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Grazing modulates soil temperature and moisture in a Eurasian steppe

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ABSTRACT

Few studies have addressed the potential grazing effects on microclimate, such as surface temperature and moisture, and their feedback effects on grassland function. A continuous, approximately three-year long study was conducted in experimental plots of various grazing intensities, and *in situ* soil temperature and moisture were measured. The results indicated that grazing significantly altered soil temperature and moisture. Soil temperature increased exponentially with increasing grazing intensity in the warm season due to the removal of aboveground biomass (AGB) and decreased linearly with increasing grazing intensity in the cold season due to decreases in both AGB and wind-blown snow accumulation. Heavy grazing increased soil temperature (10 cm depth) by an average of 2.6 °C from April to October (the largest hourly temperature increase was 8.8 °C), representing a soil warming effect 3.7 times that of global warming. Our findings showed that, compared with ungrazed plots, grazed plots had decreased soil water storage due to less winter snow accumulation, especially in the early growing season (EGS) because of the smaller amount of winter snow accumulation than in ungrazed plots. In the EGS, the average water storage in the 0–100 cm layer of the ungrazed plots was 23.3%, which was 1.3–1.8 times that of the grazed plots. Our results showed that grazing also produced warming and drying effects on grassland soil. The long-term feedback effects of grazing-induced soil warming and drying on the ecosystem might be an important mechanism accelerating the degradation and desertification of these grasslands.

1. Introduction

Soil temperature and moisture are key variables influencing almost all ecosystem processes and functions. Whereas the *in situ* soil temperature and moisture are constrained by the regional climate, the vegetation, litter layers and soil are the foundations that regulate their magnitudes and dynamics (Geiger, 1965; Aalto et al., 2013). The canopy cover, litter depth and cover are among the most important mediators of soil temperature and moisture because they directly intercept incoming/outgoing radiation (i.e., net radiation, Rn), and they are also indirect regulators of other energy fluxes, such as the sensible heat flux (H), latent heat flux (LE), and soil heat flux (G) (Campbell and Norman, 1998; Chen et al., 1999; Shao et al., 2014, 2017; Han et al., 2014). G directly controls the changes in soil temperature, and LE (i.e., evapotranspiration) determines soil moisture (Fig. 1). Following this conceptual framework, the diel to interannual changes in soil temperature would be magnified significantly by reducing the vegetation cover and litter layer, whereas the changes in soil moisture may be reduced or unchanged.

Grazing is the most significant human practice in dryland ecosystems and has profound consequences for ecosystem functions, including the soil microclimate (Qi et al., 2017). Substantial scientific investigations have been conducted to understand the effects of grazing on grassland composition, structure, and function, as well as associated ecosystem processes (Olofsson et al., 2004; Altesor et al., 2005; Stark et al., 2015; Eldridge et al., 2016), but relatively few studies have considered the potential effects of grazing on surface microclimate factors such as the dynamics of soil temperature and moisture as well as the underlying mechanisms responsible for their changes and their feedback to grassland function. This lack of understanding of the effects of grazing on the soil microenvironment limits our ability to construct sound ecosystem models for ecosystem studies and manage livestock toward the sustainability of ecosystem goods and services without degradation.

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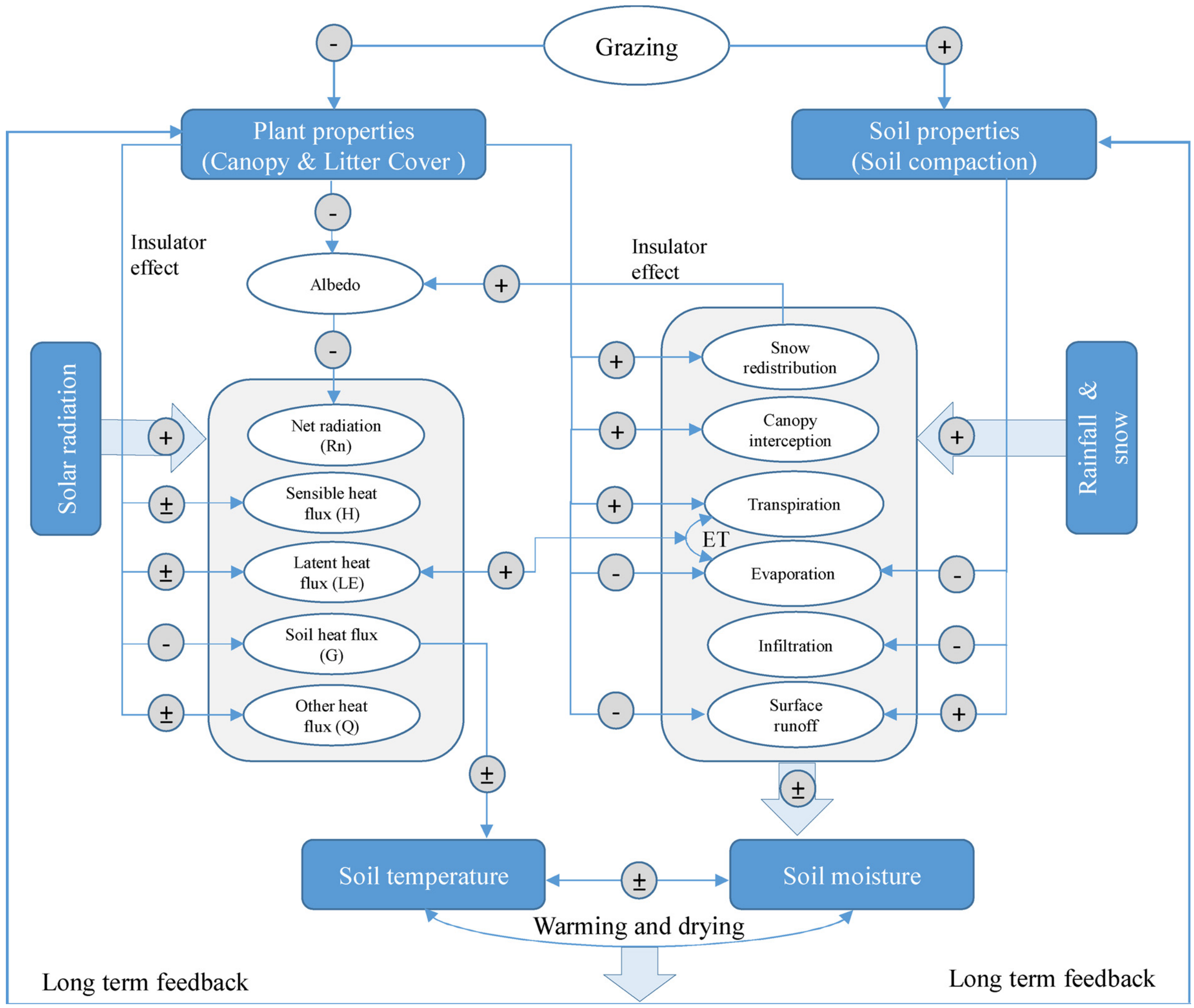

