Modeling Grazing Effects on Soil-Water Budget Under *Leymus chinensis* and *Stipa grandis* Vegetation in Inner Mongolia, China

Lei Gan,[1,2,3,4] Xinhua Peng,[3] Stephan Peth,[4] and Rainer Horn[4]

Abstract: To better understand the effects of different grazing intensities on soil-water dynamics and its budget in Inner Mongalia, China, five sites, under two representative vegetation types, *Leymus chinensis* (LC) and *Stipa grandis* (SG), were investigated: ungrazed sites since 1979, LCUG79 and SGUG79, a winter grazed site (LCWG), a continuously grazed site (SGCG) defined as a moderate grazing intensity, and a heavily grazed site (LCHG). Soil, plant, and meteorological data were collected for use in modeling soil-water content and its budget during growing seasons from 2008 to 2009 using the HYDRUS-1D. The soil-water content in 2010 was simulated using annually averaged values of initial and boundary conditions. Our results showed that grazing reduced total pores and saturated hydraulic conductivity but ungrazed sites benefited from natural recovery. Greater transpiration was observed at the SGCG site when compared with the LCWG and LCHG sites. At the two ungrazed sites, transpiration was greater in the SG region as compared with the LC region. Rainfall reduced the difference between potential and actual evapotranspiration through increasing plant-available water. The simulation of soil water in 2010 using annually averaged parameters was determined to be an acceptable alternative to actual on-site observation. Our data suggest that selection of an appropriate grazing intensity may be possible via simulation modeling for use in making land management decision, especially in the absence of on-site observations as often is the case from such remote regions.

Key Words: Evapotranspiration, grazing intensity, HYDRUS model, soil-water budget, land management

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The effect of crop residue cover and architecture on water movement in agricultural soil has been clearly demonstrated (Flerchinger et al., 2003), and although there are many studies examining the effects of various land management practices on soil properties (Hill, 1990; Cresswell et al., 1993; van Es et al., 1999; Green et al., 2003), comparatively few studies have examined their effects on soil-water flux and its budget (Chung and Horton, 1987; Drewry, 2006). Therefore, it is of value to further quantify and perhaps predict changes in soil hydraulic properties resulting from different land management practices (e.g., grazing, tillage, etc.). This is especially valuable in those regions prone to desertification, in which the deterioration of ecosystem services in arid and semiarid regions is caused in large part by human activities (Dregne, 1985). Inner Mongolian grassland of China is one such region, with rapid population growth and a quick shift of land use in the past few decades. The traditional, extensive, seminomadic sheep grazing system is rapidly evolving to a dramatically intensified stationary livestock farming system, which has in part resulted in overgrazing and overcropping in some areas. It was estimated that 60% to 70% of the grasslands in China are threatened by deterioration and desertification mainly because of heavy grazing (Graetz, 1994). Heavy grazing 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 a reduction of pore volume, alters pore size distribution (Martínez and Zinck, 2004; Kutílek et al., 2006), and, perhaps more importantly, changes water and air fluxes (Willat and Pullar, 1983; Krümmelbein et al., 2006; Reszkowska et al., 2011b). In addition, heavy grazing often destroys vegetation coverage, making the soil susceptible 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 semiarid rangelands (LeHouerou et al., 1988). Vegetation plays a very important role in flux exchange between land surface and the atmosphere (Grace et al., 1981). It is essential to better understand the effect of grazing on soil-water flux and its budget associated with the various types of cover in Inner Mongolian grassland. Changes in vegetation cover in this region are not unique because this has occurred (or is occurring) in many of the world's arid and semiarid grasslands (Daily, 1995; Jackson et al., 2002). Many of these regions have experienced a shift in dominant vegetative composition from perennial grasses to shrubs and bare soil. In the Inner Mongolian grassland, these changes coincide with desertification caused by stationary livestock farming and the increased presence of livestock during the past four decades (Cao and Yang, 1999; Scheffer et al., 2001).

Evapotranspiration (ET) is another obvious and key component of water cycle in this region (Schneider et al., 2007). Several studies have shown a clear link between grazing and 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. Such is an important component of the total water flux in arid environments, even though the soil surface moisture is very low (Saito et al., 2006).

Many models have been developed to better describe water and heat flow (Feddes et al., 1988; Saito et al., 2006). Methods

[1]College of Environmental Science and Engineering, Guilin University of Technology, Guilin, China. [2]The Guangxi Key Laboratory of Environmental Pollution Control Theory and Technology, Guilin, China. [3]State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China. [4]Institute of Plant Nutrition and Soil Science, Christian-Albrechts-University zu Kiel, Kiel, Germany.
Address for correspondence: Dr. Xinhua Peng, State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, 210008 China. E-mail: xhpeng@issas.ac.cn
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used for modeling of soil-water dynamics, ranging from basic soil-water balance calculation to more complex models based on the Richards equation, provide the opportunity to simulate water flow. Numerical solutions of the Richards equation usually need two essential hydraulic functions, water retention characteristics and hydraulic conductivity (Butters and Duchateau, 2002). The HYDRUS-1D, a public-domain Windows-based modeling environment for estimating 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 better 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* (LC) and *Stipa grandis* (SG) vegetation covers. Our objectives were to identify the effect of grazing regimes on specific soil parameters and to quantify the water budget of different grazing intensities under two vegetation covers in growing season using the HYDRUS-1D program. Most of Inner Mongolian grassland is situated in a remote region, with limited transportation, harsh living environments, and extreme weather, making on-site investigations of the long-term soil-water regimen a costly venture. 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 Mongolian grassland.

