻²	LCHG W m ⁻²	SGUG79 W m ⁻²	SGCG W m ⁻²
2008	5-20 cm	-7321	-11003	-13399	nd	nd
	20-40 cm	-11073	-2699	-16558	nd	nd
2009	5-20 cm	-4988	nd	nd	-5816	-3360
	20-40 cm	-7556	nd	nd	-9116	-18794

in both layers, indicating a general heating from the upper to the lower soil layers during the growing season. Only for few cases, soil heat was transported upwards due to rainfall. The net soil heat flux fluctuated more intensively at the LCHG site than at the other two sites in the LC region. Table 3-2 informs about the total net soil heat flux during the growing season. In the LC region the most negative values were observed at the LCHG site while in the SG region it was more negative at the SGUG79 site than at the SGCG site in 5–20 cm layer in 2009. The opposite was true for 20–40 cm layer (Table 3-2). By comparing the two un-grazed sites (UG79) under different vegetations the SG site had more negative net soil heat flux than the LC site

in 2009.

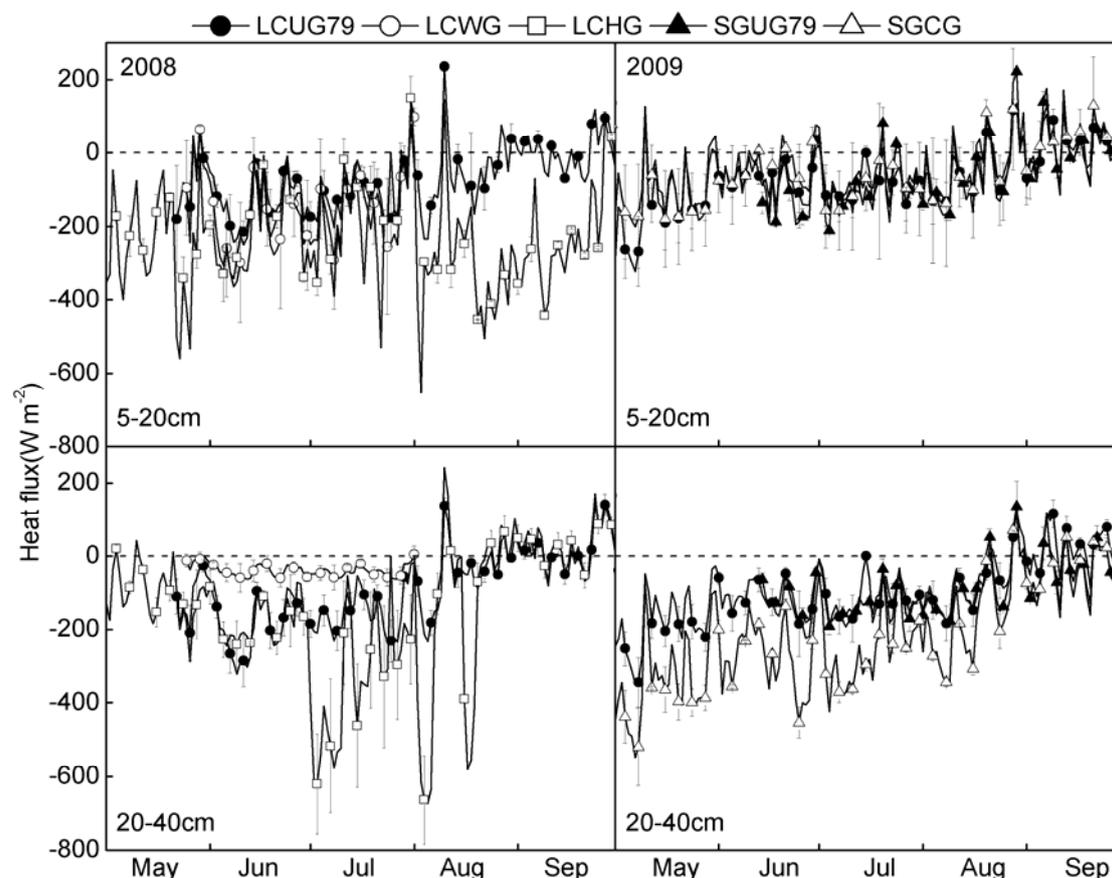


Figure 3-6: Daily changes in net soil heat flux with different grazing intensities at 5 sites during the growing season in 2008 and in 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)

The dynamic change in soil heat flux during and after rainfall events as affected by different grazing intensities revealed an intense interaction between trampling intensity and site management (Figure 3-7). Once the rain occurred, soil heat flux was directed upwards, which was faster at the LCHG site than at the LCWG and LCUG79 sites (Figure 3-7). The upward heat flux increased with increasing rain intensity. Once the rain stopped, the upward soil heat flux was reduced. The response of soil heat flux to rainfall was more sensitive at the LCHG site than at the LCWG and LCUG79 sites in the top layer. Furthermore, the change of soil heat flux was more intense at the LCHG than at the LCUG79 site, while it behaved smoothly at the LCWG site in 20–40 cm layer. Under no-rainfall condition the pattern of soil heat flux at the LCHG site depended strongly on air temperature that the maximum and minimum of the flux

occurred at the same time related to those of air temperature, respectively. However, at the LCUG79 and LCWC sites the pattern of soil heat flux was delayed as compared with air temperature. In 20–40 cm layer the coincidence was less obvious. Soil heat flux reached the peak of the upward flux around 2 hours later than that of air temperature.

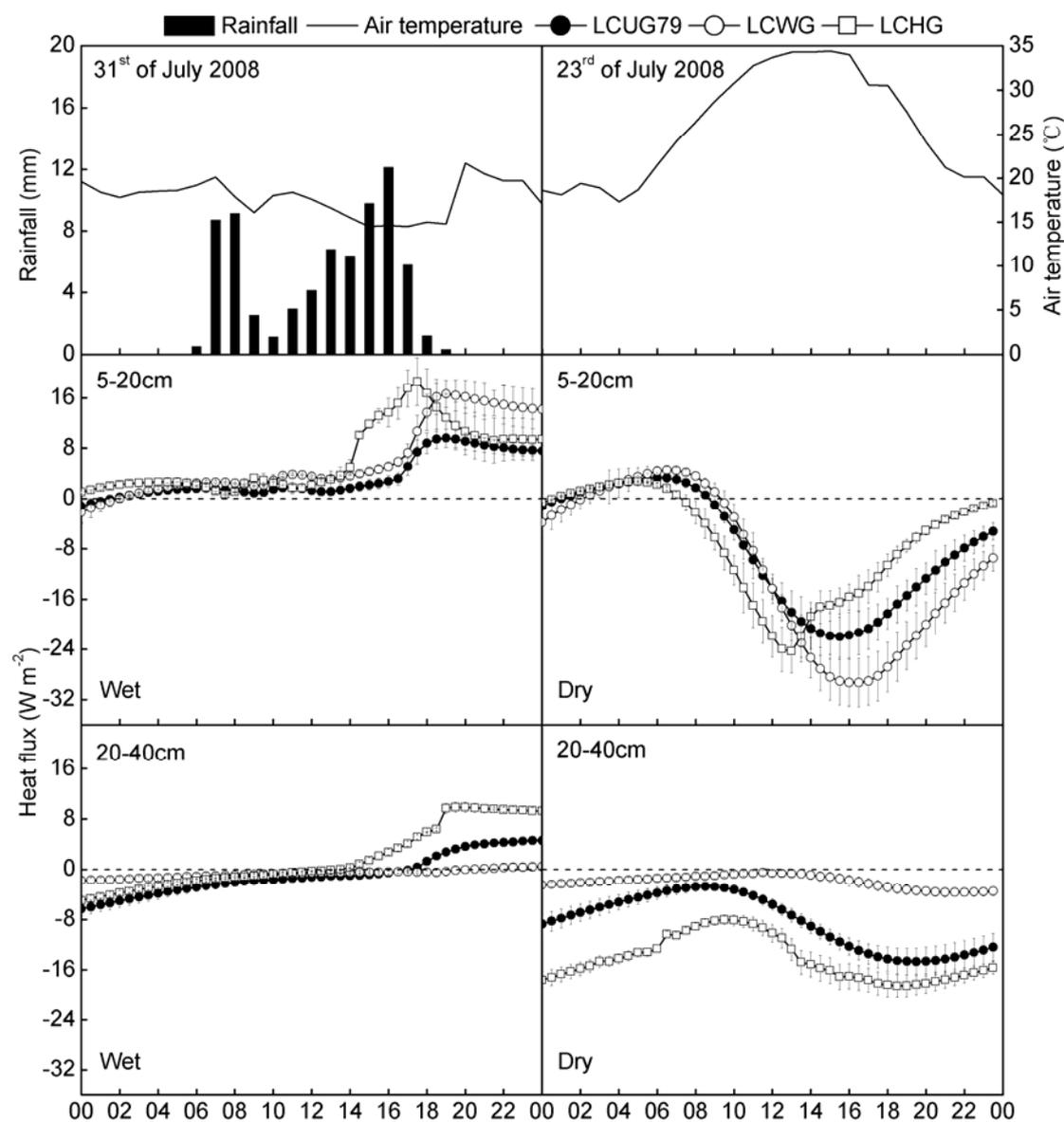


Figure 3-7: Changes in soil heat flux, rainfall and air temperature during a single day with different grazing intensities under rainfall and no-rainfall conditions (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively)

Figure 3-8 compares the effect of vegetation on soil heat flux during different weather conditions. Two cases are shown under the condition whether it is rainy or

not. The two un-grazed sites with LC and SG vegetation showed a similar pattern of soil heat flux with air temperature. But its amplitude or the sensitiveness was greater at the SGUG79 site than at the LCUG79 site under both conditions. With increasing depth down to 20–40 cm layer, soil heat flux became stable and mostly moved downwards. The difference between SGUG79 and LCUG79 sites was smaller at 20–40 cm than at 5–20 cm layer. Moreover, the short-term rain event did not change soil heat flux as much as the long-term rain did as shown in Figure 3-7.

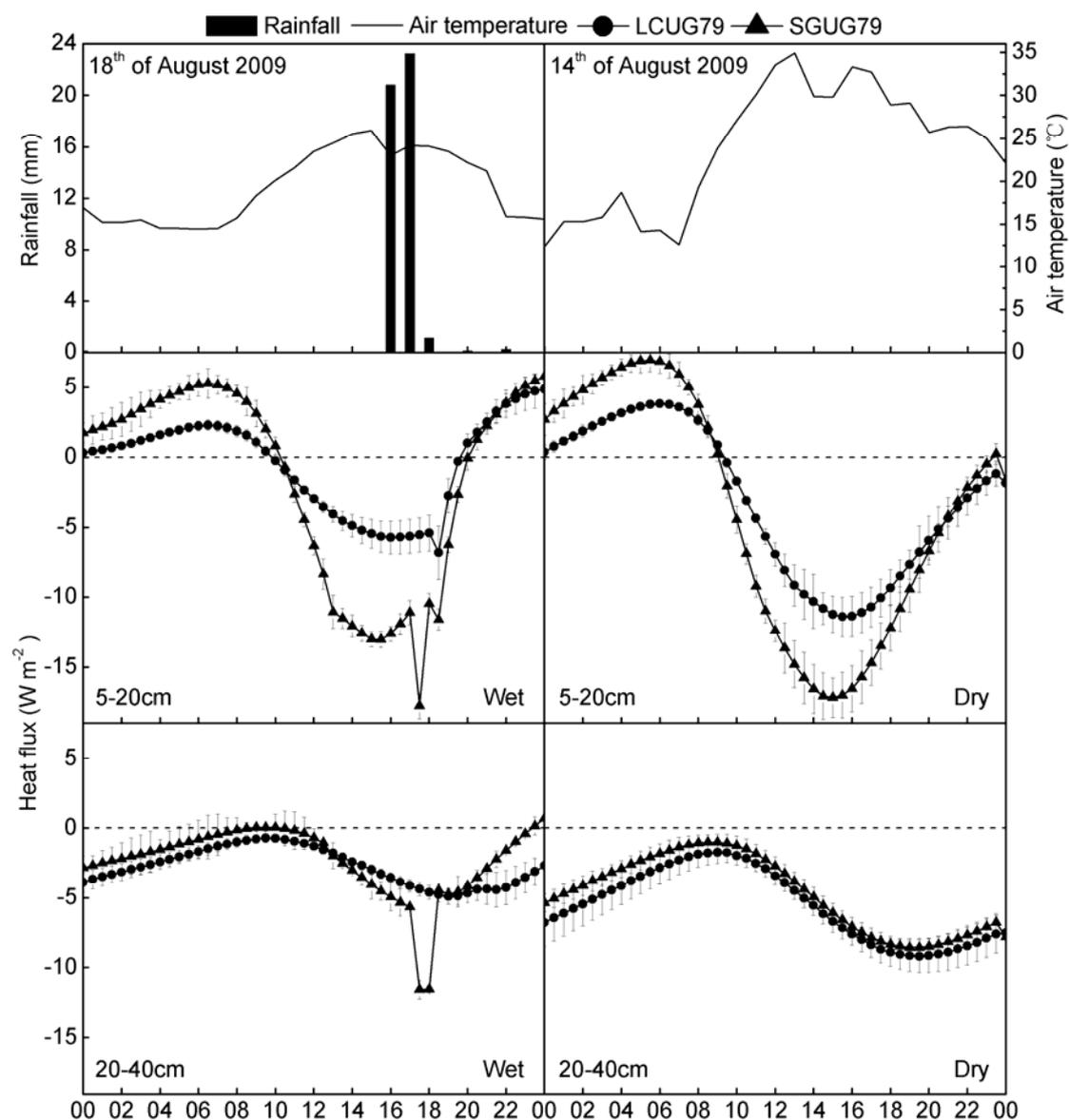


Figure 3-8: Changes in soil heat flux, rainfall and air temperature during a single day at un-grazed sites under rainfall and no-rainfall conditions for both vegetation types (LCUG79: un-grazed since 1979 under *Leymus chinensis* vegetation; SGUG79: un-grazed since 1979 under *Stipa grandis* vegetation)

3.5 Discussion

Soil thermal properties as indicated by soil volumetric heat capacity and thermal conductivity are mainly affected by soil water content (Bristow, 1998) and their spatial and temporal patterns in accordance with the changes of soil water content. Thus, soil water regime and flux is the main driver of changes in soil thermal properties and heat flux (de Vries, 1966; Dec et al., 2009; Ju et al., 2010). In this study, we focused on how soil thermal properties and heat flux were affected by grazing intensity and vegetation cover through the change of soil water content and other soil properties.