Fig. 1. Conceptual framework of grazing-driven changes to soil temperature and moisture. Grazing resulted in a series of changes to plant and soil properties. We selected the canopy and litter cover and soil compaction as the representative indicators for the plant and soil properties, respectively. We determined the positive or negative effects of these two indicators on the energy process and water process that ultimately influenced soil temperature and moisture. ET represents evapotranspiration. A plus sign surrounded by a circle indicates a positive effect; a minus sign in a circle indicates a negative effect. The presence of both a plus and a minus sign in a circle indicates that the sign (positive or negative) of the effect is unclear or depends on other conditions.

One of the major regulatory mechanisms for the changes in soil temperature by grazing is the reduction in the insulating effect of vegetation and the litter layer on Rn and G (Chen et al., 1999; Aalto et al., 2013; Cheng et al., 2008; Gornall et al., 2009; Hirsch et al., 2014; Savva et al., 2010) (Fig. 1). Decreased canopy cover and litter from grazing may decrease Rn due to increased reflection or albedo (Tian et al., 2017), but can also accelerate the incoming or outgoing of radiation on soil surface due to decreased shelter thus resulting in a higher G flux, which could increase or reduce soil temperatures depending on the direction of heat flux (Fig. 1) (Aalto et al., 2013; Blok et al., 2010; Shao et al., 2017). For example, Aalto et al. (2013) showed that vegetation plays an important role in moderating the variation in soil temperature in an Arctic-alpine system, and Porada et al. (2016) reported that bryophyte and lichen cover reduced the average soil temperature by 2.7 °C in high-altitude regions. Özkan and Gökbulak (2017) demonstrated that the removal of woody vegetation increased the mean daily soil temperatures even at a depth of 40 cm. Our studies in Inner Mongolian grasslands have indicated that grazing can cause changes in Rn by 10% and G by 45% (Shao et al., 2017). In sum, previous reports have focused mostly on the effect of vegetation on energy fluxes and soil temperature in various ecosystems, with relative few studies examining the direct effects of vegetation cover change as a result of grazing's impact on soil temperatures (Zhao et al., 2011; Odriozola et al., 2014). Currently, the quantitative relationship between grazing intensity and soil temperature remains unknown due to a lack of long term and *in situ* experimental data.

The effects of grazing on soil moisture are complex but occur mostly through the reduction in canopy cover and compaction of the litter layer and surface soil, which directly alters a series of thermo-hydrological processes such as transpiration, evaporation, infiltration, and surface runoff (Vandandorj et al., 2017) (Fig. 1). Dense vegetation can increase soil moisture by reducing evaporative losses through shading and by reducing both the horizontal and vertical water flow in the soil (Aalto et al., 2013; Asbjornsen et al., 2011; Naeth et al., 1991). In contrast, plants can also promote soil drying by increasing transpiration and the interception of precipitation (Horton and Hart, 1998; Naeth et al., 1991). Prolonged and heavy grazing can also affect soil hydrologic processes (e.g., infiltration and retention capacity) by altering the physical properties of the soil. For example, increased compaction reduces soil water conductivity, promotes surface runoff, and increases the soil water-holding capacity (Vandandorj et al., 2017) (Fig. 1). Although grazing could influence soil moisture via multiple pathways, long-term continuous soil moisture observations especially under different grazing intensities are still lacking, which hinders our