MATERIALS AND METHODS

Study Site Description

The research was carried out on a long-term experiment established at the Inner Mongolian 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 semiarid 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 mean annual temperature was 0.7°C, with the coldest and the warmest mean annual temperatures of -20°C and 30°C, respectively. Annual precipitation was 343 mm, in which less than 5% fell as snow. More than 85% of the annual precipitation occurs during the growing season (May to September). The vegetation is characterized by the perennial rhizome grass LC and bunch grass SG (Tong et al., 2004; Chen et al., 2005), covering 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 eolian sediments deposited on a Pleistocene basalt plateau (Wiesmeier et al., 2009). In this study, two representative vegetation types, LC and SG, under different grazing intensities, were investigated. In LC region, the following sites were investigated: ungrazed since 1979 (LCUG79, 24 ha), grazed in winter (LCWG, 40 ha) with 0.5 sheep U · ha^{-1} · $year^{-1}$, and heavily grazed (LCHG, 100 ha) with 2.0 sheep U · ha^{-1} · $year^{-1}$. In SG region, the following sites were investigated: ungrazed since 1979 (SGUG79, 24 ha) and continuously grazed (SGCG, 100 ha) with 1.2 sheep U · ha^{-1} · $year^{-1}$. Both the LCWG and SGCG were defined as moderate grazing intensity. The distance between LC and SG regions is about 10 km.

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 a range of 0.01 to 0.05 $cm^3 \cdot cm^{-3}$ between 0°C and 70°C (Delta-T Devices Ltd., 1999). In winter, the topsoil 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 analyzed 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 study period spanned from May 1, 2008, to July 31, 2010. However, malfunctioniong probes and/or data loggers resulted in data being unavailable at LCWG site in 2009 and the only recorded dates in June and July 2010 at both ungrazed sites and the SGCG site. Furthermore, the inability of rain gauges to record the data of snowfall resulted in missing data of heavy snowfall in winter of 2008. The daily values of soil-water content and soil temperature were averaged from every 30-min data registered in the field. Before installation of the monitors, undisturbed soil samples (cylinder, 100 cm^3, $n = 7$) were taken from each layer of 4- to 8-, 18- to 22-, and 40- to 44-cm depth for laboratory measurements (e.g., soil texture, bulk density, total porosity, organic matter, and saturated hydraulic conductivity) as described in Hartge and Horn (2009). Water retention functions were determined with a ceramic pressure plate assembly by stepwise desaturating initially saturated samples at equilibrium matric potentials of -1, -3, -6, -15, -30, and -1,500 kPa. These data were used to obtain the soil-water retention curves and to derive the van Genuchten (1980) parameters by RETC (*ret*ention *c*urve) software. Two micrometeorological stations were installed in the LC and SG regions to record the standard observations such as precipitation, net radiation, atmospheric pressure, air temperature, relative humidity, and wind speed in 2008 and 2009. The root distribution was determined monthly using a soil root auger (Cobra TT motorhammer; Eijkelkamp, the Netherlands) from four layers: 0 to 10, 10 to 20, 20 to 50, and 50 to 100 cm. Leaf area index measured with the leaf-area meter LI-3050 (LI-COR, Lincoln, Nebraska) and plant height were also recorded.

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 model modified 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 presents the variably saturated water flow above zero temperature (e.g., Saito et al., 2006).

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left[(K_L + K_V)\left(\frac{\partial h}{\partial z} + \cos\beta\right) + (K_{LT} + K_{VT})\frac{\partial T}{\partial z}\right] - S(h) \quad (1)$$

where h is the water pressure head (cm); θ is the total volumetric water content ($cm^3 \cdot cm^{-3}$); that is, 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); T is temperature (K); t is time (day); z is the spatial coordinate (cm) (positive upward); S is the sink term ($cm^3 \cdot cm^{-3} \cdot day^{-1}$); K_L is the isothermal hydraulic conductivity of the liquid phase ($cm \cdot day^{-1}$); K_{LT} is the thermal hydraulic conductivity of the liquid phase ($cm^2 \cdot K^{-1} \cdot day^{-1}$); K_V is the isothermal water vapor hydraulic conductivity ($cm \cdot day^{-1}$); K_{VT} is the thermal water vapor hydraulic conductivity ($cm \cdot K^{-1} \cdot day^{-1}$); and β is the angle between the flow direction and the vertical axis (i.e., $\beta = 0°$ for vertical flow, 90° for horizontal flow, and $0° < \beta < 90°$ for inclined flow). Overall, water flow in Eq.(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. Because several terms of this equation are a function of temperature, this equation should be solved simultaneously with the heat transport Eq.(4) to properly account for temporal and spatial changes in soil temperature. The soil hydraulic properties were expressed by van Genuchten (1980) parameters:

$$S_e(h) = \frac{\theta_L(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + |\alpha h|^n)^m} \quad (2)$$

$$K_L(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad (3)$$

where S_e is the effective saturation, and θ_s and θ_r are the saturated and residual water content ($cm^3 \cdot cm^{-3}$), respectively; α, n, and m are fitting parameters (dimensionless), and m is generally assumed to be 1 - 1/n. K_s is the saturated hydraulic conductivity ($cm \cdot day^{-1}$), and l is a pore connectivity parameter, which is set to a default value 0.5 (Mualem 1976; Šimůnek et al., 2009). In this study, the θ_s and K_s are the measured data, but θ_r, α, and n are fitted data.