3.5.1 Effect of vegetation type on soil thermal properties

Vegetation residues are good insulators (Naeth et al., 1991; Peth and Horn, 2006) which might be a reason to depress the change in temperature in the top soil in both un-grazed sites. *Leymus chinensis* and *Stipa grandis* have distinctly different leaf form characteristics (Chen et al., 2005) as can be also proofed by a larger *LAI* (Table 3-1) at the LCUG79 site as compared to SGUG79 site. Furthermore, the plant biomass of *Leymus chinensis* with a maximum of 13.1 g pot⁻¹ was greater compared to the *Stipa grandis* peaked at 3.1 g pot⁻¹, which implies the larger vegetation cover at the LCUG79 site (Xu and Zhou, 2011). Irrespective of the relatively higher precipitation at the LCUG79 site (Reszkowska et al., 2011a), the vegetation effect at both un-grazed sites can be also derived from the smaller soil water content for the former site in the top 20 cm compared with the SGUG79 site. The higher soil water repellency at the LCUG79 site characterized by Reszkowska et al. (2011a) might retard water entry. Furthermore the larger vegetation cover at the LCUG79 site was assumed to increase the interception. As a result, these effects enhanced soil water content and increased soil volumetric heat capacity at the SGUG79 site as compared with LCUG79 site.

3.5.2 Effect of grazing intensity on thermal properties

Grazing intensity plays an important role in thermal properties through altering

soil water regime and soil properties. In the SG region, continuously grazed (SGCG) resulted in higher soil water content than un-grazed (SGUG79), which can be explained with soil deformation due to grazing. This effect can be also derived from the higher bulk density induced by grazing which is in line with Greenwood and McKenzie (2001) and Drewry (2006) who documented that the grazing increased the soil bulk density, and resulted in an increased water-holding capacity. Strong water repellency at SGUG79 (Reszkowska et al., 2011a) reduced water infiltration. On the other hand, water loss through transpiration might be higher at the un-grazed site because of more complete vegetation cover. Bremer et al. (2001) reported that grazing increased soil water content through increasing water-holding capacity resulted from the trampling induced reduction of continuous pores which may cause the delayed or reduced water recharge (Zhang and Horn, 1996a, 1996b). It is in agreement with our data of higher soil moisture and a greater soil volumetric heat capacity at the SGCG site.

In the LC region, the heavily grazed site presented the lowest soil water content. Certainly, heavy grazing has a detrimental impact on soil structure and vegetation cover (Li et al., 2000; Greenwood and McKenzie, 2001; Paruelo et al., 2001), which causes degradation of soil physical, chemical, and biological properties by decreasing plant coverage and exposing the soil to erosion by wind (Zhao et al., 2006; Pei et al., 2008). Finally the destructed soil lost water fast without the coverage protection at the given high evaporation accompanied with the small saturated hydraulic conductivity which prevented a vertical infiltration, which resulted in smaller soil moisture content at the LCHG site. It is implied that an appropriate grazing intensity of approximate 1.2 sheep units ha⁻¹ year⁻¹ at the SGCG site can be suggested and can furthermore improve the soil moisture condition in this area.

3.5.3 Effect of soil properties on thermal properties

Soil thermal conductivity, calculated with Equation 3.2 by a power function, results in a great difference as a little change of soil properties (e.g., soil water content, bulk density and texture) (Figure 3-5). As we assume that this approach is appropriate which has been applied in other researches (Bristow, 1998; Abu-Hamdeh, 2000; Šimůnek et al., 2009), we can also explain the site and management effects in more

detail. In the SG region, a higher soil water content at the SGCG site than at the SGUG79 site induced a greater thermal conductivity, which is also in agreement with the findings of Bristow (1998), who reported that the increase in soil water content enhanced the thermal conductivity. In the LC region, the soil water content was lowest at the LCHG site, although the thermal conductivity was not the smallest. The discrepancy can be explained by the coarse texture due to wind transportation of finer particles on the bare soil without the protection of coverage after heavy trampling (Shao, 2001; Huang et al., 2007; Krümmelbein et al., 2009) and high bulk density resulted from heavy grazing which increased the soil compaction by reducing soil total pore space with a reduction in large pores (Greenwood and McKenzie, 2001; Drewry, 2006) at the LCHG site. In Equation 3.2 within a power function the great constant value resulting from the high bulk density and low clay fraction highly affected the soil thermal conductivity at the LCHG site. The sand fraction generally brings about a great thermal conductivity under low soil moisture condition (Shao et al., 2006), while high bulk density increases the contact area between solid particles (Hopmans and Dane, 1986; Abu-Hamdeh and Reeder, 2000; Jury and Horton, 2004). The role of bulk density on the thermal conductivity in our study is in line with Abu-Hamdeh (2000) who found that thermal conductivity increased with increasing bulk density for two different soil types. Furthermore we can also explain this general statement by the data in 40 cm depth where slightly greater bulk density values and a very high sand fraction at the LCUG79 site contributed to a greater thermal conductivity as compared with the same depth at the SGUG79 site. So to determine thermal conductivity the soil water content, soil texture and bulk density must be taken into account together.

3.5.4 Effect of vegetation type on heat flux

The distinct differences in the morphology and photosynthetic physiology between *Stipa grandis* and *Leymus chinensis* (Du and Yang, 1988; Du et al., 1999; Cui et al., 2001) certainly resulted in the greater soil heat flux at the SGUG79 site than at the LCUG79 site which had the larger vegetation cover comparing with the former one mentioned above. It proves our hypothesis that the soil under *Stipa grandis* conducts more heat energy than the soil under *Leymus chinensis* does, which indicates the amount of soil water on the transport of heat energy is more important

for the SG vegetation type. As shown in Figure 3-8, a sharp increase of the downward soil heat flux at both un-grazed sites resulted from the immediate 46%-50% increase in the equivalent thermal conductivity at the SGUG79 site during the short-term rain, compared with the smaller proportion at the LCUG79 site (<33%). Thus, soil heat movement is more intense under the *Stipa grandis* than under the ungrazed *Leymus chinensis* vegetation.

3.5.5 Effect of grazing intensity on heat flux

During the whole growing season from May to September the soil generally got warmer at all sites as shown by the downward net soil heat flux in Figure 3-6. The increase in temperature will deplete soil water by *ET* as the major loss of soil water in the semi-arid environment. Wever et al. (2002) and Frank (2003) described that almost the complete precipitation was depleted by *ET* in northern semi-arid grasslands. Vegetation residues are good insulators (Naeth et al., 1991; Peth and Horn, 2006). Due to the heavy grazing which reduced plant coverage largely reflected on the lowest *LAI* in Table 3-1 at the LCHG site, the soil is very sensitive to the solar radiation as evidenced by a rapid change of soil temperature with air temperature at the top soil forming a great downward heat flux. Under the LC vegetation, the winter grazed site induced a higher net downward soil heat flux in 5–20 cm layer than at the un-grazed site due to less pronounced residue coverage (Table 3-1). The smaller vegetation coverage induced a faster increasing soil temperature in the top soil at the LCWG site which contributed to a more intense change in the temperature gradient as calculated by Equation 3.8. Finally the net downward soil heat flux increased compared with the LCUG79 site because of its better vegetation coverage of the latter one. However, we seem to have a different behavior in both regions because we did not find it in the SG region, where the protection of a better coverage at the SGUG79 site depressed the change in the top soil temperature, but did not reduce soil heat flux in 5–20 cm layer as compared to the SGCG site.

The argument for these differences can be given by the higher soil water content and the resulting significantly higher volumetric heat capacity at SGCG site (Figure 3-4), which kept the soil temperature change smaller as compared with the solar radiation. The soil thermal conductivity only reflects on the ability of transport the

heat, but the temperature gradient affected by solar radiation is the major force to induce the heat movement. So with the higher soil thermal conductivity at the SGCG site the change of temperature gradient was considerably smaller, which resulted in the smaller net downward heat flux compared with the SGUG79 site. It suggests that the soil water content is more beneficial to impair the net downward heat flux in this research area. Moreover, it also implies that an appropriate grazing intensity as indicated by the SGCG site (1.2 sheep units ha⁻¹ year⁻¹) could decrease the heat movement if for comparison we analyze the trends in the plots of the winter grazed (0.5 sheep units ha⁻¹ year⁻¹) and heavily grazed sites (2.0 sheep units ha⁻¹ year⁻¹) in LC region.

In generally the temperature changes considerably between day and night in Inner Mongolia, even though during growing season. The intense fluctuation of temperature during a single day caused the transition of direction in soil heat flux (Figures 3-7 and 3-8). Whether it was rainy or not, the un-grazed (LCUG79) and moderately grazed (LCWG) sites showed a time lag with air temperature. On the other hand, the heat flux at the heavily grazed site was more sensitive than at other sites. This difference might be caused by vegetation canopy and residues on the ground. Hares and Novak (1992a, 1992b) and Azooz et al. (1997) reported that the removal of residues or a bare soil conducted a rapid warming of soil and higher heat flux. This can be also proofed by our data, because the lowest vegetation canopy resulted from heavy grazing enhanced the change of temperature gradient at LCHG site which resulted in a most sensitive feedback to soil heat flux within the high thermal conductivity.

3.5.6 Management implication

Briefly, different soil thermal properties and heat flux between *Stipa grandis* and *Leymus chinensis* are observed, which is in line with our hypothesis. Grazing intensity plays an important role in soil thermal properties and heat flux through the interaction between soil structure and vegetation cover. The heavily grazed and winter grazed in the LC region induced more soil heat flux than the un-grazed site, whereas the continuously grazed in the SG region decreased soil heat flux due to higher soil water content than un-grazed site. It is suggested the continuously grazed (1.2 sheep units

ha⁻¹ year⁻¹) benefit to depress soil heat movement, while heavily grazed (2.0 sheep units ha⁻¹ year⁻¹ at the LCHG site) and slightly grazed (0.5 sheep units ha⁻¹ year⁻¹ at the LCWG site) fail, and heat flux relies much on soil moisture regime and movement. It does not proof our hypothesis that grazing enhances the heat flux compared with un-grazed. In a word, our results may provide a reference to land use management that an appropriate grazing intensity (1.2 sheep units ha⁻¹ year⁻¹) could improve the soil water and thermal regime comparing with the long-term un-grazed in this area.

3.6 Conclusions

The effect of different grazing intensities under *Leymus chinensis* and *Stipa grandis* vegetation on the soil heat regime can be concluded in the more sensitive top 20 cm layer.

Soil thermal properties increased with depth at all sites except for the LCWG site, and its variation decreased with depth. Such changes were consistent to the spatial and temporal patterns of soil water content. Under *Leymus chinensis* vegetation heavy grazing with the lowest soil moisture condition caused greater soil thermal conductivity and heat flux. The net soil heat flux of the LCWG site was greater than at the LCUG79 site, but there was no significant difference in soil volumetric heat capacity between the three sites. Under *Stipa grandis* vegetation continuously grazed (SGCG) resulted in higher soil water content, increased soil volumetric heat capacity and thermal conductivity, and the lower net soil heat flux than at the un-grazed site. It also provided a reference to land management related to an appropriate grazing intensity which could improve the soil water and thermal regimes in Inner Mongolia grassland.

The net soil heat flux was directed downwards at all sites during the growing season. As a result, it increased soil temperature but depleted soil water. Vegetation type played an important role in soil heat flux. The heat transport was greater under *Stipa grandis* vegetation than under *Leymus chinensis* vegetation at the un-grazed sites. The long-term rainfall could result in an evidently upward heat flux, but the short rainfall caused a sharp increase in downward heat flux. On a single day without

rainfall the daily maximum and minimum of soil heat flux appeared at the same time related to air temperature at the LCHG site, however, they were delayed at the other sites.