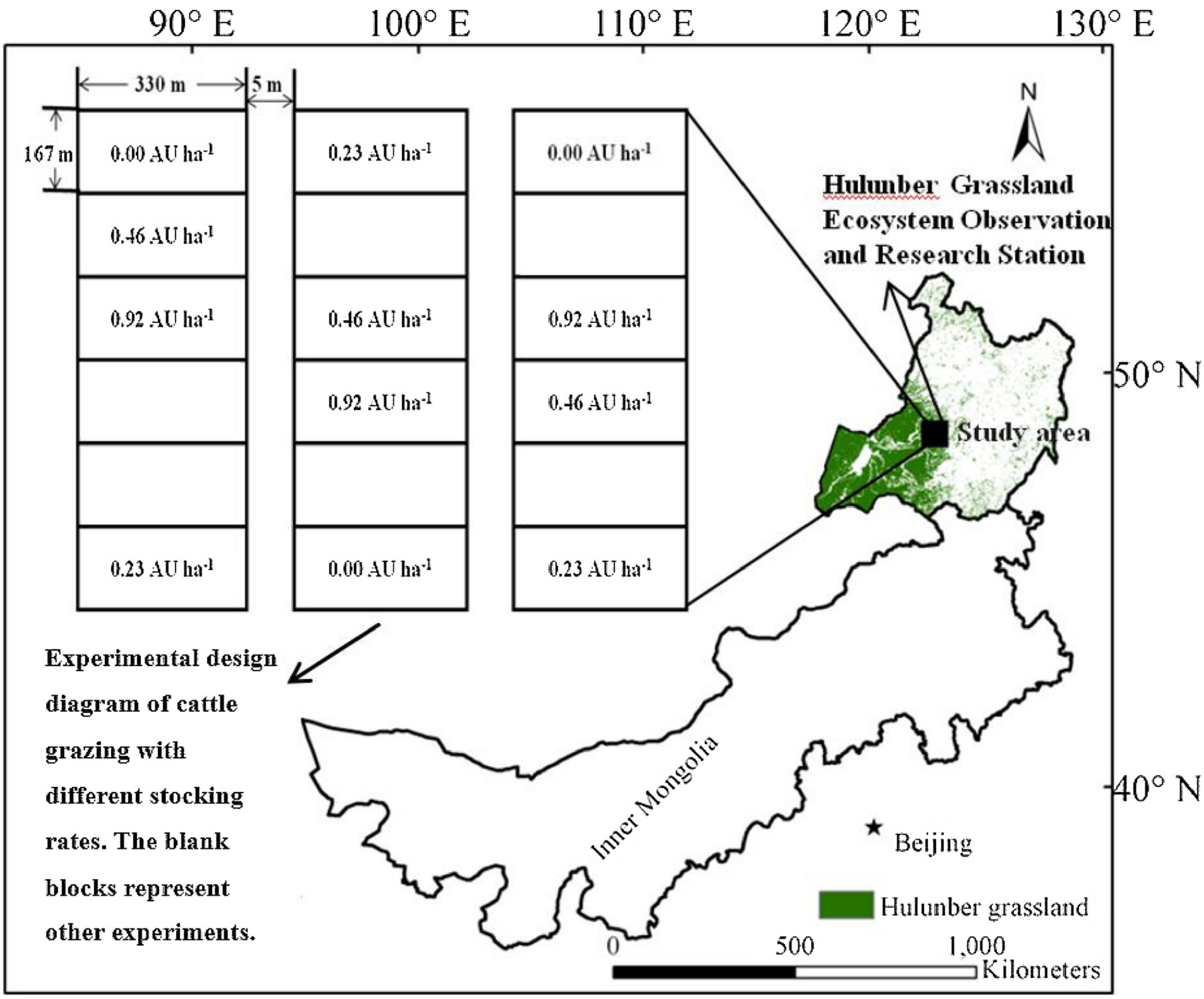

Fig. 2. Geographic location of the study sites and the experimental design. The values 0.00, 0.23, 0.46 and 0.92 AU ha^{-1} correspond to the ungrazed (UG), light grazing (LG), moderate grazing (MG) and heavy grazing (HG) treatments, respectively (where 1 AU = 500 kg of adult cattle). The stocking rates were achieved using 0, 2, 4 or 8 young cattle (250–300 kg) per plot.

understanding of how grazing affects soil moisture and its dynamics, in turn hindering our ability to manage grazing toward reasonable water resource use.

We used a typical meadow steppe in eastern Eurasia as our study site to examine the consequences of various grazing intensities on soil temperature and moisture. Our overall study objective is to quantify the relationship between grazing intensity and soil temperature and moisture at multiple temporal scales. We expect that the changes in soil temperature can be predicted from the grazing intensity. However, the changes in soil moisture with grazing intensity may not be modeled with a high level of confidence due to the conflicting processes that result from grazing.

2. Methods

2.1. Study site and experimental plots

This study was conducted at the Hulunber Grassland Ecosystem Observation and Research Station, which is located in the center of the Hulunber meadow steppe (49.342 °N, 120.009 °E) in the northeastern region of Inner Mongolia, China (Fig. 2). The elevation in the study area ranges from 666 m to 680 m above sea level. The climate is temperate continental with an average of 110 frost-free days per year. The annual mean precipitation ranges from 350 to 400 mm, approximately 80% of which falls between July and September. The annual mean air temperature ranges between −5 °C and −2 °C with a daily maximum of 36.2 °C in July and a daily minimum of −48.5 °C in January. The soil type is chernozem or chestnut soil. The meadow steppe is dominated by *Leymus chinensis*, *Stipa baicalensis*, *Carex duriuscula*, *Galium verum*, *Bupleurum scorzonerifolium*, and *Filifolium sibiricum*.