When the effects of water vapor diffusion cannot be neglected, the heat transport must be expanded to Eq.(4) as follows (Saito et al., 2006):

$$C_p \frac{\partial T}{\partial t} + L_0 \frac{\partial \theta_V}{\partial t} = \frac{\partial}{\partial z}\left(\lambda(\theta)\frac{\partial T}{\partial z}\right) - C_L q_L \frac{\partial T}{\partial z} - C_V q_V \frac{\partial T}{\partial z} - L_0 \frac{\partial q_V}{\partial z} \quad (4)$$

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

$$\lambda(\theta) = b_1 + b_2\theta + b_3\theta^{0.5} \quad (5)$$

where b_1, b_2, and b_3 are empirical parameters.

In our study, the initial and boundary conditions were specified at each site. Initial conditions were determined as measured soil-water content and temperature at the beginning of the period modeled. The atmospheric boundary condition was set using the daily precipitation data, potential ET (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 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 the Beer law that partitions the solar radiation component of the energy budget *via* interception by the canopy (for more detailed information, see 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 was adapted from grass (Wesseling, 1991) and adjusted to the local conditions with a value of -1,500 kPa for the wilting point. Furthermore, a root growth model as described by the root distribution was imposed to reflect the dynamics of plant water, which is beneficial to partition calculated 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 increased 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 May 1 to September 30 (153 days) during our research period. The domain of soil profile was down to a 100-cm depth, with observations located at 2, 5, 20, 40, and finally at 100 cm. The soil hydraulic parameters were laboratory derived from soil cores and then fitted by RETC software (van Genuchten et al., 1991). In this procedure, θ_s and K_s were fixed by the measured values, but the parameters θ_r, α, and n were fitted. The model within these parameters was verified with the measured data for 1 month at the beginning of the growing season compared with the soil hydraulic parameters derived by neural network prediction tool ROSETTA based on data of soil texture and bulk density (Schaap et al., 2001), except for the SGUG79 site set up in 2009, which was calibrated in 2009. After those, the model was then applied to the whole growing season in 2008 and 2009, respectively. The soil thermal parameters were calculated from the soil-water content by Eq.(5), which means that the temperature is largely affected by soil-water content. It suggested that temperature did not need to be recalibrated. For simulation purposes without the measured initial and boundary conditions in soil and plant functions in 2010, the annually averaged values from 2008 and/or 2009 were specified to the model in 2010. The meteorological data in 2010 were obtained from IMGERS, 13 km from our study sites. The model efficiency was evaluated by the root mean square errors (RMSE):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - Q_i)^2} \quad (6)$$

where N is the number of observations, and P_i and O_i are the modeled and monitored values of soil-water content, respectively.

RESULTS

Basic Soil Properties

Some basic soil properties, including soil texture, bulk density, total porosity, soil organic matter, and saturated hydraulic conductivity, are listed in Table 1. Soil texture was coarser at

the LCHG site except for 40- to 44-cm depth at the LCUG79 site, where the high sandy fraction was assumed to have resulted from a coarser parent material. Bulk density increased with soil depth expect for the LCWG site, particularly increasing with the increasing grazing intensity at top depth in both LC and SG regions. Soil organic matter and total porosity decreased with soil depth at all sites, and the former was generally higher at ungrazed sites than at grazed sites. The saturated hydraulic conductivity was lowest at the LCWG site. The values of saturated hydraulic conductivity were generally twice as low as those observed at grazed sites than at ungrazed sites in both regions. Moreover, it was greater in SG region compared with those in corresponding sites in LC region.

Model Calibration and Validation

Before simulating soil water, the model was calibrated at five sites. In the calibration procedure, the hydraulic parameters were derived by pedotransfer functions via the neural network prediction tool ROSETTA based on soil texture and bulk density (Schaap et al., 2001) and the laboratory-derived hydraulic parameters fitted by RETC code (van Genuchten et al., 1991) previously mentioned, respectively. When these observed sites were set up, the model quality was tested by field-observed water content data in the first month of monitoring period, for example, May 2008. Only in the procedure using the fitted values by RETC were all the RMSE coded for soil-water content less than the maximal error (0.05 $cm^3 \cdot cm^{-3}$) of the Theta probe, which determined that in the following study this option was used in modeling soil-water content. The model accuracy with these hydraulic parameters is listed in Table 2. Figure 1, as an example, indicates good agreement on the daily soil-water content between the monitored and modeled data at the SGCG site along a soil profile except at 5-cm depth on raining days.