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4 MODELING GRAZING EFFECTS ON SOIL WATER BUDGET UNDER LEYMUS CHINENSIS AND STIPA GRANDIS VEGETATION IN INNER MONGOLIA, CHINA

4.1 Abstract

The improper grazing manner led to soil deterioration in Inner Mongolia grassland. To understand effects of different grazing intensities on soil water and its budget, 5 sites under two representative vegetation types: *Leymus chinensis* (LC) and *Stipa grandis* (SG) in Inner Mongolia, China were investigated: two un-grazed sites since 1979 (LCUG79 and SGUG79), a winter grazed site (LCWG, 0.5 sheep units ha⁻¹ year⁻¹) and a continuously grazed site (SGCG, 1.2 sheep units ha⁻¹ year⁻¹) defined as a moderate grazing intensity, and a heavily grazed site (LCHG, 2.0 sheep units ha⁻¹ year⁻¹). The soil, plant and meteorological data were collected to model soil water content and its budget during growing season (May to September) from 2008 to 2009 using HYDRUS-1D. Meanwhile the soil water content in 2010 was simulated with annually averaged values of initial and boundary conditions in soil and plant functions. The results showed that grazing reduced total pores and saturated hydraulic conductivity but un-grazed benefited to the natural recovery. The ratio of transpiration decreased from 71% to 47%, but the proportion of evaporation increased from 26% to 54% as increasing of grazing intensity in LC region. In SG region due to more infiltrated thawing snow and better water holding capacity at the SGCG site transpiration was greater than at the SGUG79 site in 2009. Furthermore more transpiration at the SGCG site than at the LCWG and LCHG sites suggested the adjusted grazing intensity as 1.2 sheep unit year⁻¹ ha⁻¹ is appropriate for grass growing. For two un-grazed sites the transpiration was greater in SG region. Rainfall reduced the great difference between potential and actual evapotranspiration through increasing available water. The simulation of soil water in 2010 using the annually averaged parameters was acceptable. We concluded that an appropriate grazing intensity is beneficial for sustainable development of grassland. The species *Stipa grandis* adapts to the drought environment better than *Leymus chinensis*. Rainfall

plays an important role in lessening drought stress. Lacking of located observations in desolate districts such way of simulation in 2010 provides the essential information for the decision-making of land management.

Key words: model; grazing intensity; soil water budget; evapotranspiration; land management

4.2 Introduction

The different land managements affect the water movement in the unsaturated soil through shifting the plant architecture and soil functions (Flerchinger et al., 2003). Although many quantitative studies on management effects on soil properties have been noted at various times in the literature (Hill, 1990; Cresswell et al., 1993; van Es et al., 1999 Green et al., 2003), few researches have been treated with their consequences on soil water flux and its budget (Chung and Horton, 1987; Drewry, 2006). It is necessary to quantify and predict the potential alterations to the water flow processes resulted from the change of soil hydraulic properties on the effect of different land managements such as grazing, vehicle traffic and other agriculture practices.

Desertification is the process of deterioration in ecosystems of arid and semi-arid areas resulting from interactions of climatic variations and human activities (Dregne, 1985). In Inner Mongolia grassland, China, a fast population growth and a quick land-use change happened in the past decades. The traditional extensive, semi-nomadic sheep grazing system changed to a dramatically intensified stationary livestock farming, which resulted in over-grazing and over-cropping in some areas. It is estimated by the UNEP (United Nations Environment Programme) that 60–70% of the grasslands in China are affected by deterioration and desertification mainly due to heavily grazed (Graetz, 1994). Heavily grazed accompanied with animal trampling normally has detrimental effects on soil hydraulic and mechanical properties (Greenwood and McKenzie, 2001; Reszkowska et al., 2011a). Especially in the topsoil, it results in reduction of pore volume which alters not only pore size distribution, soil water retention characteristics (Martínez and Zinck, 2004; Kutílek et al., 2006), but even more important are the changes in water and air fluxes (Willat and Pullar, 1983; Krümmelbein et al., 2006; Reszkowska et al., 2011b). Meanwhile heavily grazed also destroys the vegetation coverage, leaving the soils vulnerable to wind and water erosion (Li et al., 2000; Gao et al., 2002).

Soil water content is the most limiting factor for primary productivity in semi-arid rangelands (LeHouerou et al., 1988). Vegetation plays the very important

role in flux exchange between land surface and the atmosphere (Grace et al., 1981). A good understanding of grazing effect on soil water flux and its budget associated with the various types of cover is essential in Inner Mongolia grassland. Many arid and semi-arid types of grassland have experienced a shift in dominant vegetative composition from perennial grasses to shrubs and bare soil, a change which coincides with desertification caused by stationary livestock farming and the increase of livestock in Inner Mongolia grassland in the past four decades (Daily, 1995; Cao and Yang, 1999; Scheffer et al., 2001; Van Auken, 2000; Jackson et al., 2002). Evapotranspiration (*ET*) is a key component of water cycle in Inner Mongolia (Schneider et al., 2007). Some studies have shown that grazing can change the *ET* (Bremer et al., 2001; Chen et al., 2007), but the extent of grazing effect and the partition between evaporation and transpiration are still not clear. Furthermore the effect of vapor transport on soil water movement is rarely taken into account, which is an important part of the total water flux in arid environment although the soil surface moisture is very small (Satio et al., 2006).

Many numerical solutions have been developed to describe water and heat flow (Feddes et al., 1988; Saito et al., 2006). The various soil water models ranging from simple water balance calculation to complex ones based on Richards' equation provide the opportunity to simulate the water flow. The numerical solutions of Richards' equation usually need two essential hydraulic functions including water retention characteristics and hydraulic conductivity (Butters and Duchateau, 2002). HYDRUS-1D program which improved the Richards' equation for saturated and unsaturated water flow and Fickian-based advection dispersion equations for heat transport is compatible to simulate one-dimensional water flow in variably-saturated soils (Šimůnek et al., 2009).

The MAGIM project (Matter fluxes in grasslands of Inner Mongolia as influenced by stocking rate) was carried out in Inner Mongolia grassland to understand how sheep grazing affects water, carbon and nitrogen fluxes at various spatial and temporal scales. Under the framework of this project, we focused on modeling the soil water flow in differently grazed plots under *Leymus chinensis* and *Stipa grandis* vegetation covers. Our objectives were: i) to identify the grazing effect on soil functions and ii) quantify the water budget with different grazing intensities

under two vegetation covers in growing season using HYDRUS-1D program. The most Inner Mongolia grassland are situated in desolate district, which leads tremendous problems to investigate the long-term soil water regime because of the transportation, living circumstance, extremity weather and experiment costing. Our hypothesis was that the soil water content could be simulated using HYDRUS-1D program with the annually averaged values of initial and boundary conditions in soil, and plant functions when these dynamic values were not available in Inner Mongolia grassland.

4.3 Materials and methods

4.3.1 Study site description

The research was carried out on a long-term experiment established at the Inner Mongolia Grassland Ecosystem Research Station (IMGERS; 43°37'50"N, 116°42'18"E) situated in the Xilin River catchment, Northern China. The experiment evaluated the effect of grazing intensity on mass flux in the continental semi-arid grasslands of the Central Asian steppe ecosystem, with a dry and cold middle latitude climate (Kawamura et al., 2005). In the last two decades, the annual mean air temperature was 0.7 °C and the annual mean minimum temperature was approx -20 °C. Annual precipitation was 343 mm in which less than 5% fell as snow. More than 85% of the annual precipitation is concentrated during the growing season (May to September). The vegetation is characterized by the perennial rhizome grass *Leymus chinensis* (LC) and bunch grass *Stipa grandis* (SG) (Tong et al., 2004; Chen et al., 2005), which cover about 60% of the land area in the Xilin River catchment (Li et al., 1988). Soils were classified as Calcic Chernozems (IUSS Working Group WRB, 2006), which were developed from aeolian sediments deposited on a pleistocene basalt plateau (Wiesmeier et al., 2009). In this case study, two representative vegetation types: *Leymus chinensis* (LC) and *Stipa grandis* (SG) under different grazing intensities were investigated. In LC region the following sites were investigated: un-grazed since 1979 (LCUG79, 24 ha), grazed in winter (LCWG, 40 ha) with 0.5 sheep units ha⁻¹ year⁻¹, and heavily grazed (LCHG, 100 ha) with 2.0 sheep units ha⁻¹ year⁻¹. In SG region the following sites were investigated: un-grazed since

1979 (SGUG79, 24 ha), and continuously grazed (SGCG, 100 ha) with 1.2 sheep units $\text{ha}^{-1} \text{ year}^{-1}$. Both the LCWG and SGCG were defined as moderate grazing intensity. The distance between LC and SG regions is about 10 km.

4.3.2 Soil sampling and analyses

At each site three replicate profiles within a distance of 15 m were installed and connected to one solar powered automatic data-logger, which recorded soil water content and soil temperature at 30-min intervals. In each soil profile, soil moisture was monitored using horizontally inserted Theta-probes (Type ML2x, Delta-T Devices, Cambridge, UK) at 5, 20 and 40 cm depths. These Theta-probes were calibrated for the site-specific soil using the gravimetric method. The technical specifications of the Theta-probe defined the error with the range 0.01 to 0.05 ($\text{cm}^3 \text{ cm}^{-3}$) between 0 to 70 °C (Delta-T Devices Ltd., 1999). In winter the top soil was almost frozen at all sites, thus the limitation of Theta-probe might induce the errors of soil water content in winter so that only the data of the growing season were further analysed and presented in this study. The temperature at 2, 5, 20, 40 and 100 cm soil depths was monitored by Platinum ground temperature probes (Pt-100). The rainfall was measured by rain gauges (DECAGON DEVICES ECRN-100) at all sites. The whole study period lasted from 1st of May 2008 to 31st of July 2010. However, some probes and/or data loggers which were out of order led to be data unavailable at LCWG site in 2009 and only recorded data in June and July 2010 at both un-grazed sites and the SGCG site. The daily values of soil water content and soil temperature were averaged from every 30-min data registered in field. Before the installation of the monitors undisturbed soil samples (cylinder 100 cm^3 , $n=7$) were taken from each layer of 4–8, 18–22 and 40–44 cm depth for laboratory measurements. The basic soil properties including soil texture, bulk density, total porosity, organic matter and saturated hydraulic conductivity (K_s) were measured in the laboratory (for more detailed methods please see in Hartge and Horn, 2009). Two micrometeorological stations were installed in LC and SG regions, respectively, to record the standard observations such as precipitation, net radiation, atmospheric pressure, air temperature, relative humid, and wind speed in 2008 and 2009. The root distribution was done monthly by the soil root auger (Cobra TT motorhammer, Eijkelkamp, The Netherlands) from four layers of 0–10, 10–20, 20–50, and 50–100 cm. Meanwhile the

vegetation parameters as leaf area index (*LAI*) and plant height were also recorded. The *LAI* was measured with the leaf-area meter LI-3050 (LI-COR, Nebraska, USA).

4.3.3 Numerical modeling

HYDRUS-1D is used to simulate one-dimensional water flow, heat transport, and the movement of solutes involved in consecutive first-order decay reactions in variably-saturated soils (Šimůnek et al., 2009). This program improved the Richards' equation for saturated and unsaturated water flow and Fickian-based advection dispersion equations for heat and solute transport. The water flow equation incorporates a sink term to account for water uptake by plant roots. The heat transport equations consider the conduction and convection with flowing water (Šimůnek et al., 2009).

The modified Richards' equation 4.1 presents the variably saturated water flow above zero temperature (e.g., Saito et al., 2006).

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z} \left[(K_L + K_V) \left(\frac{\partial h}{\partial z} + \cos \beta \right) + (K_{LT} + K_{VT}) \frac{\partial T}{\partial z} \right] - S(h) \quad (4.1)$$

where h is the water pressure head (cm), θ is the total volumetric water content ($\text{cm}^3 \text{cm}^{-3}$), being the sum ($\theta = \theta_L + \theta_V$) of the volumetric liquid water content, θ_L , and the volumetric water vapor content, θ_V (both expressed in terms of equivalent water content) ($\text{cm}^3 \text{cm}^{-3}$), T is temperature (K), t is time (day), z is the spatial coordinate (cm) (positive upward), S is the sink term ($\text{cm}^3 \text{cm}^{-3} \text{day}^{-1}$), K_L is the isothermal hydraulic conductivity of the liquid phase (cm day^{-1}), K_{LT} is the thermal hydraulic conductivity of the liquid phase ($\text{cm}^2 \text{K}^{-1} \text{day}^{-1}$), K_V is the isothermal water vapor hydraulic conductivity (cm day^{-1}), K_{VT} is the thermal water vapor hydraulic conductivity ($\text{cm K}^{-1} \text{day}^{-1}$), and β is the angle between the flow direction and the vertical axis (i.e., $\beta = 0^\circ$ for vertical flow, 90° for horizontal flow, and $0^\circ < \beta < 90^\circ$ for inclined flow). Overall water flow in equation 4.1 is given as the sum of isothermal liquid flow, isothermal water vapor flow, gravitational liquid flow, thermal liquid flow, and thermal water vapor flow. Since several terms of this equation are a function of temperature, this equation should be solved simultaneously with the heat transport equation 4.4 to properly account for temporal and spatial changes in soil

temperature. The soil hydraulic properties were expressed by van Genuchten parameters (1980):

$$S_e(h) = \frac{\theta_L(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + |\alpha h|^n)^m} \quad (4.2)$$

$$K_L(h) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2 \quad (4.3)$$

where S_e is the effective saturation, θ_s and θ_r are the saturated and residual water content ($\text{cm}^3 \text{ cm}^{-3}$), respectively, α is often referred to as the air entry value or bubbling pressure, K_s is the saturated hydraulic conductivity (cm day^{-1}), and l is a pore connectivity parameter which normally is set 0.5.