We established a grazing experiment in 2009 that included three levels of grazing intensity and one control plot (i.e., without grazing). The grazing levels were set at stocking densities of 0, 0.23, 0.46, and 0.92 AU/ha (where 1 AU = 500 kg), representing no grazing (UG), light grazing (LG), moderate grazing (MG), and heavy grazing (HG). Each treatment was conducted in three replicated 5-ha fenced plots, which yielded a total of 12 plots that were randomly assigned to each treatment over a largely homogeneous land area of 60 ha (Fig. 2). The four levels of grazing were simulated with grazing livestock of 0, 2, 4, and 8 head of 250–300 kg cattle. The grazing was conducted for 120 days annually during June-October from 2009 to 2017, with the cattle maintained inside the plots. Drinking water was supplied from an outside water source. Prior to the experiment, the study area had been used for the long-term free grazing of cattle or sheep.

2.2. Soil temperature and moisture measurements

ECH$_2$O 5TE sensors (Decagon Devices, Pullman, Washington, USA) were used to measure soil water content (cm^3 cm^{-3}) and soil temperature (°C) (D'Odorico et al., 2007; Li et al., 2013). The 5TE sensors were calibrated prior to installation, programmed to record soil temperature and moisture every 10 s and averaged every 10 min for final storage. In each of the 12 experimental plots, we created a 1-m soil profile to measure the soil water content and soil temperature at depths of 10, 20, 40, 60 and 100 cm with a total of 60 sensors. All sensors were installed in June 2014 and maintained until May 2017.

2.3. Meteorological observations

A permanent meteorological station (Milos 520, Vaisala, Finland), located approximately 2 km from the experiment site, was maintained by the Hulunber Grassland Ecosystem Research Station, Chinese Academy of Agricultural Sciences. The station recorded air temperature, relative humidity, shortwave solar radiation, and precipitation at 30 min intervals.

2.4. Plant community and soil physical and chemical properties

Five 1×1 m^2 quadrats were randomly placed in each experimental plot during the peak biomass period (typically in August) in 2014. Within each quadrat, we assessed the species composition and the canopy height and cover by species. A 50×50 cm point frame with a grid of 100 crosshairs was used to measure the plant cover, and the plant height was measured at five points to obtain a composite. The canopy was subsequently clipped at ground level and separated into living plant matter and litter. The plant material was dried at 65 °C for 48 h to a constant weight to determine the above-ground biomass (AGB).

Soil samples (0–10 cm) were collected from ten points per plot in early August 2014 for soil nutrient analyses (Bao, 2000). Soil particle size distribution was measured with a Mastersizer 2000 laser particle size analyzer (0–2000 μm); soil organic carbon (OC) content was determined using the dichromate oxidation method; total nitrogen (TN) was determined via semi-micro Kjeldahl determination, and total phosphorus (TP) was determined using the molybdenum antimony resistance-colorimetric method. Soil pH was measured in a 1:5 soil water extract using a pH meter. Soil bulk density (BD) was measured from 5-cm-diameter cores by depth, and volumetric soil moisture was determined by drying the samples at 104 °C for 24 h.

2.5. Delineation of the growing season and the warm and cold seasons

According to the soil freezing-thawing process and plant growth dynamics, we divided the year into four periods: 1) the early growing season (EGS; late March to mid-June), during which the soil temperatures are > 0 °C, the accumulated snow melts, and soil thawing occurs; 2) the mid- growing season (MGS; mid-June to mid-August), during which plants grow and reach peak AGB; 3) the late growing season (LGS; mid-August to mid-October), during which plant growth slows and stops; and 4) the non-growing season (NGS; late October until the following March), during which the soil temperature is < 0 °C (i.e., frozen soil). We also divided the study period into a “warm season” and “cold season” to examine the differences in soil temperature between various grazing intensities. The warm season is when the monthly average soil temperature is above 0 °C, and the cold season is when the monthly average soil temperature is below 0 °C. Due to the pronounced variation in soil temperature with depth, the warm season is from April to October for the 10, 20 and 40 cm soil layers and from May to November for the 60 and 100 cm soil layers. The cold season is from November to the following March for the 10, 20 and 40 cm soil layers and from December to the following April for the 60 and 100 cm soil layers.

2.6. Statistical analyses

We used a randomized complete block ANOVA to test the differences among the four treatments using the [Block x Treatment] interaction as the residual (error) term. Tukey’s HSD test was used to test potential differences in plant, soil and environmental attributes among the grazing treatments. The relationships between soil temperature and grazing intensity as well as AGB were tested using linear, exponential, logarithmic and binomial regression models for model selection based on corrected Akaike Information Criterion (AICc). An exponential model was consequently selected for the warm season data and a linear model was selected for the cold season data to determine the relationship between the grazing intensity and soil temperature, whereas a linear model was chosen for the warm season data and an exponential model for the cold season data for the relationship between the AGB and soil temperature. All statistical analyses were carried out using the SPSS package (v17.0, SPSS, Inc.).

3. Results

3.1. Local climate

From 2014–2016, the mean daily air temperature was −1.6 °C, with a maximum of 29.4 °C and a minimum of −41.8 °C. The mean daily air relative humidity was 66.4%, with a maximum of 96.7% and a minimum of 19.7%. The mean daily incoming solar radiation was 201.5 W m^{-2}, with a maximum of 402.4 W m^{-2} and a minimum of 12.5 W m^{-2}. The total precipitation was 382.8, 210.5 and 298.3 mm in 2014, 2015 and 2016, respectively (Fig. S1). Among the four divided growing seasons (EGS, MGS, LGS and NGS), the mid-growing season (MGS) and non-growing season (NGS) had the highest and the lowest average air temperature, solar radiation and cumulative precipitation, respectively (Table 1).