Grazing had an effect on van Genuchten parameters for the soil-water retention curve with the increasing grazing intensity (Table 3). The saturated soil-water content (θ_s), as deduced from total soil porosity, decreased as the grazing intensity increased at all depths in the SG region, but this was observed only at top depth in the LC region. The residual soil-water content (θ_r) was greater at the SGCG site than at the SGUG79 site at all depths, which was generally contrasting to soil-water content in the LC region. The parameter α increased as the grazing intensity increased in the topsoil.

After model calibration, the hydraulic parameters were applied to model the soil temperature (Fig. 2) and soil-water content (Fig. 3) for the two following growing seasons in the wet year (2008) and in the dry year (2009). In general, the RMSE for soil-water content was lower than the maximal error (0.05 $cm^3 \cdot cm^{-3}$) of the instrument (Table 2). The increase in modeled soil-water content during rainy days generally reflected rainfall well at most depths, with the exception being an overestimation at the topsoil layer. During the period of extended drought, the modeled soil-water content decreased faster than the monitored data, especially at the end of growing season in wet year of 2008.

Water Budget

The water budgets at the five sites were estimated in the growing seasons in the wet year of 2008 and in the dry year of 2009 (Table 4). The rainfall was more in the LC region than in the SG region and was greatest at the LCHG site in both growing seasons. Because of the differences in rainfall for each site, the following description takes into account the proportion of factors affected by the rainfall. The proportion of calculated interception decreased with an increase in grazing intensity from 10% to 3% in the LC region and from 11% to 7% in the SG region. These results also suggested that most of the infiltrated water was consumed by ET during a single growing season. However, the partition of ET was different between grazing intensities. In the LC region, the proportion of calculated transpiration decreased from 71% to 47%, but the ratio of calculated evaporation increased from 26% to 54% as grazing intensity

TABLE 1. Soil Texture, BD, TP, SOM, and K_s at Five Sites

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

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

LCUG79, LCWG, and LCHG are ungrazed since 1979, winter grazed, and heavily grazed under LC vegetation, respectively; SGUG79 and SGCG are ungrazed since 1979 and continuously grazed under SG vegetation, respectively.

BD: bulk density; K_s: saturated hydraulic conductivity; nd: not determined; SOM: soil organic matter; TP: total porosity.

TABLE 2. Root Mean Square Errors at Five Sites During Growing Season in 2008 and 2009

	Model Calibration			Growing Season in 2008			Growing Season in 2009		
Site	5 cm	20 cm	40 cm	5 cm	20 cm	40 cm	5 cm	20 cm	40 cm
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

LCUG79, LCWG, and LCHG are ungrazed since 1979, winter grazed, and heavily grazed under LC vegetation, respectively; SGUG79 and SGCG are ungrazed since 1979 and continuously grazed under SG vegetation, respectively.

nd: not determined.

increased in two growing seasons. In the SG region, both values were greater at the grazed site than at the ungrazed site in the dry year of 2009. Furthermore, the proportion of calculated transpiration at the SGCG site (70–81%) was greater than that at the other grazed sites (47–67%) in the LC region in both growing seasons. In growing season of 2009, the ratio of calculated transpiration was greater at the SGUG79 site (75%) than at the LCUG79 site (71%), whereas the proportion of calculated evaporation was lower at the former site. In general, the proportion of calculated drainage was less than 4% at all sites, except the LCHG site at which it was 14% in wet year of 2008. Nevertheless, at grazed sites, a higher calculated drainage was observed at the LCHG site than at the SGCG site (1%), followed by the LCWG site (<1%). At ungrazed sites, it was slightly greater at the LCUG79 site (4%) than at the SGUG79 site (<1%). In our research regions, the calculated surface runoff could be neglected with only over 1% at the LCHG site in the wet year (2008). As indicated in Table 5, there was a large difference between the calculated ET_0 and actual ET at all sites during growing season in the wet year of 2008 and in the dry year of 2009. The ratio of ET/ET_0 increased from 58% to 67% in the LC region in 2008 and from 30% to 37% in the SG region in the dry year of 2009 as the grazing intensity increased. In the three grazed sites, the lowest ratio was observed at the SGCG site and highest at the LCHG site in 2 years. However, there was no difference in these ratios at the two ungrazed sites during the same period. Negative water storage indicated the loss of water after growing season, which was more obvious in the dry year of 2009 because of the lesser rainfall.

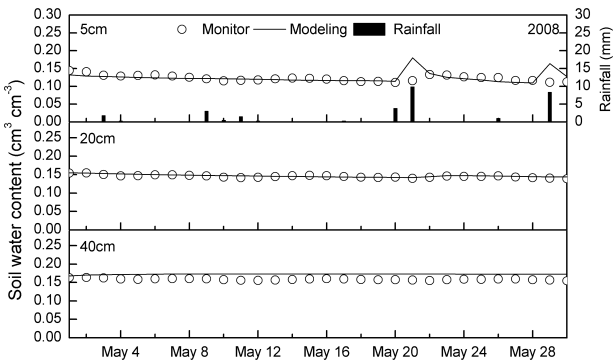

FIG. 1. Modeling calibration for the hydraulic parameters at the SGCG site in May 2008. SGCG: continuously grazed under SG vegetation.