When the effects of water vapor diffusion can not be neglected, the heat transport must be expanded to this form (e.g., Saito et al., 2006):

$$C_p \frac{\partial T}{\partial t} + L_0 \frac{\partial \theta_v}{\partial t} = \frac{\partial}{\partial z} \left(\lambda(\theta) \frac{\partial T}{\partial z} \right) - C_L q_L \frac{\partial T}{\partial z} - C_V q_V \frac{\partial T}{\partial z} - L_0 \frac{\partial q_V}{\partial z} \quad (4.4)$$

where L_0 is the volumetric latent heat of vaporization of liquid water (e.g., J m^{-3}), C_p is the volumetric heat capacity of bulk soil ($\text{J m}^{-3} \text{ K}^{-1}$) which is determined by the respective volumetric fraction of mineral, organic, liquid water (C_L), and vapor (C_V), q_L and q_V are the liquid water and water vapor flux density (cm day^{-1}), respectively. $\lambda(\theta)$ is the thermal conductivity ($\text{J m}^{-3} \text{ K}^{-1} \text{ day}^{-1}$) described with the following equation (Chung and Horton, 1987):

$$\lambda(\theta) = b_1 + b_2 \theta + b_3 \theta^{0.5} \quad (4.5)$$

where b_1 , b_2 , and b_3 are empirical parameters.

In our study the initial and boundary conditions should be specified at each site. Initial conditions were delivered to in terms of measured soil water content and temperatures at the beginning of the modeled period. The atmospheric boundary condition was set using the daily data of precipitation, potential evapotranspiration (ET_0), and soil surface temperature. At the bottom of the domain the soil temperature at 100 cm depth and free drainage condition were imposed. It was assumed that the water table is situated far below such domain and heat transfer occurs only by convection of liquid water and water vapor through the lower boundary. In the improved HYDRUS-1D progress the potential evapotranspiration (ET_0) and interception can be calculated. The FAO Penman-Monteith combination equation

(Monteith, 1981; Monteith and Unsworth, 1990; Šimůnek et al., 2009) was used to estimate the ET_0 . Ritchie (1972) advises that the potential evaporation and transpiration can be calculated from ET_0 by Beer's law that partitions the solar radiation component of the energy budget via interception by the canopy (for more detailed information please see in Šimůnek et al., 2009). Root water uptake was simulated using the model of Feddes et al. (1978) in which the response function of critical pressure heads in the water stress were adapted from grass (Wesseling, 1991), and adjusted to the local conditions with a value of -1500 kPa for the wilting point. Furthermore a root growth model described the root distribution was imposed to reflect dynamics of plant water, which is beneficial to partition calculated evapotranspiration (ET) into actual evaporation and transpiration. In the root growth model the maximum rooting depth was considered to be 100 cm, with the greatest root density in the upper 30 cm. The rooting depth increases linearly from 0 cm at the beginning of modeling to a maximum value at the date of harvest.

The modeling period was assigned to the growing season from 1st of May to 30th of September (153 days) during our research time. The domain of soil profile was above 100 cm depth with observations located at 2, 5, 20, 40, and 100 cm. The soil hydraulic parameters were laboratory-derived from soil cores, and then fitted by RETC software (van Genuchten et al., 1991). θ_s , θ_r , and K_s were generally fixed at the observed values. The model within these parameters was verified with the measured data for one month at the beginning of the growing season, except for the SGUG79 site setted up in 2009 which was calibrated in 2009. After those the model was applied to the whole growing season in 2008 and 2009, respectively. For simulation purpose without the measured initial and boundary conditions in soil and plant functions in 2010, the annually averaged such values from 2008 and/or 2009 were specified to the model in 2010. The meteorological data in 2010 was gotten from IMGERS which is 13 km far away from our sites. The modeling results were used in the calibration with the availably monitored data. The model efficiency was evaluated by the root mean square errors ($RMSE$):

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (P_i - Q_i)^2} \quad (4.6)$$

where N is the number of observations, and P_i and Q_i are the modeled and monitored

Table 4-1: Soil texture, bulk density (*BD*), total porosity (*TP*), soil organic matter (*SOM*) and saturated hydraulic conductivity (*K_s*) at 5 sites (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)

Site	Depth cm	Sand %	Silt %	Clay %	<i>BD</i> g cm ⁻³	<i>TP</i> %	<i>SOM</i> %	<i>K_s</i> cm day ⁻¹
LCUG79	4–8	60.9(±2.7)b	24.9(±3.7)a	14.2(±1.0)b	1.14(±0.02)c	56.9(±0.8)a	3.3	165(±113)ab
	18–22	64.4(±2.8)b	21.8(±1.2)a	13.8(±3.9)bc	1.39(±0.04)ab	47.6(±1.5)cd	1.5	133(±67)b
	40–44	78.0(±0.3)a	13.5(±1.4)c	8.5(±1.1)c	1.43(±0.03)ab	45.9(±1.2)b	1.1	72(±23)b
LCWG	4–8	51.6(±2.5)c	30.2(±2.8)a	18.2(±0.3)a	1.18(±0.02)c	55.6(±0.8)a	3.1	55(±13)b
	18–22	55.9(±2.4)b	27.1(±1.3)a	17.0(±0.1)a	1.29(±0.01)c	51.4(±0.5)a	1.6	70(±36)b
	40–44	56.2(±1.9)b	27.7(±0.3)ab	16.1(±1.6)a	1.34(±0.04)b	50.4(±0.9)a	0.8	61(±5)b
LCHG	4–8	67.9(±3.5)a	20.6(±2.9)a	11.5(±1.0)c	1.30(±0.02)b	51.0(±0.6)b	2.1	93(±18)b
	18–22	75.1(±3.6)a	14.6(±2.2)b	10.3(±1.4)c	1.42(±0.03)a	46.2(±1.3)d	1.0	93(±22)b
	40–44	71.6(±2.3)a	17.1(±1.8)bc	11.3(±0.7)c	1.45(±0.03)a	45.1(±1.2)b	0.6	79(±16)ab
SGUG79	4–8	62.3(±2.6)b	25.1(±1.9)a	12.6(±1.3)c	1.27(±0.04)b	52.0(±1.4)b	3.0	216(±62)a
	18–22	60.0(±3.2)b	26.0(±2.4)a	14.0(±0.9)b	1.33(±0.03)bc	49.8(±1.3)ab	2.2	268(±44)a
	40–44	55.6(±0.5)b	28.7(±1.5)a	15.7(±1.4)ab	1.37(±0.04)b	48.5(±1.6)a	1.6	143(±32)a
SGCG	4–8	65.5(±1.9)ab	21.4(±1.4)a	13.1(±0.5)bc	1.36(±0.01)a	48.8(±0.5)c	2.5	133(±37)ab
	18–22	62.3(±3.0)b	24.1(±3.0)a	13.6(±0.1)bc	1.35(±0.03)b	49.2(±1.1)bc	2.1	130(±31)b
	40–44	58.1(±3.8)b	27.9(±3.3)a	14.0(±0.6)b	1.44(±0.04)a	45.6(±1.5)b	1.4	112(±24)a

Different lowercase letters indicate the significant difference between sites at the same depth ($p < 0.05$)

values of soil water content, respectively.

4.4 Results

4.4.1 Basic soil properties and van Genuchten parameters

Some basic soil properties including soil texture, bulk density, total porosity, soil organic matter and saturated hydraulic conductivity are listed in Table 4-1. Soil texture was coarser at the LCHG site compared with the others, except for 40–44 cm depth at the LCUG79 site where the high sandy fraction was assumed to be resulted from a coarser parent material. Bulk density increases with soil depth expect for the LCWG site, particularly it increased with the increasing grazing intensity at top depth

Table 4-2: van Genuchten parameters (θ_r : residual water content; θ_s : saturated water content; α : reciprocal value of air entry pressure; n : the smoothness of pore size distribution and $m=1-1/n$) fitted by RETC software (R^2 : determination coefficient) from the laboratory-derived hydraulic parameters in soil cores at 5 sites (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)

Site	Depth cm	θ_r cm ³ cm ⁻³	θ_s cm ³ cm ⁻³	α	n	R^2
LCUG79	4–8	0.075	0.569	0.026	1.766	0.98
	18–22	0.086	0.476	0.019	2.199	0.98
	40–44	0.071	0.459	0.016	2.120	0.98
LCWG	4–8	0.075	0.556	0.021	1.638	0.99
	18–22	0.050	0.514	0.023	1.616	0.99
	40–44	0.079	0.504	0.014	1.742	0.98
LCHG	4–8	0.057	0.510	0.014	1.718	0.98
	18–22	0.049	0.462	0.013	2.030	0.98
	40–44	0.058	0.451	0.013	2.108	0.98
SGUG79	4–8	0.084	0.520	0.019	1.855	0.98
	18–22	0.101	0.498	0.021	1.807	0.98
	40–44	0.103	0.485	0.020	1.677	0.99
SGCG	4–8	0.097	0.488	0.015	2.113	0.99
	18–22	0.112	0.492	0.021	1.960	0.98
	40–44	0.112	0.456	0.024	1.596	0.98

in both LC and SG regions. The soil organic matter and total porosity decreased with soil depth at all sites. Furthermore the soil organic matter and saturated hydraulic conductivity were generally higher at un-grazed sites than at grazed sites. The lowest saturated hydraulic conductivity was observed at the LCWG site. The values of saturated hydraulic conductivity were generally twice as low at grazed sites than at un-grazed sites in both regions. Moreover, the saturated hydraulic conductivity was greater in SG region comparing corresponding sites in LC region.

Grazing had the effect on the van Genuchten parameters with the increasing grazing intensity (Table 4-2). The saturated soil water content (θ_s) decreased as the increasing grazing intensity at all depths in SG region, which was only observed at top depth in LC region. However the residual soil water content (θ_r) was greater at the SGCG site than the SGUG79 site at all depths, which was generally contrary in LC region. The parameter of α increased as the grazing intensity increased of in top soil.

4.4.2 Model calibration and validation

Before simulating soil water, the model calibration was done at five sites. The model accuracy with these hydraulic parameters was listed in Table 4-3. The values of

Table 4-3: Root mean square errors (*RMSE*) at 5 sites during growing season in 2008 and 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively; nd=not determined)

Site	Model calibration			Growing season in 2008			Growing season in 2009		
	5cm	20cm	40cm	5cm	20cm	40cm	5cm	20cm	40cm
LCUG79	0.019	0.007	0.003	0.042	0.022	0.052	0.039	0.022	0.050
LCWG	0.045	0.006	0.006	0.058	0.030	0.036	nd	nd	nd
LCHG	0.025	0.006	0.009	0.042	0.022	0.026	0.053	0.018	0.016
SGUG79	0.038	0.025	0.019	nd	nd	nd	0.050	0.026	0.043
SGCG	0.016	0.005	0.017	0.042	0.037	0.024	0.034	0.021	0.024

root mean square errors (*RSME*) for soil water content were less than the maximal

error ($0.05 \text{ cm}^3 \text{ cm}^{-3}$) of Theta-probe. Furthermore Figure 4-1 as an example shows the daily change of soil water content with monitored and modeled data at the SGCG site. The data generally reflected on the monitored data well at all depths. But at 5 cm depth the model overestimated a bit the effect of rainfall on soil water content.

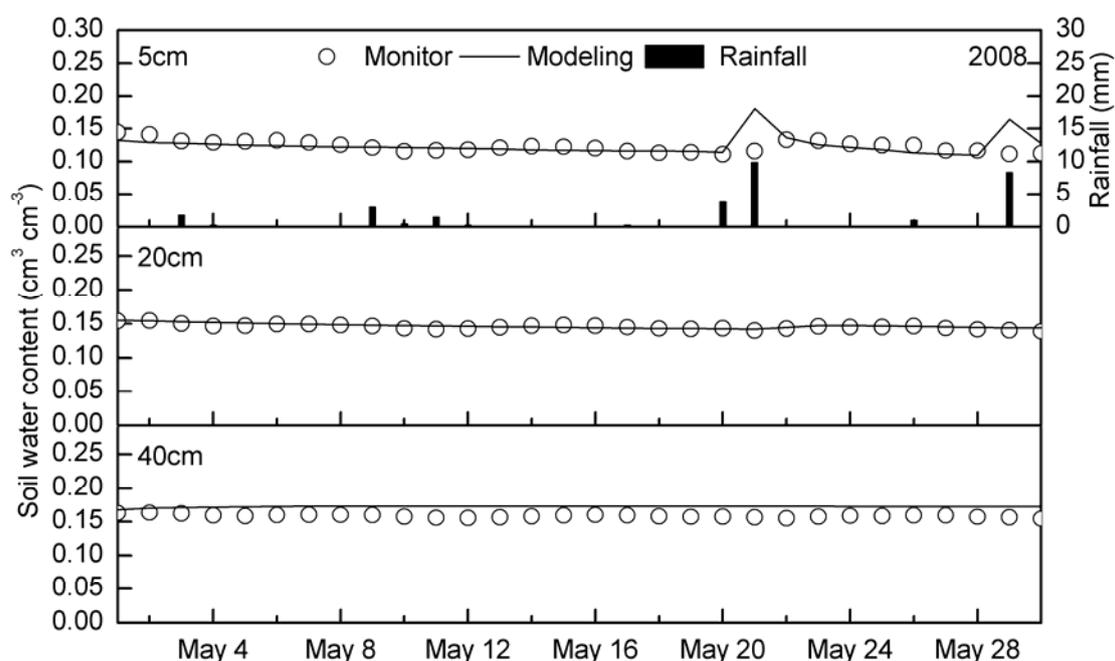


Figure 4-1: Modeling calibration for the hydraulic parameters at the SGCG site in May 2008 (SGCG: continuously grazed under *Stipa grandis* vegetation)