3.2. Vegetation and soil properties

Aboveground biomass, litter biomass, plant cover and plant height declined significantly with increasing grazing ($p < 0.05$, Table 1). The aboveground living biomass under the UG treatment was 205 g m^{-2}, but decreased by 14.1%, 46.3% and 60.5% in the LG, MG and HG treatments, respectively. There was no significant difference in soil BD among the three grazed levels (LG, MG and HG), but all these plots showed a higher BD than that of UG ($p < 0.05$). There was no significant difference in soil texture, pH, OC, TN or TP among the grazing treatments (Table 2).

3.3. Soil temperature dynamics

The soil temperature varied significantly over the study period (Fig. S2). The average temperature of the topsoil (10 cm) was the highest in July (18.6 °C) and the lowest in January (−11.2 °C). It decreased with depth in the summer but increased in the winter. The diel soil temperature range also decreased with depth throughout the year.

Table 1
Averaged air temperature, relative humidity, solar radiation and total precipitation in the divided seasons during 2014-2016. The early growing season (EGS; March 26 to June 15), the mid- growing season (MGS; June 16 to August 15), the late growing season (LGS; August 16 to October 15), and the non-growing season (NGS; October 16 to the following March 25).

Seasons	Air temperature (°C)	Relative humidity (%)	Precipitation (mm)	Solar radiation (W m^{-2})
EGS	8.2	56.1	78.4	269.2
MGS	19.7	67.7	122.6	291.8
LGS	10.7	67.9	69.7	204.56
NGS	−19.2	70.6	26.5	131.6
Annual mean	−1.6	66.4	297.2	201.5

Table 2
Plant community and soil properties (mean ± SE) under various grazing intensities. Different letters in a row indicate significant differences between grazing intensities at the 5% level (Tukey's test). UG, ungrazed treatment; LG, light grazing treatment; MG, moderate grazing treatment; HG, heavy grazing treatment.

Characteristic		UG	LG	MG	HG
Living biomass (g m^{-2})		205.0 ± 21.9a	176.4 ± 20.9b	109.4 ± 16.5c	81.3 ± 15.7c
Litter (g m^{-2})		181.1 ± 49.7a	52.0 ± 4.7b	26.2 ± 3.4b	16.5 ± 1.7b
Coverage (%)		68.6 ± 2.5a	64.8 ± 3.9ab	62.1 ± 7.2ab	47.2 ± 3.3c
Height (cm)		27.4 ± 1.8a	21.4 ± 2.0b	16.7 ± 0.7bc	6.27 ± 0.7d
Soil bulk density (g cm^{-3})		0.90 ± 0.04b	1.03 ± 0.01a	1.10 ± 0.04a	1.02 ± 0.01a
Soil texture	Clay (%)	7.89 ± 0.88a	7.28 ± 0.52a	7.15 ± 0.73a	7.56 ± 0.61a
	Silt (%)	60.93 ± 3.82a	60.44 ± 1.84a	57.35 ± 3.91a	59.74 ± 1.24a
	Sand (%)	31.19 ± 4.7a	32.29 ± 2.17a	35.50 ± 4.52a	32.70 ± 1.72a
pH		6.85 ± 0.50a	6.85 ± 0.21a	6.83 ± 0.20a	6.97 ± 0.33a
Soil organic carbon (OC) (g kg^{-1})		41.11 ± 3.48a	43.94 ± 0.84a	48.89 ± 2.80a	40.82 ± 1.12a
Total nitrogen (TN) (g kg^{-1})		3.12 + 0.33a	3.41 ± 0.08a	3.64 ± 0.12a	3.20 ± 0.15a
Total phosphorus (TP) (g kg^{-1})		0.53 ± 0.03a	0.53 ± 0.03a	0.56 ± 0.04a	0.57 ± 0.02a

Additionally, the freezing and thawing processes started later in the deeper soil (Fig. S2).

The average soil temperature across all soil layers increased with grazing intensity in the warm season but decreased in the cold season (Fig. S2). Over the study period, the largest differences in the hourly soil temperature between the grazed and ungrazed plots was 8.79 °C at 17:00 h on July 19, 2016 and −6.41 °C at 7:00 h on January 31, 2016 (Fig. 3). More importantly, the difference in the soil temperature between the treatments remained significant in the deep soil layers, including 100 cm depth. However, the difference decreased with depth. Our regression analyses suggested that the average soil temperature across all depths increased exponentially with grazing intensity in the warm season but decreased linearly in the cold season (Fig. 4). The mean soil temperature at a depth of 10 cm in the warm season ranged from 10.7 °C in the UG treatment to 13.3 °C in the HG treatment. During the cold season, it ranged from −8.4 °C in UG to -10.9 °C in HG (Fig. 4). Subsequent regression analyses showed that the average soil temperatures of all depths decreased linearly with AGB and decreased exponentially with canopy height and canopy coverage in the warm season, but increased exponentially with the AGB and increased linearly with canopy height as well as coverage in the cold season (Fig. 5).