The rainfall was reduced by approximately 30% in the growing season from the wet year of 2008 to the dry year of 2009 (Table 4). Correspondingly, the calculated transpiration and evaporation declined by 30% and 9% at the LCUG79 site, respectively, which was greater than those at the LCHG site (19% and 8%). A decrease in calculated transpiration (19%) was also observed at the SGCG site. Furthermore, the difference between ET_0 and ET was greater in the dry year of 2009 as compared with the wet year of 2008 at all sites (Table 5). To better explain the differences, ET_0 and ET are presented at the SGCG site in the wet year (2008) and the dry year (2009) as an example (Fig. 4). Once the rain events occurred, both ET_0 and ET were reduced, which was followed by a sharp increase in which the ET was even equivalent to ET_0. However, during the drying

TABLE 3. Van Genuchten Parameters Fitted by RETC Software From the Laboratory-Derived Hydraulic Parameters in Soil Cores at Five Sites

Site	Depth, cm	θ_r, $cm^3 \cdot cm^{-3}$	θ_s, $cm^3 \cdot cm^{-3}$	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

LCUG79, LCWG, and LCHG are ungrazed since 1979, winter grazed, and heavily grazed under LC vegetation, respectively; SGUG79 and SGCG are ungrazed since 1979 and continuously grazed under SG vegetation, respectively.

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 $m = 1 - 1 / n$; R^2: determination coefficient.

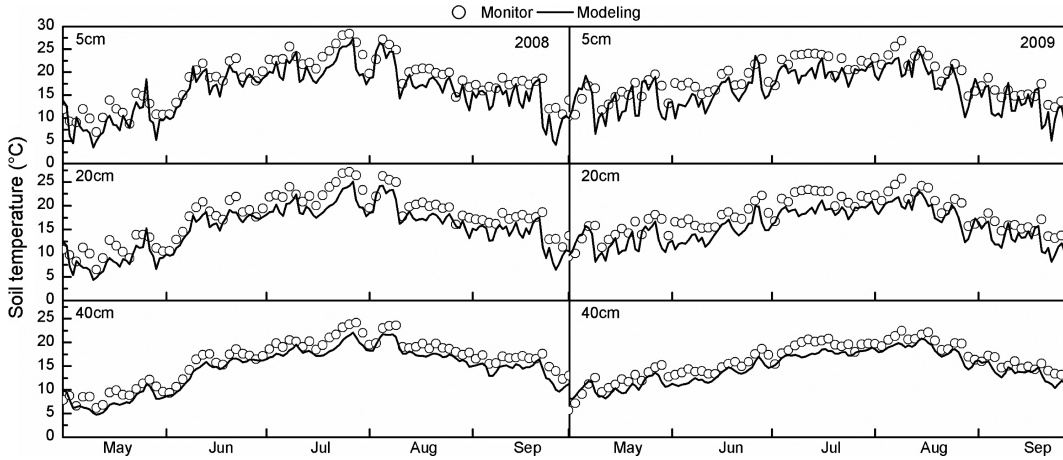

FIG. 2. Comparison between monitored and modeled soil temperature at the SGCG site in 2008 and 2009. SGCG: continuously grazed under SG vegetation.

period, the ET was very low, which was also more obvious in the dry year of 2009 than the wet year of 2008.

Simulation of Soil-Water Content in Dry Year of 2010

Precipitation was approximately 210 mm during the growing season of 2010, making it a relatively dry year. Soil-water content was simulated at all available sites in this year, 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 2010, simulated data were compared with only these same 2 months (Table 6). The RMSE for soil-water content ranged from 0.013 to 0.059. Figure 5, as an example, shows the similarities in soil-water content changes as monitored and simulated data at the SGCG site. At the 5-cm depth, the soil-water content was more sensitive to rainfall and drought as previously mentioned (Fig. 3). The simulation model also fitted the soil-water content well at the 20-cm depth, but with an overestimation at the 40-cm depth. Table 7 shows that the water budget, as simulated using the meteorological conditions from IMGERS in 2010, indicates that the calculated interception of rainfall declined with the decrease in grazing intensity. Calculated drainage and surface runoff values were also small, yet the water storage change increased at all sites in the dry year. In addition, calculated transpiration was reduced, but calculated evaporation increased as the grazing intensity increased.

DISCUSSION

Effect of Model Parameterization on Model Accuracy

During modeling calibration, the neural network analyses and the laboratory-derived hydraulic parameters fitted by RETC code were applied for use in comparing accuracy of hydraulic parameters. However, the neural network analyses, based on soil texture, bulk density, and one or two water retention points (Rawls et al., 1982; Schaap et al. 2001), may result in an inaccurate estimate of hydraulic parameters (Schaap et al., 2001; Hayashi et al., 2006; Ghanbarian-Alavijeh et al., 2010), when considering the effects of grazing intensity. Consequently, the parameters of K_s and θ_s, which reflect the soil structural changes resulting from grazing, must be incorporated in such process-oriented modeling techniques when they are used to evaluate the impact of land management practices on soil hydraulic