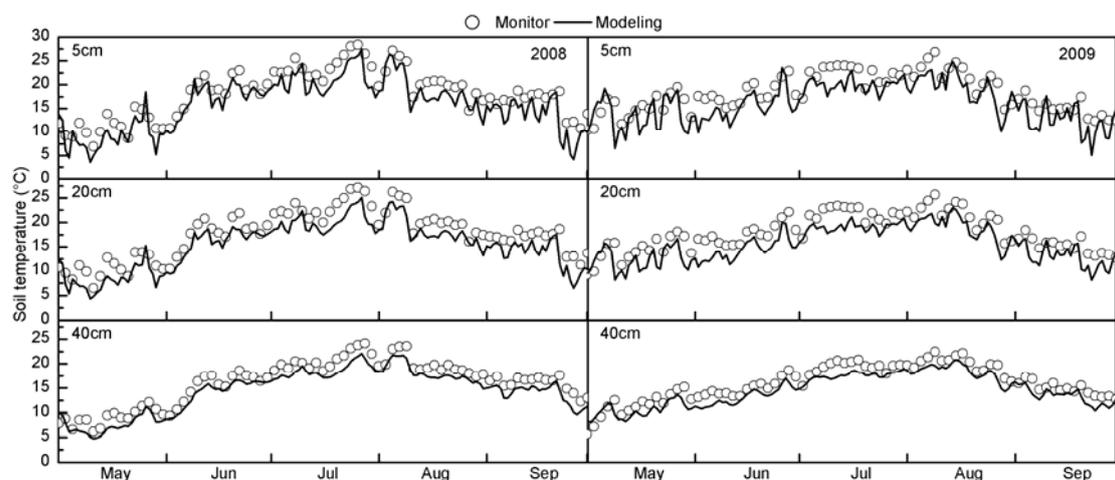


Figure 4-2: Comparison between monitored and modeled soil temperature at the SGCG site in 2008 and 2009 (SGCG: continuously grazed under *Stipa grandis* vegetation)

After model calibration the hydraulic parameters were applied to model the soil

water content and soil temperature for the two following growing seasons in 2008 and 2009, respectively. In generally the values of *RSME* for soil water content were lower than the maximal error ($0.05 \text{ cm}^3 \text{ cm}^{-3}$) of the instrument (Table 4-3). The monitored and modeled soil temperature (Figure 4-2) and soil water content (Figure 4-3) were generally in a good agreement in both growing seasons at the SGCG site as an example. For the modeled soil water content in the rainy days its increase generally reflected well on rainfall at all depth, but a bit overestimation at top soil. During the long-term drought period the modeled soil water content decreased faster than the monitored data, especially at the end of growing season in 2008.

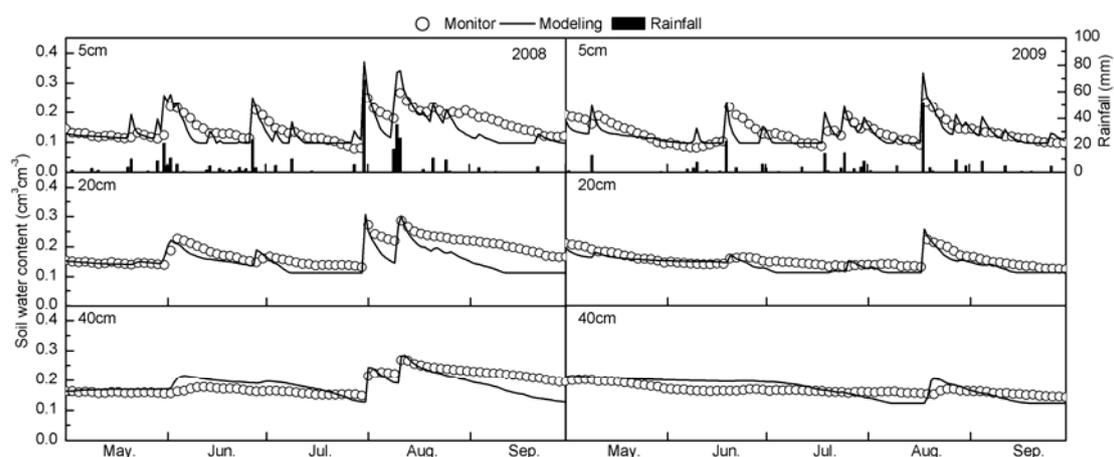


Figure 4-3: Comparison between monitored and modeled soil water content at the SGCG site in 2008 and 2009 (SGCG: continuously grazed under *Stipa grandis* vegetation)

4.4.3 Water budget

The estimated water budgets at 5 sites in growing seasons of 2008 and 2009 were listed in Table 4-4. The rainfall was more in LC region than that in SG region, and the greatest at the LCHG site in both growing seasons. Due to the difference in rainfall for each site, the following description took into account the proportion of factors to the rainfall. The proportion of interception decreased with increase in grazing intensity in LC region from 10% to 3% and in SG region from 11% to 7%. These results also showed that the most infiltrated water was consumed by *ET* during a single growing season. But there was a difference in the partition of *ET* as the

increasing grazing intensity. In LC region the proportion of transpiration decreased from 71% to 47%, but the ratio of evaporation increased from 26% to 54% as the increasing grazing intensity in two growing seasons. In SG region both of them were greater at grazed site than that at un-grazed site in 2009. Furthermore the proportion of transpiration at the SGCG site (70%–81%) was greater than that at other grazed sites (47%–67%) in LC region in both growing seasons. In growing season of 2009 the ratio of transpiration was greater at the SGUG79 site (75%) than at the LCUG79 site (71%), whereas the proportion of evaporation was a little lower at former site. In

Table 4-4: Estimated water budget components (R : rainfall; I : interception; T_p : transpiration; E_s : evaporation; FD : free drainage; SR : surface runoff; ΔS : water storage change; Error: modeled water balance errors) at 5 sites during growing seasons in 2008 and 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively; nd=not determined)

Year	Site	R mm	I mm	T_p mm	E_s mm	FD mm	SR mm	ΔS mm	Error mm
2008	LCUG79	386.1	27.1	268.6	101.8	9.2	0.7	-19.5	1.8
	LCWG	372.0	18.0	249.0	106.0	0.0	0.6	-0.2	1.4
	LCHG	392.3	10.6	167.1	168.7	55.6	5.7	-8.5	6.9
	SGUG79	nd	nd	nd	nd	nd	nd	nd	nd
	SGCG	327.0	16.7	229.0	95.0	4.3	1.5	-14.9	4.6
2009	LCUG79	253.3	26.1	180.1	92.5	9.4	1.5	-57.3	-1.0
	LCWG	nd	nd	nd	nd	nd	nd	nd	nd
	LCHG	288.9	8.9	135.6	157.3	12.1	0.6	-23.0	2.6
	SGUG79	233.0	24.6	175.6	78.9	0.3	1.6	-45.6	2.4
	SGCG	228.2	16.1	185.4	92.8	5.3	0.2	-70.8	0.8

generally the proportion of drainage was small (less than 4%) at all sites, except the LCHG site at which it was 14% in 2008. Nevertheless at grazed sites the higher drainage was observed at the LCHG site than at the SGCG site (1%), followed by at the LCWG site (under 1%) in 2008. In un-grazed sites it had a bit greater at the LCUG79 site (4%) than at the SGUG79 site (less than 1%). In our research regions the surface runoff could be neglected with such small value which was only over 1% at the LCHG site in 2008. As indicated in Table 4-5, there was a large difference between the potential evapotranspiration (ET_0) and actual evapotranspiration (ET) at

all sites during growing season in 2008 and 2009. The ratio of ET/ET_0 increased from 58% to 67% in LC region in 2008 and from 30% to 37% in SG region in 2009, respectively, as the increase of grazing intensity. In the three grazed sites the lowest ratio was observed at the SGCG site and highest at the LCHG site in two years. Nevertheless there was no difference in such ratios at two un-grazed sites in 2009. All negative values of water storage change at all sites indicated that the loss of water after a cycle of growing season, which was more in 2009 because of the less rainfall.

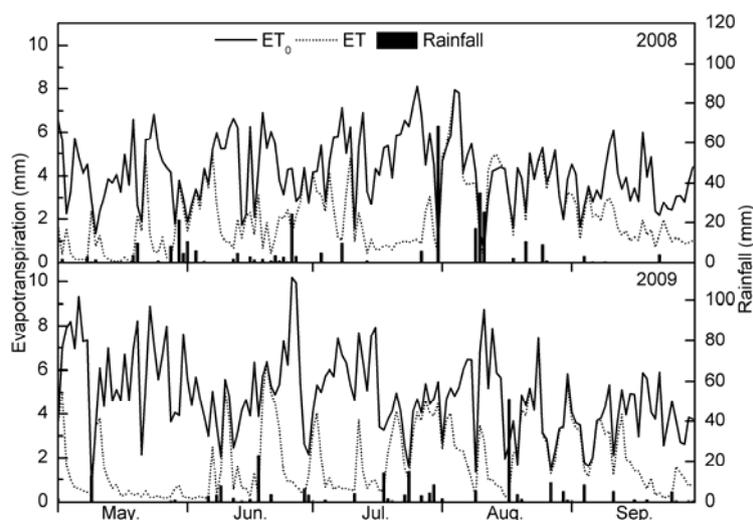


Figure 4-4: Comparison between potential and actual evapotranspiration at the SGCG site in 2008 and 2009 (SGCG: continuously grazed under *Stipa grandis* vegetation)

The modeling time of 2008 and 2009 presented the wet and dry hydrological growing seasons, respectively. The rainfall reduced around 30% in growing season from 2008 to 2009 (Table 4-4). Correspondingly, the transpiration and evaporation declined 30% and 9% at the LCUG79 site, respectively, which was greater comparing to the LCHG site (19% and 8%). Such obvious decrease in transpiration (19%) was also observed at the SGCG site. Furthermore the difference between ET_0 and ET was greater in dry year of 2009 compared with the wet year of 2008 at all sites (Table 4-5). In order to research such difference as daily change the comparison between ET_0 and ET was presented at the SGCG site in 2008 and 2009 as an example (Figure 4-4). Once the rainy events occurred both ET_0 and ET reduced, then followed by a sharp increasing process in which the value of ET even equivalent to that of ET_0 in two

years. During the dry days the ET was extremely low, and such difference was also larger in 2009 compared to the wet year of 2008.

Table 4-5: Potential evapotranspiration (ET_0) and actual evapotranspiration (ET) at 5 sites during growing season in 2008 and 2009 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively; nd=not determined)

Year	Evapotranspiration	LCUG79 mm	LCWG mm	LCHG mm	SGUG79 mm	SGCG mm
2008	ET_0	639.3	577.9	501.8	nd	645.3
	ET	370.4	354.3	335.8	nd	324.0
2009	ET_0	888.8	nd	530.8	838.2	745.1
	ET	272.6	nd	292.9	254.5	278.2

4.4.4 Simulation of soil water content in 2010

The soil water content was simulated at all available sites in growing season 2010 using the annually averaged values of initial and boundary conditions in soil and plant functions. Because only monitored data at the LCUG79, SCUG79 and SGCG sites were recorded in June and July in 2011, the simulated data was only compared to

Table 4-6: Root mean square errors ($RMSE$) of simulation at 3 sites in 2010 (LCUG79 is un-grazed since 1979 under *Leymus chinensis* vegetation; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)

Site	5(cm)	20(cm)	40(cm)
LCUG79	0.041	0.022	0.050
SGUG79	0.036	0.013	0.059
SGCG	0.033	0.013	0.043

these two months (Table 4-6). The range of $RSME$ for soil water content was from 0.013 to 0.059, which was similar to that in 2008 and 2009 (Table 4-3). Furthermore Figure 4-5 as an example shows the change of soil water content with monitored and simulated data at the SGCG site. The tendency of simulation was well identical to the monitored data. At 5 cm depth the reactions to rainfall and drought were more sensitive as mentioned above (Figure 4-3). This simulation fitted well at 20 cm depth, but overestimated a little at 40 cm depth. The results of simulated water budget (Table

4-7) using same meteorological condition from IMGERS in 2010 were also analogical with that in former two years (Table 4-4). The interception declined with the decreasing of grazing intensity. The values of drainage and surface runoff were also small, and the change of water storage was great at all sites in a dry hydrological year. The transpiration reduced, but evaporation increased as the enhanced grazing intensity at all sites. However the only difference was that the transpiration presented an inverse tendency comparing with that in 2009 in SG region.