3.4. Soil moisture dynamics

The soil moisture showed similar seasonal changes between the four grazing treatments throughout the 3-year study period with clear shifts

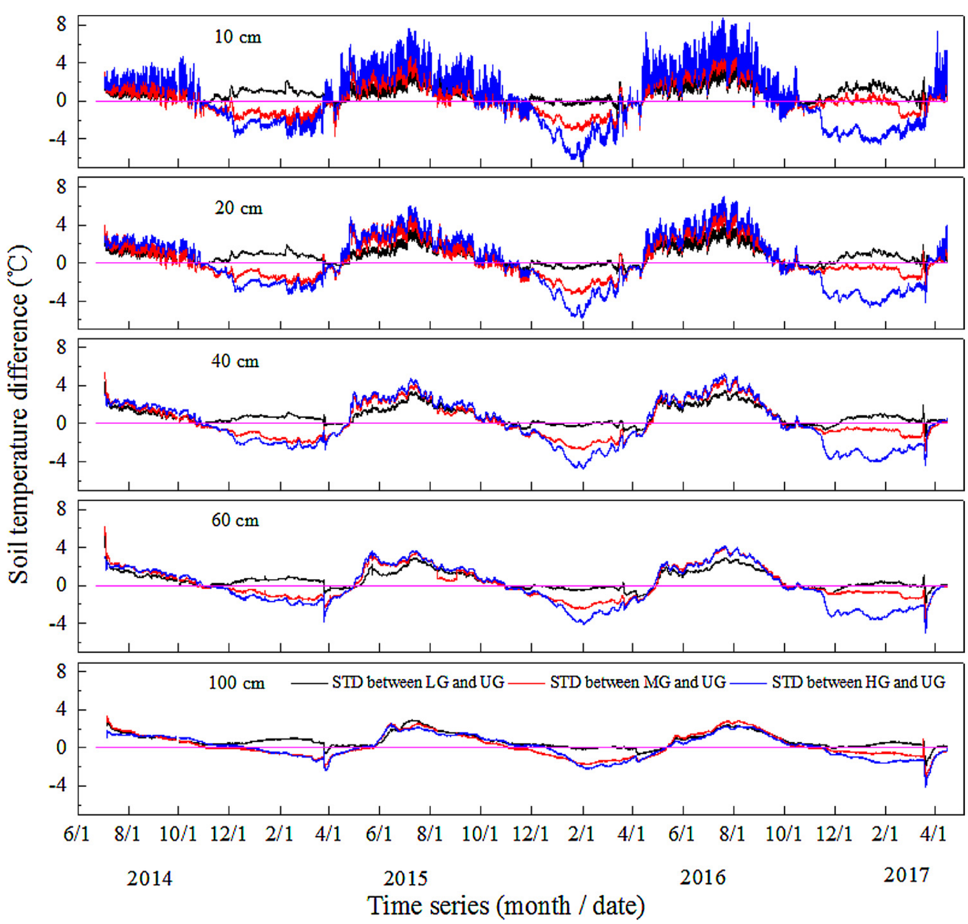

Fig. 3. Hourly soil temperature differences between each of the three grazing intensity treatments and the ungrazed treatment at different soil depths. STD, soil temperature difference; UG, ungrazed treatment; LG, light grazing treatment; MG, moderate grazing treatment; HG, heavy grazing treatment.

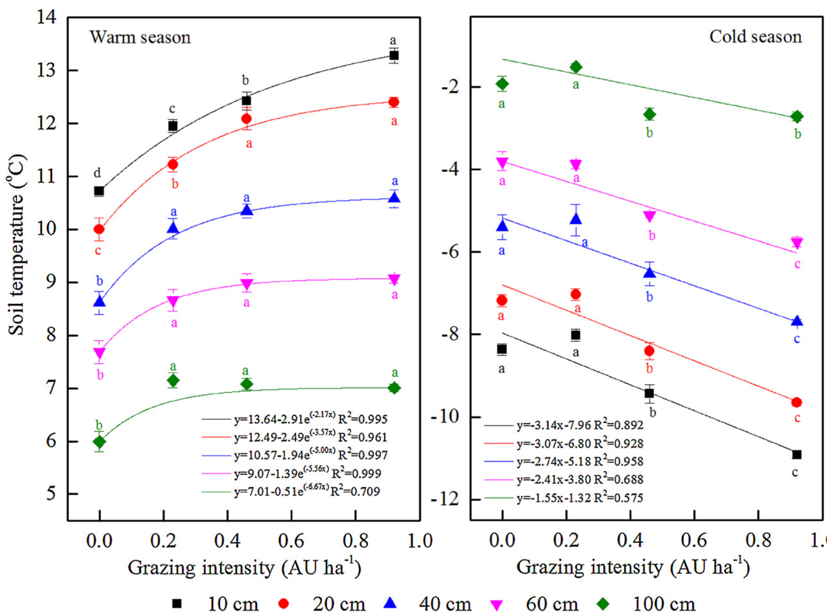

Fig. 4. Relationship between grazing intensity and soil temperature (mean ± SE) at various soil depths in different seasons. The symbols labeled with different letters differ significantly ($p < 0.05$) among grazing intensities within a given soil layer. The warm season is when the monthly average soil temperature was above 0 °C, and the cold season is when the monthly average soil temperature was below 0 °C. Due to the pronounced variation in soil temperature among soil depths, the warm season is from Apr to Oct for the 10, 20 and 40 cm soil layers and from May to Nov for the 60 and 100 cm soil layers. The cold season is from Nov to next Mar for the 10, 20 and 40 cm soil layers and from Dec to the following Apr for the 60 and 100 cm soil layers.

during thawing, snow melting and precipitation events (Fig. 6). The soil moisture was the lowest during the cold season. The first peak in soil moisture occurred at the end of March, when the soils had thawed and the snow began to melt; the soil moisture then gradually decreased until the first significant rainfall.