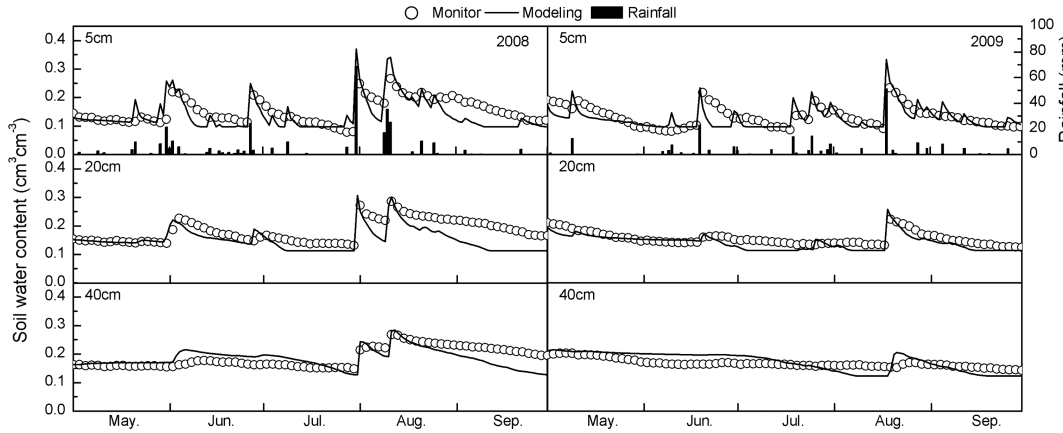

FIG. 3. Comparison between monitored and modeled soil-water content at the SGCG site in 2008 and 2009. SGCG: continuously grazed under SG vegetation.

TABLE 4. Estimated Water Budget Components at Five Sites During Growing Seasons in 2008 and 2009

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

LCUG79, LCWG, and LCHG are ungrazed since 1979, winter grazed, and heavily grazed under LC vegetation, respectively; SGUG79 and SGCG are ungrazed since 1979 and continuously grazed under SG vegetation, respectively.

ΔS: water storage change; error: modeled water balance errors; E_S: evaporation; FD: free drainage; I: interception; nd: not determined; R: rainfall; SR: surface runoff; T_P: transpiration.

properties (Hayashi et al., 2006; Ghanbarian-Alavijeh et al., 2010). Following the laboratory-derived model parameterization, there was a good correlation between measured and simulated soil moisture and temperature at each site, especially at the top 20-cm depth. This indicated that HYDRUS-1D progress was an appropriate code to estimate the soil water and temperature under the impact of different land management practices. However, the use of measured K_s led to a faster response of soil moisture on rain events than the monitored data. Generally, the K_s in Mualem–van Genuchten equations do not reflect the real K_s when macropores are included, which theoretically induces the low fitted K_s value because these equations do not take into account the influence of macropore flow (Kosugi and Inoue, 2002; Hayashi et al., 2006). However, the measured K_s value was so high as a result of soil disturbance and cut-through of dead-end pores during sampling that it resulted in a total uplift of the conductivity characteristic (Stolte et. al., 2003). This could cause the overestimated infiltration and the deviation between modeled and measured data.

Effect of Grazing on Soil Hydraulic Properties

The more intense the animal trampling, the more pronounced the changes in the pore distribution and in the absolute volume are. The van Genuchten parameters (Table 3) represented the water retention characteristics and also reflected the pore size distribution well at the different sites. Increased grazing intensity and subsequently increased trampling induced the lower fraction of total pores (higher bulk density) in topsoil at grazed sites than at ungrazed sites in both LC and SG regions. These data are in agreement with Villamil et al. (2001), who demonstrated a grazing-induced change of water retention characteristics in a southern Caldenal soil in Argentina. The decrease in saturated hydraulic conductivity with the increase in grazing intensity in both the LC and SG regions resulted from the loss of total pores by grazing or the improved pore continuity without grazing for 30 years. Proffitt et al. (1995) and Drewry (2006) examined the natural recovery of soil physical properties without or with reduced animal trampling. The lowest saturated hydraulic conductivity at the LCWG site might be related to a platy soil structure caused by animal trampling as suggested by Krümmelbein et al. (2006). In addition, the higher saturated hydraulic conductivity at the SGCG site than at the LCWG site may also suggest 1.2 sheep U · year^{-1} · ha^{-1} as an appropriate grazing intensity in our research area.

TABLE 5. Potential Evapotranspiration (ET_0) and Actual ET at Five Sites During Growing Season in 2008 and 2009

		LCUG79	LCWG	LCHG	SGUG79	SGCG
Year	ET	mm	mm	mm	mm	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

LCUG79, LCWG, and LCHG are ungrazed since 1979, winter grazed, and heavily grazed under LC vegetation, respectively; SGUG79 and SGCG are ungrazed since 1979 and continuously grazed under SG vegetation, respectively.

nd: not determined.