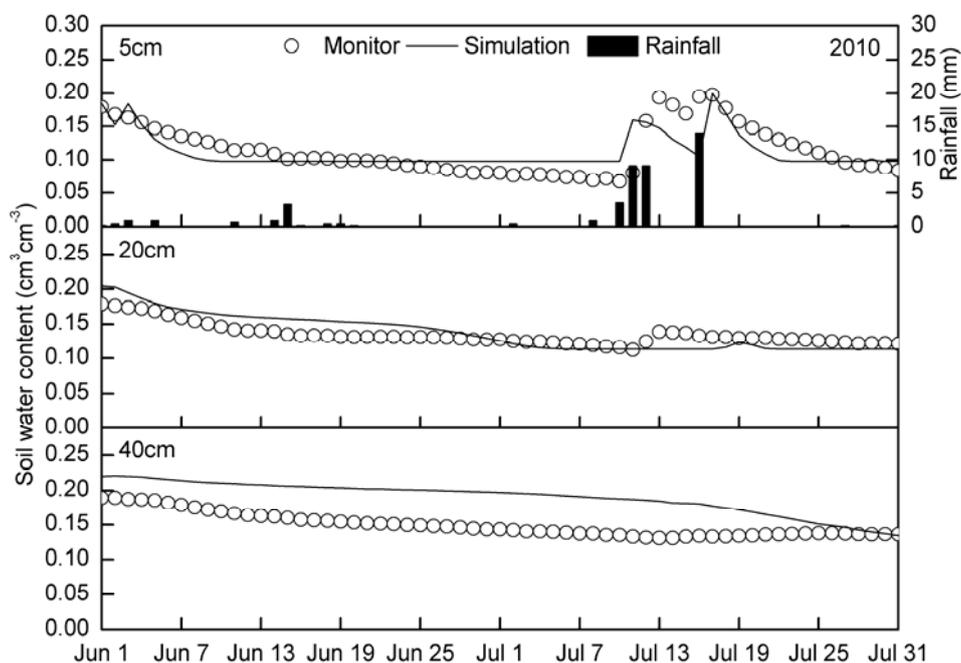


Figure 4-5: Comparison between monitored and simulated soil water content at SGCG site in 2010 (SGCG: continuously grazed under *Stipa grandis* vegetation)

Table 4-7: Simulated water budget components (R : rainfall; I : interception; T_p : transpiration; E_s : evaporation; FD : free drainage; SR : surface runoff; ΔS : water storage change; Error: modeled water balance errors) at 5 sites during growing seasons in 2010 (LCUG79, LCWG and LCHG are un-grazed since 1979, winter grazed and heavily grazed under *Leymus chinensis* vegetation, respectively; SGUG79 and SGCG are un-grazed since 1979 and continuously grazed under *Stipa grandis* vegetation, respectively)

Year	Site	R mm	I mm	T_p mm	E_s mm	FD mm	SR mm	ΔS mm	Error mm
2010	LCUG79	210.6	22.9	159.6	65.4	11.9	0.9	-49.0	1.1
	LCWG	210.6	15.5	152.5	69.6	0.0	0.1	-28.7	-1.6
	LCHG	210.6	7.1	110.2	115.3	2.7	0.3	-24.5	0.5
	SGUG79	210.6	22.7	185.9	64.8	6.5	0.8	-64.9	5.2
	SGCG	210.6	14.4	167.7	74.3	4.6	0.4	-46.9	3.9

4.5 Discussions

4.5.1 Model parameterization and validation

In order to get more accurate simulations of soil water budget, parameters including soil hydraulic properties, plant characteristics and micrometeorological conditions were improved. Neural network analyses (Schaap and Bouten, 1996; Minasny and McBratney, 2007), and the use of tables based on soil texture, bulk density, and one or two water retention points (Rawls et al., 1982; Schaap et al. 2001) might produce uncertainty estimates of the predicted hydraulic parameters (Schaap et al., 2001; Hayashi et al., 2006; Ghanbarian-Alavijeh et al., 2010). Consequently the measurements of saturated hydraulic conductivity, θ_s and θ_r which reflect the soil structural changes resulted from grazing are necessary to be adopted when process-oriented modeling techniques are used to evaluate the impact of land management (Hayashi et al., 2006; Ghanbarian-Alavijeh et al., 2010). In the model of Feddes et al. (1978) used to predict the root water uptake, the water stress was adjusted to the local conditions with a value of -1500 kPa for the wilting point of grass (Wesseling, 1991). A root growth model described the root distribution was imposed to reflect dynamics of plant water, which is beneficial to partition evapotranspiration comparing with other models. In the former version of HYDRUS-1D, both potential evapotranspiration (ET_0) and interception can not be calculated. For example the interception should be estimated by model SHAW (Flerchinger and Saxton, 1989), which might induce uncertainty estimates of water budget due to difference in mechanisms between different models. However in the improved HYDRUS-1D progress, both them are able to be estimated (Šimůnek et al., 2009). After the model parameterization, there was a good matching between measured and simulated soil moisture and temperature at each site, especially at top 20 cm depth, which indicated that HYDRUS-1D progress was an appropriate code to estimate the soil water and temperature under the impact of different land

management.

4.5.2 Effect of grazing on pore size distribution and saturated hydraulic conductivity

Soil deformation due to animal trampling always includes soil compaction but even more essential soil shearing which finally results in a complete change of the pore systems and pore functioning. The more intense the trampling is, the more pronounced the changes result in a change in the pore distribution and absolute volume. The van Genuchten parameters (Table 4-2) represented the water retention characteristics also reflected the pore size distribution well at different sites. The saturated and residual water content indicated the fraction of total and fine pores, respectively. As the increase in grazing intensity the more animal trampling induced the lower fraction of total pores (smaller saturated water content) in top soil at grazed sites than at un-grazed sites in both LC and SG regions, which is agreement with Villamil et al. (2001) proofed a change of water retention characteristics by grazing for a southern Caldenal soil in Argentina. However the more fine pores (residual water content) indicates the better water-holding capacity at continuously grazed site (1.2 sheep units year⁻¹ ha⁻¹) comparing to un-grazed site in SG region, which is in line with Bremer et al. (2001) who reported that grazing increased water-holding capacity. Such phenomenon was not observed at winter grazed (0.5 sheep units year⁻¹ ha⁻¹) and heavily grazed (2.0 sheep units year⁻¹ ha⁻¹) sites in LC region. It may be suggested that the adjusted grazing intensity as 1.2 sheep units year⁻¹ ha⁻¹ contributed to the better water-holding capacity. The decreasing saturated hydraulic conductivity as the increase of grazing intensity in both LC and SG regions results from the cost of total pores by grazing or the improved pore continuity without grazing over 30 years. Proffitt et al. (1995) and Drewry (2006) stated that the natural recovery of soil physical properties without or reduced animal trampling. The lowest saturated hydraulic conductivity at the LCWG site might be related to a platy soil structure caused by animal trampling (Krümmelbein et al., 2006). Furthermore the higher

saturated hydraulic conductivity at the SGCG site than at the LCWG site may also proved the grazing intensity with 1.2 sheep unit year⁻¹ ha⁻¹ is an appropriate grazing intensity in our research area.

4.5.3 Effect of grazing on modeling soil water budget under different vegetation types

As the increasing grazing intensity the vegetation cover was reduced, which resulted in the less interception at grazed sites (Neath and Chanakyk, 1995), furthermore the different partition of evapotranspiration. At the LCHG site the almost bare soil caused by heavily grazed induced the greatest evaporation but smallest transpiration in LC region. Gao et al. (2008) reported that the heavily grazed induced the lowest live root biomass and belowground net primary productivity in this area. Meanwhile with the destructive structure and fewest vegetation resulted from heavily grazed (Li et al., 2000; Greenwood and McKenzie, 2001; Paruelo et al., 2001) the surplus water was not stored in the root zone, while consumed by evaporation (Donkor et al., 2006) or formed drainage (He et al., 2010), especially in wet hydrological growing season of 2008 (Table 4-4). The good vegetation cover contributed to the highest transpiration while lowest evaporation at un-grazed site in LC region. However the greater transpiration at the SGCG site may result from the more available water for grass growing in 2009. Firstly the more accumulative snow in winter 2008 brought more infiltrated water at the SGCG site, which heightened the initial moisture condition at the beginning of growing season (Naeth and Chanasyk, 1995), otherwise the greater water repellency at the SGUG79 site (Reszkowska et al., 2011a) impeded water infiltrating. Secondly the better water-holding capacity at the SGCG site (Gan et al., 2012b) provided more water for grass growing in dry days. Nevertheless it was assumed that the initial moisture condition was not improved much at the beginning of growing season in 2010 without such heavy snow in winter 2009 as a result it induced the lower transpiration at the SGCG site than that at the SGUG79 site in 2010. It may be also implied that the thawing snow at the beginning

of growing season has the important influence on the grass growing during the whole growing period (Naeth and Chanasyk, 1995). Anyway the grazing at the SGCG site reduced partly vegetation cover, which caused the greater evaporation comparing with the SGUG79 site. In both un-grazed sites the greater transpiration at the SGUG79 site also resulted from the better soil condition caused by increase in water infiltration from less water repellency (Reszkowska et al., 2011a) and greater saturated hydraulic conductivity comparing to the LCUG79 site, which can supply more water in dry days. Chen et al. (2005) also documented that the *Stipa grandis* can endure the dry condition better than *Leymus chinensis* in Inner Mongolia grassland. Furthermore the coarser texture in deeper soil at the LCUG79 site brought about more drainage which also minified the available water comparing to the SGUG79 site. The higher transpiration at the SGCG site than at the LCWG site also resulted from the better water-holding capacity which offered more water at former site. It may suggest that the continuously grazed ($1.2 \text{ sheep units year}^{-1} \text{ ha}^{-1}$) benefits to the grass growing than the winter grazed ($0.5 \text{ sheep units year}^{-1} \text{ ha}^{-1}$).

Rainfall also plays a key role in grass growing in Inner Mongolia grassland. Most studies documented that all precipitation was almost consumed by evapotranspiration (ET) and the water supply limited ET in steppe ecosystems (Wever et al., 2002; Frank, 2003). The ratio of evapotranspiration/precipitation is also greater than 1.0 in our research area (Miao et al., 2009). The decreasing ET at all sites from wet growing season in 2008 to dry period in 2009 presents that the rainfall is one of dominant factors in this area (Miao et al. 2009), which is also proved by greater difference between ET_0 and ET in 2009 which indicates that such grassland always suffers from the strong drought stress. The decrease in temperature resulted from rain events reduced the difference between the declined ET_0 and ET (Figure 4-4), while the increasing soil water content after rainfall also contributed to the sharp increase in ET . Li et al. (2007) also reported that the ET in a Mongolian stepper under grazing was highly dependent on the variability in soil water content caused by rainfall and increased with soil water content. The limited water supply in dry days restricted the

ET (Li et al., 2007) and enlarged the difference between ET_0 and ET . In order to support the consumed water by ET in dry year the more stored water was depleted in 2009 and 2010 (Naeth and Chanasyk 1995) comparing with the wet year of 2008 (Tables 4-4 and 4-7).

4.5.4 Simulation and land management implication

The long-term measurement of soil water regime in situ is expensive in such widest landscape in Inner Mongolia consideration of the socioeconomic aspects. Our study provided an insight into simulation of soil water content within annually averaged parameters of initial and boundary conditions in soil, and plant functions in this area. The root system is mostly assembled in the top 20 cm layer in our research area (Gao, 2007), which indicates that the activity of soil water generally occurs in this layer during growing season. Although the error existed in simulation using the annually averaged initial conditions like initial soil water content and soil temperature the simulation of top 20 cm depth fitted well as shown in Figure 4-5. The most Inner Mongolia grassland are situated in desolate district, which leads tremendous problems to investigate the long-term soil water regime because of the transportation, living circumstance, extremity weather and experiment costing. Such simulation can provide the essential information for the department of land management who can adjust the land-use manners in future in Inner Mongolia, China.

The present study also offered helpful advices to the grazing manner in our research area. Our results indicated that the rainfall was the one of the most important factors to improve the soil water condition and ET in such steppe ecosystem as an immutable essential. Taking into account the economic and social development strategy the grassland in Inner Mongolia can not be chronically protected from the grazing. So adjusting the grazing intensity is the breaking point for the sustainable development of grassland in our studied area. Heavily grazed (2.0 sheep unit year⁻¹ ha⁻¹) destroyed the soil structure and resulted in the worst soil water condition

(Greenwood and McKenzie, 2001; Martínez and Zinck, 2004; Zhao et al., 2007). Continuously grazed (1.2 sheep unit year⁻¹ ha⁻¹) led to the greater transpiration than winter grazed (0.5 sheep unit year⁻¹ ha⁻¹) indicated the more plant productivity under former grazing intensity. As mentioned above the adjusted grazing intensity 1.2 sheep unit year⁻¹ ha⁻¹ is appropriate in our research grassland considering the integrated effect on socioeconomic and environmental aspects. The pattern of simulating soil water regime under different grazing intensities can be applied to other specific grassland in Inner Mongolia to find the appropriate grazing intensity for the sustainable development of grassland.