The soil water content varied with the grazing intensity, especially in the EGS ($p < 0.05$) (Fig. 7). For the 2016 EGS, the average water storage (0–100 cm depth) reached 23.3 mm in UG, which was 1.7–1.8 times of that in the grazed plots (Table S1). The soil moisture varied slightly among the grazed plots in the MGS and LGS except in the deep soil layer (100 cm), where it was higher in the UG plots than in the grazed plots (Fig. 7).

4. Discussion

4.1. Effects of grazing on soil temperature

Ecosystem management, such as harvesting, grazing, etc., can greatly and directly alter the microclimate of ecosystems (Chen et al., 1999). In this study, soil temperature was increased/decreased during the warm/cold season, respectively, by grazing. These changes are mainly due to the grazing-induced reduction in vegetation (canopy and litter) and snow cover that act as insulators for soil heat flux – the primary energy source responsible for the thermal energy of the soil (Shao et al., 2017). The direction of G is from the air to the soil in the warm season when air temperature is higher than soil temperature; a

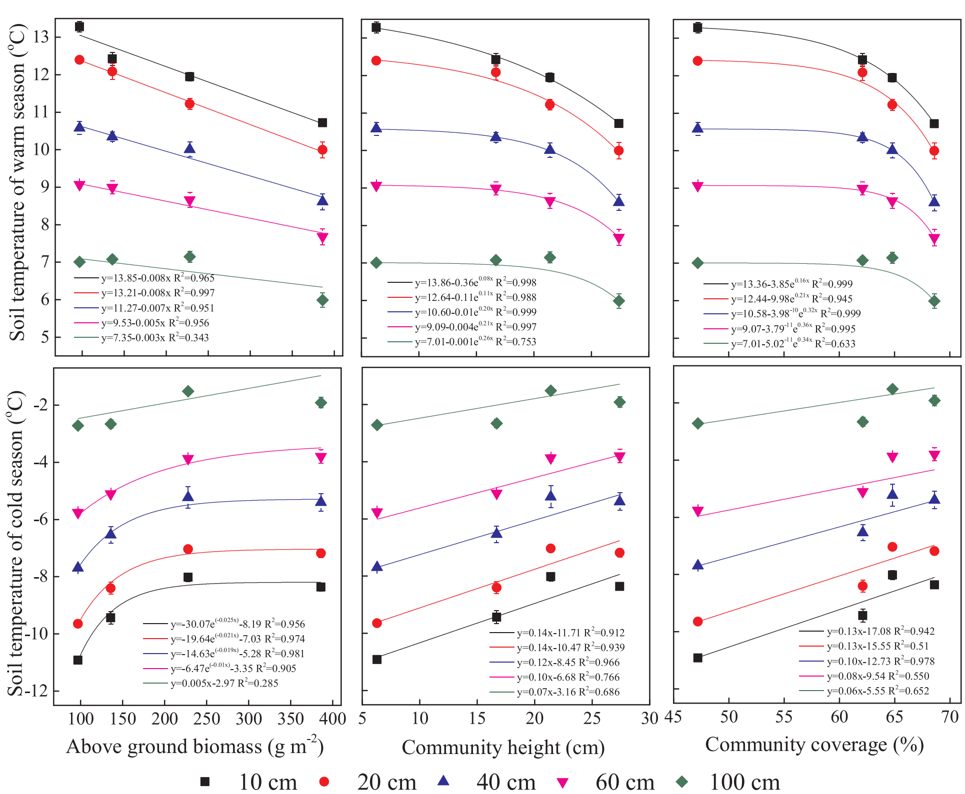

Fig. 5. Relationship between aboveground biomass (AGB), canopy height and canopy coverage and soil temperature (mean ± SE) at various soil depths in different seasons. The warm season is when the monthly average soil temperature was above 0 °C, and the cold season is when the monthly average soil temperature was below 0 °C. Due to the pronounced variation in soil temperature among soil depths, the warm season is from Apr to Oct for the 10, 20 and 40 cm soil layers and from May to Nov for the 60 and 100 cm soil layers. The cold season is from Nov to next Mar for the 10, 20 and 40 cm soil layers and from Dec to the following Apr for the 60 and 100 cm soil layers.