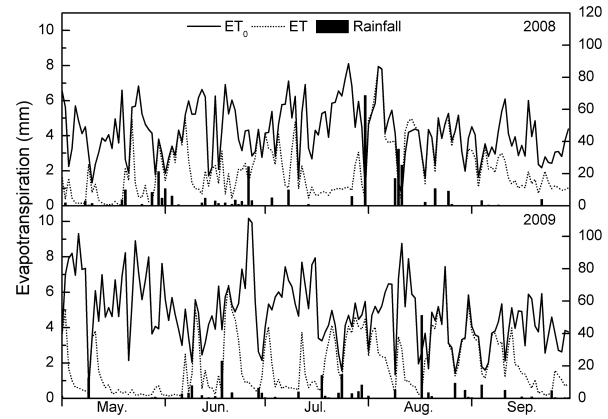

FIG. 4. Comparison between potential and actual ET at the SGCG site in 2008 and 2009. SGCG: continuously grazed under SG vegetation.

TABLE 6. Root Mean Square Errors of Simulation at Three Sites in 2010

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

LCUG79 is ungrazed since 1979 under LC vegetation; SGUG79 and SGCG are ungrazed since 1979 and continuously grazed under SG vegetation, respectively.

Effect of Grazing on Soil-Water Budget Under Two Vegetation Types

With the increase in grazing intensity, the vegetation cover was reduced, and consequently interception was less at grazing sites. At the LCHG site, the almost bare soil induced the greatest evaporation rate but the smallest transpiration rate in the LC region (Table 4). Gao et al. (2008) reported that heavy grazing also induced the lowest live root biomass and belowground net primary productivity. This is important because of the reduced root biomass resulting from heavy grazing, which reduces root water storage and increases the potential for evaporative or runoff loss, especially in wet years. In addition, with the destructive structure and least vegetation resulting from heavy grazing, the surplus water was not stored in the root zone while being lost because of evaporation or drainage, especially in the wet year of 2008 (Table 4). The increased vegetation cover found at the ungrazed site in the LC region likely contributed to the higher transpiration and lower evaporation. However, the greater calculated transpiration at the SGCG site likely resulted from the greater water availability supporting grass growth in the dry year of 2009. First, the accumulated snow in the winter of 2008 brought more water to the SGCG site, which subsequently improved the initial moisture condition at the beginning of growing season. Second, the greater water availability at the SGCG site (Gan et al., 2012) provided more water for grass growth in the dry period. Nevertheless, it was assumed that the initial moisture condition was not greatly improved at the beginning of growing season in the dry year of 2010 when there was no heavy snow as occurred in the winter of 2009. As a result, it induced the lower transpiration at the SGCG site

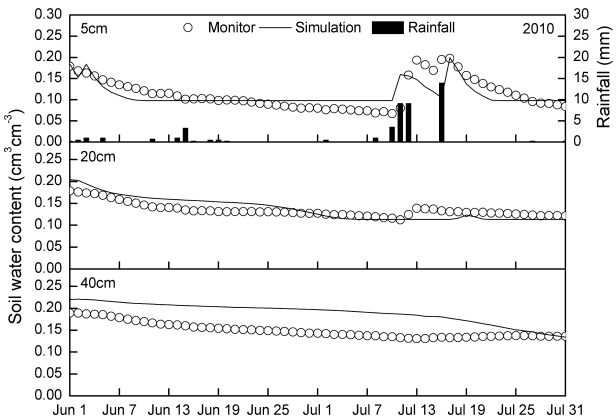

FIG. 5. Comparison between monitored and simulated soil-water content at SGCG site in 2010. SGCG: continuously grazed under SG vegetation.

TABLE 7. Simulated Water Budget Components at Five Sites During Growing Seasons in 2010

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

LCUG79, LCWG, and LCHG are ungrazed since 1979, winter grazed, and heavily grazed under LC vegetation, respectively; SGUG79 and SGCG are ungrazed since 1979 and continuously grazed under SG vegetation, respectively.

ΔS: water storage change; Error: modeled water balance errors; E_S: evaporation; FD: free drainage; I: interception; R: rainfall; SR: surface runoff; T_P: transpiration.

than that at the SGUG79 site in the dry year of 2010. This is in line with the results reported by Neath and Chanasyk (1995), who demonstrated that thawing snow has an important influence on grass growth. In both ungrazed sites, the greater calculated transpiration at the SGUG79 site than that at the LCUG79 site implies that there was more water consumed by the grass for growth. This indicates that the SG uses the soil water more than LC under dry conditions Chen et al. (2005) also documented that SG can tolerate drier conditions than LC in Inner Mongolian grasslands.