4.6 Conclusions

Using the observed data during the growing season in 2008 and in 2009 in Inner Mongolia grassland the effect of different grazing intensities under *Leymus chinensis* and *Stipa grandis* vegetation on the calibrated soil water budget and the simulation of soil water content with annually averaged values of initial and boundary conditions in soil and plant functions by HYDRUS-1D in 2010 can be concluded as follows:

1) Under *Leymus chinensis* vegetation heavily grazed (2.0 sheep unit year⁻¹ ha⁻¹) induced the lowest water-holding capacity and transpiration but highest evaporation through increasing the bare soil. Winter grazed (0.5 sheep unit year⁻¹ ha⁻¹) decreased the transpiration but increased the evaporation comparing to un-grazed site since 1979. However under *Stipa grandis* vegetation continuously grazed (1.2 sheep unit year⁻¹ ha⁻¹) led to better water-holding capacity comparing to un-grazed site since 1979. Better initial soil water condition at the SGCG site resulted in more transpiration in 2009 than at the SGUG79 site, which implied that thawing snow at the beginning of growing season had the important influence on the grass growing. Furthermore the continuously grazed contributed into the more transpiration than heavily and winter grazed which suggested that the adjusted grazing intensity as 1.2 sheep unit year⁻¹ ha⁻¹

is appropriate in the area for the sustainable development of grassland.

2) At two un-grazed sites the great saturated hydraulic conductivity resulted from the natural recovery of soil physical properties over 30 years. The more transpiration at the SGUG79 site than at the LCUG79 site indicated that the species *Stipa grandis* adapted to the drought environment better than *Leymus chinensis* in Inner Mongolia grassland.

3) The great difference between potential and actual evapotranspiration denoted that such grassland always suffered from the strong drought stress. Rainfall played an important role in lessening the drought stress. After rainfall the more soil water was consumed by evapotranspiration to reduce such difference.

4) The simulated soil water content in 2010 was acceptable with the annually averaged values of initial and boundary conditions in soil and plant functions using HYDRUS-1D. It suggested that lacking of located observations in desolate districts such simulation would provide the essential information for the department of land management who could adjust the land-use manners in Inner Mongolia.

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5 GENERAL DISCUSSION AND CONCLUSIONS

In Inner Mongolia grassland, China, both population growth and a quick land-use change enhanced over the past decades. The traditional extensive, semi-nomadic sheep grazing system changed to a dramatically intensified stationary livestock farming, which resulted in over-grazing and over-cropping and caused soil degradation, severe soil erosion, nutrient depletion and desertification (Li et al., 2000; Su et al., 2005). So the effect of different grazing intensities on soil water and thermal regimes in Inner Mongolia grassland, China, is urgent to be understood because these insights are the prerequisite for the definition of an appropriate grazing intensity concept by also including socioeconomic and environmental aspects. Therefore our study concentrates on the impact of different grazing intensities on soil hydraulic, mechanical and thermal properties and functions, and on modeling the interaction of soil water and heat fluxes in the different soil depth under *Leymus chinensis* (LC) and *Stipa grandis* (SG) vegetation in order to define an adjusted grazing intensity for the sustainable development of Inner Mongolia grassland, China.

Effects of precipitation pattern on soil properties and functions

Precipitation is the main source for soil water content during growing season in such semi-arid environment (Miao et al., 2009; Lu et al., 2011) which always happens accompanying with the change of temperature, so the rainy or no-rainy days and patterns of precipitation should influence the changes in soil water and heat flux. Otherwise evapotranspiration (*ET*) is a major component of the terrestrial hydrological budget (Brutsaert, 1982), which depends on the availability of water and energy at a given site, and thus is site-specific (Sala et al., 1992; Li et al., 2007; Wilske et al. 2010). The *ET* rates at our sites ranged from 1.7 to 2.4 mm day⁻¹ in the observed time were relatively lower compared with that (2.1–9.5 mm day⁻¹) in other grasslands in USA where the plants with larger leaf area index (*LAI*) could get more

replenishment from precipitation (Verma et al., 1992; Weltz and Blackburn, 1995; Ham and Knapp, 1998; Dugas et al., 1999; Bremer et al., 2001). It is in line with the study by Li et al. (2007) who documented that the Mongolian steppe had lower *ET* rates than the tall grass native prairies of the USA at the similar latitude. The decreasing *ET* at all sites from wet growing season to dry period and the greater difference between potential evapotranspiration and actual evapotranspiration in dry period both proved that water was the dominant factor in our study area. Limited precipitation could cause a decrease in soil moisture and limit the refilling of dry soil, which will decrease the *ET* (Yamanaka et al., 2007; Chen et al., 2009), while the increasing soil water content after rainfall also contributed to the sharp increase in *ET* (Li et al., 2007). Welker et al. (1991), Neath and Chanakyk (1995) and Lu et al. (2011) concluded that the huge rainfall could compensate the soil storage, nevertheless the majority of summer precipitation events did not recharge soil water but instead of increasing the *ET*, which was also observed in our study that after most rainfall events in the growing season, a sharp increasing of upward net flux in 5-20 cm layer suggests the rainfall-derived increase of *ET*. As the changes in the soil water depleted by *ET*, the soil heat flux also behaved differently responding to the different rain patterns. Our results showed that the long-term rainy events resulted into obviously upward heat flux because of the increase in equivalent thermal conductivity which resulted from increasing soil water content (Bristow, 1998; Lipiec et al., 2007), and decreasing topsoil temperature as the rain persisted. It produced the upward temperature gradient as the major force to induce the heat movement (Cahill and Parlange, 1998). On the contrary the short-term rainfall produced the sharp increase of downward heat flux, which can be explained by as follows: Soil temperature could not be reduced immediately during short-term rain events to produce the upward temperature gradient.

Lu et al. (2011) pointed out that the Inner Mongolia grassland is always under water stress during most of the growing season. Rainfall could lighten the water stress to some extent, which is reflected by the less negative values of water storage change

in wet hydrological growing season of 2008. While great rainy events also increase the drainage (Lodge et al., 2003; Bird et al., 2004). He et al. (2010) stated that both lower quantity and intensity of rainfall in 2006 reduced the drainage compared with the greater rainfall in 2007 in the Northeast China, which can be found in our data between the wet hydrological growing seasons of 2008 and dry hydrological growing seasons of 2009. However the amount of thawing snow accumulated in winter and the frozen soil water were important to determine the initial soil water condition at the beginning of plant growth. Naeth et al. (1991), Naeth and Chanasyk (1995) and Chen et al. (2009) stressed the importance of snowmelt for soil water recharge in the prairie grassland. It can explain that the heavy snow in winter of 2008 induced greater initial soil water moisture and enlarged the amount of stored water, which finally provided the more soil water for plants during the dry season in the dry hydrological year of 2009.

Effects of different vegetation types on soil properties and functions

Leymus chinensis and *Stipa grandis* have differences in the morphology within distinctly different leaf form characteristics (Chen et al., 2005), and photosynthetic physiology (Du and Yang, 1988; Du et al., 1999; Cui et al., 2001). The greater leaf area index (*LAI*) and plant biomass under former vegetation (Gan et al., 2012b; Xu and Zhou, 2011) proof these statements. Such difference between two species should modify the soil water budget and heat flux.

Water distributions of cropland and grassland related to native vegetation are inconsistent due to differences in plant species (Burba and Verma, 2005). Naeth and Chanasyk (1995), Twerdoff et al. (1999) and Cubera and Moreno (2007) all documented the good vegetation coverage increased the interception, which is one of the reasons to induce the lower soil water content at the LCUG79 site compared to the SGUG79 site. The higher soil water repellency at the LCUG79 site characterized by Reszkowska et al. (2011a) might also retard the water entry. However, in both

un-grazed sites the greater proportion of transpiration at the SGUG79 site could be concluded from the better soil water condition which can supply more water in dry days. Chen et al. (2005) also documented that *Stipa grandis* can endure the dry condition better than *Leymus chinensis* in Inner Mongolia grassland. Vegetation and the residues as good insulators (Hanamean et al., 2003; Jamiyansharav et al., 2011) might be a reason to depress the increase of temperature in both un-grazed sites compared to grazed sites throughout the growing season, which may inhibit heat transfer into the soil and provide barriers to vapor flow with a higher shortwave reflectivity than most soils (Gausman et al., 1975; Horton et al., 1996; Sauer et al., 1997). Finally, soils with a large proportion of the surface covered by vegetation and the residues cover at the LCUG79 site tended to have lower heat flux, which is in agreement with Hares and Novak (1992a, 1992b) and Azooz et al. (1997) who also reported that the removal of residues or a bare soil conducted a rapid warming of soil and a higher heat flux. Meanwhile the replacement of grass with more shallow-rooted annual species also increases deep drainage which is the movement of water through the soil profile to beyond the root zone (Ridley et al., 1997; Hughes et al., 2006). Moitra et al. (1996) also declared that with good residue cover the drainage loss was reduced. Gao (2007) and Gao et al. (2008) both reported that the heavy grazing caused the shallowest root distribution, and the lowest live root biomass and belowground net primary productivity at the LCHG site. So it is one of the reasons to bring about the greatest drainage at the LCHG site, finally further decline the soil water content accompanying with increased the heat transfer at this site. The vegetation effect can be derived from the smaller soil water content and heat flux for the LCUG79 site in the top 20 cm compared with the SGUG79 site. It also proves that the differentia of morphology and photosynthetic physiology of different species behaves the difference in soil water and heat flux.

Effect of different grazing intensities on soil properties and functions

Grazing accompanied with animal trampling normally has changed the soil

hydraulic, mechanical, and chemical properties (Greenwood and McKenzie, 2001; Zhao et al., 2006; Pei et al., 2008). Furthermore with increasing animal trampling intensity, the changes in soil structure and properties indeed have further implications for the hydraulic and thermal processes.

The increase in soil bulk density is usually accompanied by reduction in porosity during the grassland desertification process (Wang et al., 2004). In our study the bulk density was greater at grazed sites than at un-grazed sites, however the total porosity was less at former sites. It is in line with Pei et al. (2008) and Li et al. (2011) who found that the soil bulk density in the surface as well as deeper soil layers was significant lower at un-grazed sites than at the overgrazed site. The higher bulk density in the grazed site presumably resulted from compaction by livestock trampling and a decrease in the belowground biomass (Su et al., 2004). In turn, excluding sheep trampling, resulted not only in the higher organic matter content at the un-grazed sites which derived mostly from a higher decay of dead plants compared to the grazed sites (Derner et al., 1997; Hoshino et al., 2009). Furthermore it also contributed to a decrease in bulk density (Horn, 2004). The increased bulk density after heavy trampling reduced soil total pore space, which resulted into a reduction in large pores (Willatt and Pullar, 1983; Greenwood and McNamara, 1992). It contributed to the increased soil thermal conductivity at the LCHG site in despite of the lowest soil moisture. The latter is true because the contact area between solid particles was increased (Abu-Hamdeh and Reeder, 2000; Jury and Horton, 2004; Lipiec et al., 2007). Furthermore, not only the total pore volume but also the pore size distribution was affected by animal treading with a most pronounced reduction in large pores (Willatt and Pullar, 1983; Greenwood and McNamara, 1992). The effect of grazing intensity also affected the van Genuchten parameters, which resulted from the total pore volume decrease, particularly under heavy grazing intensity (Krümmelbein et al., 2009). The accordant results related to the water retention characteristics have been proofed by Villamil et al. (2001), who showed a loss of total porosity and a change of pore size distribution, due to the loss of macropores and

increase of the mesopore fraction for a soil from southern Caldenal area in Argentina. Meanwhile Peth and Horn (2006) reported that the matric potential was more negative at a given soil water content at the trampled sites than at the undisturbed site. This is also in agreement with our data. With increased grazing intensity the saturated hydraulic conductivity decreased, except for winter grazed site which might be related to a platy soil structure (Krümmelbein et al., 2006). Singleton and Addison (1999) and Drewry et al. (1999) also found that the saturated hydraulic conductivity declined with increasing grazing intensity, especially in the topsoil. It can be ascribed to the increase of bulk density and decrease in pore space caused by animal trampling (Schaap et al., 2000), particularly in macropores which play the major role as conductive pathway for water flow (Schaap et al., 2000; Tuli et al., 2005).

Grazing also induced the coarser soil texture at the grazed sites, especially at the LCHG site, which is consistent with Pei et al.(2008) and Li et al.(2011) because of the stronger wind transportation of finer particles at grazed sites (Huang et al., 2007; Krümmelbein et al., 2009). In deeper depth the texture effect is caused by the originally properties in soils. With the coarse texture in deep soil at the LCUG79 site due to a coarser parent material, more drainage occurred than at LCWG site where animal trampling caused a platy soil structure (Krümmelbein et al., 2006). Flint and Childs (1986) also assessed greater soil thermal properties in deeper soil layers which were related to the soil self like higher rock fragment percentage. It is also inline with our data in 40 cm depth where slightly greater bulk density value at the LCUG79 site contributed to a greater thermal conductivity as compared with the same depth at the SGUG79 site. Therefore in deep layer, soil water and thermal regime, due to differences in the composition of the soil, can differ from those at the top layer (Dec et al., 2009).

The primary effect of grazing on plants is the reduction of herbage mass, ground cover and litter mass (Lodge et al., 2003), especially, under the heavy grazing pressure (Li et al., 2008). With increased grazing intensity, the vegetation cover was

destroyed, which is the element as a good insulator and plays an important role in determining surface thermal regime (Lu et al., 2001; Peth and Horn, 2006). It generally increases evaporative process and decrease plant interception and transpiration process in grasslands (Naeth and Chanakyk, 1995; Frank, 2003), which is reflected by our results. Meanwhile the almost bare soil without the protecting vegetation and litter increased the vulnerability to wind erosion at the LCHG site. It can be confirmed by Li et al. (2000) and Shao (2001) who stated that the long time grazing induced the reduction of the height, cover and dry weight of grass and shrub by livestock, consequently increased the soil surface which was exposed directly to wind erosion. The lowest soil organic matter at the LCHG site is also the result of the combined effect of heavily sheep trampling, and the reduced input of organic matter from the small vegetation cover (Steffens et al., 2008). As the consequence, heavy grazing exposed the soil to erosion by wind (Zhao et al., 2006; Huang et al., 2007) and resulted in the highest sensitivity to the solar radiation as evidenced by the formation of the greatest downward heat flux, which again depleted soil water by *ET* (Frank, 2003; Sun et al., 2010; Lu et al., 2011). Thus the destructed heavily grazed site lost water very fast due to the destroyed coverage protection at the given high evaporation.