Precipitation is the main source for soil-water content during growing season in such semiarid environment (Miao et al., 2009; Lu et al., 2011). Conversely, ET is a major loss in the water budget, which depends on the availability of water and energy at a given site (Sala et al., 1992; Li et al., 2007; Wilske et al. 2010). Several studies have documented that precipitation is nearly all consumed by ET in steppe ecosystems (Wever et al., 2002; Frank, 2003). The calculated ET rates at our sites ranged from 1.7 to 2.4 mm · day^{-1} in the observation period, relatively lower compared with that (2.1–9.5 mm · day^{-1}) in other grasslands in the United States (Weltz and Blackburn, 1995; Ham and Knapp, 1998; Dugas et al., 1999; Bremer et al., 2001). This may be caused by the smaller leaf area index compared with other areas. It is in line with the study by Li et al. (2007), who documented that the Mongolian steppe had reduced ET rates compared with the tall grass native prairies of the United States at similar latitudes. The decrease in calculated ET at all sites from wet growing season to dry period and the greater difference between ET_0 and actual ET in dry period both indicated that water is a dominant factor in our study area. Welker et al. (1991), Neath and Chanasyk (1995), and Lu et al. (2011) concluded that the large rainfall events could compensate for the reduced soil storage; nevertheless, in our study, the majority of summer precipitation events did not recharge soil water but merely increased the ET. We also observed that a sharp increase in ET occurred after most rainfall events in the growing season (Fig. 4). The decrease in temperature resulting from rain events reduced the difference between ET_0 and ET, whereas the increased soil-water content after rainfall contributed to the sharp increase in ET (Fig. 4). 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. The limited water supply in the dry period restricted the ET (Li et al., 2007) and magnified the

difference between ET_0 and ET. As a result of greater water loss through ET, the more soil water was depleted in the dry year of 2009 and 2010 compared with that in the wet year of 2008 (Tables 4 and 7).

Simulation and Land Management Implication

Long-term measurements of soil-water regimens *in situ* are costly in remote regions founded in Inner Mongolia. Our study provides some insights into the use of simulation data for determining soil-water content within annually averaged parameters of initial and boundary conditions in soil. 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 the growing season. Although some errors existed in simulation using the annually averaged initial conditions (e.g., initial soil-water content and soil temperature), the simulation fitted the soil-water content of 20-cm depth well, as shown in Fig. 5. Most of Inner Mongolian grasslands are situated in desolate district, which leads to tremendous problems in investigating the long-term soil-water regimen because of the transportation, living circumstance, extreme weather, and experiment costs. Such simulation can provide essential information for the Department of Land Management that can adjust the land-use patterns in the future in Inner Mongolia, China.

The present study provides some useful information for use in recommending management of grazing in this region. Our results indicate that the rainfall is one of the most important factors in improving the soil-water conditions and ET in such steppe ecosystems. When consideration is given to economic and social development strategy, it is clear that grazing is, and will continue to be, an important component in Inner Mongolia agriculture. Our data further suggest suboptimal and optimal grazing intensities for maintaining good soil structure throughout the region. Heavy grazing (2.0 sheep U $\cdot$ year^{-1} $\cdot$ ha^{-1}) destroys the soil structure and results in the worst soil-water conditions, which subsequently increases the risk of soil desertification (Krümmelbein et al., 2006). Continuously grazed (1.2 sheep U $\cdot$ year^{-1} $\cdot$ ha^{-1}) leads to greater transpiration than winter grazed (0.5 sheep U $\cdot$ year^{-1} $\cdot$ ha^{-1}), indicating more plant productivity under the former grazing intensity. The pattern of simulated soil-water regimen under different grazing intensities can be applied to other specific grasslands in Inner Mongolia, aiding in efforts to determine appropriate grazing intensities for sustainable development of grassland.

CONCLUSIONS

The effects of different grazing intensities under LC and SG vegetation on soil-water budget were analyzed during the growing season in 2008 and 2009 in Inner Mongolian grassland. The simulation of soil-water content with annually averaged values of initial and boundary conditions in soil by HYDRUS-1D was conducted in 2010. Our conclusions can be summarized as follows:

1) Under LC vegetation, heavily grazed (2.0 sheep U $\cdot$ year^{-1} $\cdot$ ha^{-1}) induced the worst water availability, the lowest transpiration, but the highest evaporation through the increase in bare soil area. Winter grazed (0.5 sheep U $\cdot$ year^{-1} $\cdot$ ha^{-1}) decreased the transpiration but increased the evaporation as compared with ungrazed site since 1979. However, under SG vegetation, continuously grazed (1.2 sheep U $\cdot$ year^{-1} $\cdot$ ha^{-1}) led to better water condition when compared with ungrazed site since 1979. The improved initial soil-water condition at the SGCG site resulted in more transpiration when compared with that of the SGUG79 site in 2009. This was likely a result of snowmelt at the beginning of growing season having an important influence on grass growth. Furthermore, the continuously grazed site contributed more transpiration than heavily and winter grazed sites, suggesting that the adjusted grazing intensity as 1.2 sheep U $\cdot$ year^{-1} $\cdot$ ha^{-1} is appropriate for supporting grassland sustainability in this area.

2) Two ungrazed sites presented greater saturated hydraulic conductivity caused by natural recovery of soil physical properties for 30 years. The greater transpiration at the SGUG79 site than at the LCUG79 site indicated that the species SG was better adapted to the drought environment than LC in the Inner Mongolian grassland.

3) The difference between potential and actual ET suggests that such grassland always suffers from drought. Rainfall plays an important role in reducing the drought stress. After a rainfall event, more soil water was lost via ET, further reducing such difference.

4) The simulated soil-water content in 2010 was acceptable with the annually averaged values of initial and boundary conditions in soil using HYDRUS-1D. It suggests that in the absence of on-site observations in such remote regions, such simulation may provide essential information for use by the Department of Land Management in adjusting land-use practices in Inner Mongolia.

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