The effect of grazing on soil water content could be arranged into two groups. On the one hand the decreased soil water content through grazing is attributed to soil compaction and sealing by animal trampling and reduced litter cover (Naeth et al., 1991; Donkor et al., 2006). Because grazing generally reduces the infiltration rates as trampling compacts and seals the soil surface (Donkor et al., 2006). Meanwhile grazing also reduces litter, which affects soil water through increased evaporation (Naeth et al. 1991). On the other hand increased soil water through grazing is reported due to the removal of herbage which reduced interception and evapotranspiration (*ET*) (Naeth and Chanasyk, 1995; Donkor et al., 2006). It is the reason that the large vegetation and litter biomasses under un-grazed intercepted precipitation and increase the *ET* while their absence under grazing would increase soil water (Naeth and

Chanasyk, 1995). Both cases have observed in our study: the continuously grazed site (1.2 sheep units ha⁻¹ year⁻¹ at the SGCG site) presented greater soil water content than the un-grazed site, but heavily grazed (2.0 sheep units ha⁻¹ year⁻¹ at the LCHG site) and slightly grazed (0.5 sheep units ha⁻¹ year⁻¹ at the LCWG site) failed. It was assumed that such specific grazing intensity at the SGCG site might increase the water holding capacity which induced the delayed or reduced water recharge through the reduction of continuous pores due to animal trampling (Zhang and Horn, 1996a, 1996b). Furthermore the good water holding capacity induced the greater plant transpiration at the SGCG site in 2009 comparing to the SGUG79 site. The greater water storage change at the SGCG site in 2009 also proved that more water was used by transpiration from plant biomass. It is in line with Bird et al. (2004) who documented that under upgraded pasture by not employing a higher stocking rate could increase water use through increased transpiration. On the other hand, water loss due to the strong water repellency at the SGUG79 (Reszkowska et al., 2011a) reduced water infiltration, and more interception by complete vegetation cover (Naeth and Chanasyk, 1995; Twerdoff et al., 1999; Cubera and Moreno, 2007) at the un-grazed site enhanced the difference in SG region. Finally the higher soil water content and its results of higher volumetric heat capacity at the SGCG site could keep the soil temperature change smaller as compared with the solar radiation (Radke, 1982). It is assumed that the soil water content is more beneficial to impair the heat flux under the same vegetation type. Dec et al. (2009) also stressed that soil water content was the most important factor affecting soil thermal regime.

As discussed above, grazing intensity as the land-use management is the key factor to influence the soil water and thermal regimes in this area. The soil under heavy grazing (LCHG) suffered more serious water stress than that under continuous grazing (SGCG) in the growing season as shown with the more negative soil matric potential and lower plant available water (Figures 2-5 and 2-6). Moreover, the continuous grazing could decrease the heat movement if for comparison we analyze the trends in the plots of the winter grazing (LCWG) and heavy grazing. It might

imply that the site-adjusted grazing intensity (1.2 sheep units ha⁻¹ year⁻¹) at the SGCG site could improve the soil water and thermal conditions in our study area.

Measuring and modeling limitations

The technical specification of the Theta-probe is determined to measure volumetric soil moisture above 0 °C by the well established method of responding to changes in the apparent dielectric constant which are converted into a DC voltage, virtually proportional to soil moisture content (Delta-T Devices Ltd., 1999). In Inner Mongolia, China the temperature in winter was always lower than 0 °C, which affected the accuracy of the instrument. Meanwhile the almost frozen soil at all sites reduced the liquid content of soil water, which also induced the errors of volumetric soil water content. It was reflected by the missing calculated soil matric potential in winter. It is the reason that we only analyzed the data during the growing season.

In our research the van Genuchten model was used to predict soil hydraulic parameters. Generally accurate simulation of θ_s is difficult especially for soils that contain macropores (Kosugi and Inoue, 2002), and the θ_r in the van Genuchten equation is set to zero in order to avoid the negative fitted values being obtained (Groenevelt and Grant, 2001). Such cases might produce uncertainty estimates of the predicted hydraulic parameters and also further modeling (Schaap et al., 2001; Hayashi et al., 2006; Ghanbarian-Alavijeh et al., 2010). In our modeling both of them were fixed to our measured data, while it still induced the errors in prediction of soil water content, which might be one of the reasons to underestimate the soil water content during the long-term dry period. In the improved HYDRUS-1D progress the potential evapotranspiration can be calculated (Šimůnek et al., 2009), but the partitions of plant transpiration and soil evaporation only were derived from the root water uptake and evaporation, respectively, in the Water Flow – Boundary Fluxes and Heads. It might result into some errors in the distribution of soil water budget. During the process for the simulation of soil water content using the annually averaged soil

and vegetation information by HYDRUS-1D, the modeled soil water content only fitted well in the actively top 20 cm layer in 2010, but not at 40 cm depth as the inactive layer of soil water movement with few roots (Gao, 2007). The reason for this error is not clear. It may be the integrated influence of modeling limitations mentioned above, which need further research in the future.

Conclusions

1. Heavily grazed site had a smaller soil water content compared with the un-grazed one, however, appropriate continuous grazing can improve the soil water regime. Soil moisture condition was better under *Stipa grandis* coverage than under *Leymus chinensis* coverage.
2. An appropriate continuous grazing improved the soil thermal regime, while heavy grazing and slightly winter grazing failed. The soil heat flux was greater under *Stipa grandis* coverage than under *Leymus chinensis* coverage.
3. Heavily grazing had destructive effects on the soil hydraulic properties, while during long-term un-grazing resulted in a better recovery. Different grazing intensities had the impact on the partitions of soil water budget. The distribution of soil water budget differed between *Stipa grandis* coverage and *Leymus chinensis* coverage. Within the annually averaged parameters, the improved HYDRUS-1D could be used to simulate soil water regime.

6 SUMMARY

The research was carried out on a long-term experiment established at the Inner Mongolia Grassland Ecosystem Research Station under the framework of MAGIM project (Matter fluxes in grasslands of Inner Mongolia as influenced by stocking rate). In the following the effect of different grazing intensities on soil properties, soil water regime and soil thermal regime under *Leymus chinensis* (LC) and *Stipa grandis* (SG) vegetation covers had be investigated at five sites: two un-grazed sites since 1979 (LCUG79 and SGUG79), two moderately grazed sites which were winter grazed in LC (LCWG, 0.5 sheep units ha⁻¹ year⁻¹) and continuously grazed in SG (SGCG, 1.2 sheep units ha⁻¹ year⁻¹), and one heavily grazed site (LCHG, 2.0 sheep units ha⁻¹ year⁻¹) to model the interactions and define an appropriate grazing system.

Grazing generally decreased the soil organic matter and saturated hydraulic conductivity, but increased the soil bulk density accompanying with the reduction of total porosity comparing with the un-grazed. Heavily grazed had the destructive impact on soil properties which caused the coarsest soil texture and increased the risk to wind erosion. As the consequence heavy grazing induced the lowest soil water content and highest soil heat flux. On the contrary, continuous grazing caused higher soil moisture and lower soil heat flux compared with un-grazed, which can be explained by the on site adjusted grazing intensity. At two un-grazed sites, both soil water content and heat flux were greater under SG vegetation than under LC vegetation. The net soil heat flux, generally moved downwards during the growing season at all sites, resulted into the increase of soil temperature, finally depleted the soil water. Soil thermal properties increased with depths, which was in accordance with soil moisture, but were also affected by the soil texture and bulk density. The partitions of soil water budget behaved differently as the different grazing intensities and vegetation covers. The improved model HYDRUS-1D was verified with a reasonable agreement between measured and modeled data. The simulation of soil

water in 2010 using the annually averaged parameters was acceptable, which implies that without the long-term monitor and repeated soil and plant sampling every year, the application of such simulation could provide the essential information for the department of land management

Our study showed that the rainfall, as the natural essential which can not be controlled by human, was one of the most important factors to improve the soil water and thermal conditions, and also evapotranspiration in such steppe ecosystem. So adjusting the grazing intensity is the breaking point for the sustainable development of grassland. The continuous grazing intensity at the SGCG site benefited to increase soil water content and plant transpiration, and depress soil heat movement, while heavy grazing and slight grazing fail. Taking into account the economic and social development strategy the grassland in Inner Mongolia can not be chronically protected from the grazing. To enable a sustainable agricultural system, our results provided a reference with an appropriate grazing intensity $1.2 \text{ sheep units ha}^{-1} \text{ year}^{-1}$ to land-use management in this area.

7 ZUSAMMENFASSUNG

Die vorliegenden Untersuchungen wurden im Rahmen des MAGIM Projektes als Langzeitexperiment in der „Grassland Ecosystem Research Station“ in der Inneren Mongolei durchgeführt. In der vorliegenden Arbeit wurden die Auswirkungen unterschiedlicher Beweidungsintensitäten auf Bodeneigenschaften, den Bodenwasserhaushalt sowie den Bodenwärmehaushalt auf fünf mit *Leymus chinensis* (LC) und *Stipa grandis* (SG) bewachsenen Flächen untersucht: auf zwei seit dem Jahre 1979 unbeweideten Flächen (LCUG79 und SGUG79), auf zwei moderat beweideten Flächen, im Winter beweidet und mit LC bewachsen (LCWG, 0.5 Schafeinheiten $\text{ha}^{-1} \text{a}^{-1}$) bzw. permanent beweidet und mit SG bewachsen (SGCG, 1.2 Schafeinheiten $\text{ha}^{-1} \text{a}^{-1}$) sowie eine stark beweidete Fläche (LCHG, 2.0 Schafeinheiten $\text{ha}^{-1} \text{a}^{-1}$). Aus den Ergebnissen sollen Schlussfolgerungen für eine ökologisch angepasste Beweidungsintensität gezogen werden.

Im Allgemeinen verringert die Beweidung den Anteil an organischem Bodenmaterial sowie die gesättigte hydraulische Leitfähigkeit, erhöht im Gegenzug jedoch die Lagerungsdichte einhergehend mit einem Verlust der Gesamtporosität im Vergleich zu den unbeweideten Flächen. Eine starke Beweidung wirkt sich negativ auf die Bodeneigenschaften aus, da dieser Prozess grobkörnigeres Bodensubstrat hinterlässt und dadurch die Anfälligkeit für Winderosion erhöht. Als Konsequenz konnten der niedrigste Wassergehalt und die höchste Wärmeleitung im Boden bei einer starken Beweidungsintensität ermittelt werden. Verglichen mit der unbeweideten Fläche konnte bei kontinuierlicher Beweidung eine höhere Bodenfeuchtigkeit und geringerer Wärmefluss nachgewiesen werden. Dies kann auf die Beweidungsintensität zurückgeführt werden. Auf den beiden unbeweideten Flächen war sowohl der Wassergehalt als auch der Wärmefluss unter dem Vegetationsbewuchs mit SG höher als unter dem mit LC bewachsenen Boden. Die Netto-Wärmeleitfähigkeit sank im Laufe der Wachstumsperiode auf allen Flächen,

was zu einem Temperaturanstieg führt und folglich den Bodenwassergehalt verringert. Die thermischen Bodeneigenschaften stiegen in Korrelation mit der Bodenfeuchte mit zunehmender Tiefe an, wurden jedoch ebenso durch die Bodentextur sowie die Lagerungsdichte determiniert. Die Tiefenverteilung des Bodenwassers hing ebenfalls von der Beweidungsintensität und Vegetationsbedeckung ab. Die Anwendung des Modells Hydrus-1D zeigte eine sichere Übereinstimmung zwischen gemessenen und modellierten Daten.

Unsere Untersuchungen haben gezeigt, dass natürliche Niederschlagsereignisse eine der wichtigsten Faktoren sind, um den Wasser- und Wärmehaushalt des Bodens sowie die Evapotranspiration in den Steppenökosystemen zu verbessern. Daher muss die Beweidungsintensität an die Standortbedingungen angepasst werden, um eine nachhaltige Entwicklung des Weidelandes zu gewährleisten. Die dauerhafte Beweidung auf der Fläche SGCG trägt zu einem höheren Bodenwassergehalt und erhöhter Transpiration bei und senkt die Wärmeleitfähigkeit, während dies auf Flächen mit starker oder sehr geringer Beweidung nicht der Fall ist. Unter Berücksichtigung der ökonomischen und sozialen Entwicklungsstrategie wird deutlich, dass die Weideflächen in der Inneren Mongolei z.T. sehr empfindlich auf die Beweidung reagieren. Unsere Ergebnisse deuten darauf hin, dass eine adäquate Beweidungsintensität von 1.2 Schafeinheiten $\text{ha}^{-1} \text{a}^{-1}$ möglich ist, um in diesem Gebiet eine nachhaltige Landnutzung zu gewährleisten.

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