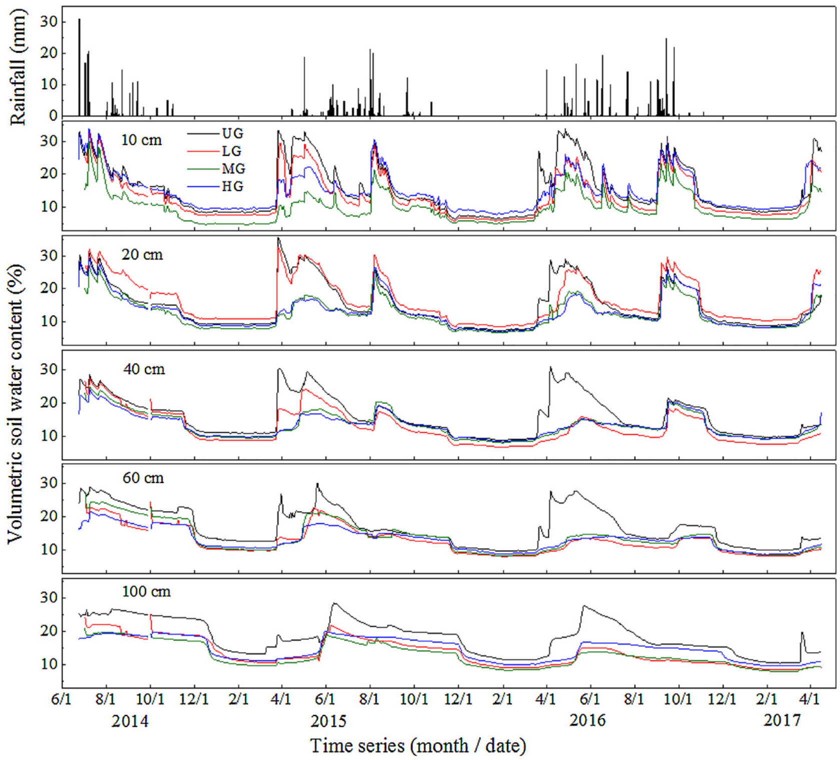

Fig. 6. Daily time series of precipitation and volumetric water content (VWC) under various grazing intensities at soil depths of 10, 20, 40, 60 and 100 cm. UG, ungrazed treatment; LG, light grazing treatment; MG, moderate grazing treatment; HG, heavy grazing treatment.

reverse energy flow exists in the cold season. While we expected the temperature differences between grazed and ungrazed plots, we were surprised by the magnitude of the difference, i.e. 8.8 °C in the warm season and 6.4 °C in the cold season (Fig. 3). On average, the mean soil temperature (10 cm) in the HG plot was 2.6 °C higher than that in the ungrazed plot in the warm season and 2.5 °C lower in the cold season (Fig. 4). These differences far exceeded the amplitude of current warming predicted by many models by up to 3.7 times (IPCC, 2013). Due to the global warming projections have been often referred to air temperature, if considering the temperature change in soil was less than in air, these differences was greater than the 3.7 times of the actual soil warming resulted from global warming. Not only are the temperature changes large enough to have significant consequences for many ecosystem processes (e.g., nutrient cycling, microbial activity, root growth, etc.) (Stark et al., 2015), but the changes can be triggered in a much shorter time period (< year) than the gradual warming of the region.

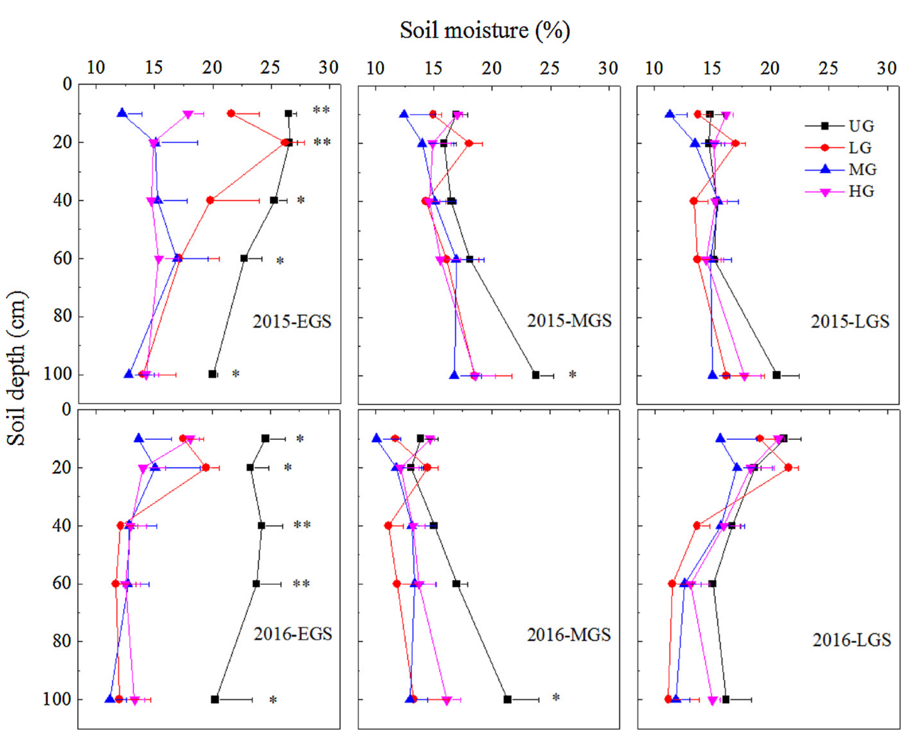

Fig. 7. Soil moisture (mean ± SE) under various grazing intensities at various soil depths in different periods: the early growing season (EGS; March 26 to June 15), the mid- growing season (MGS; June 16 to August 15), and the late growing season (LGS; August 16 to October 15). One asterisk and two asterisks represent a significant difference in soil moisture between UG and the grazed plots at a significance level of < 0.05 and < 0.01, respectively, within a given soil layer. UG, ungrazed treatment; LG, light grazing treatment; MG, moderate grazing treatment; HG, heavy grazing treatment.

From this perspective, our results support the argument that human activities in the Inner Mongolian grasslands play a much stronger role than the long term climatic change (Chen et al., 2013).

Several previous studies have reported no significant difference in soil temperature between grazed and ungrazed treatments, although they have also found a trend of heating in the soils during the warm season and cooling during the cold season under grazing (Zhao et al., 2011; Shao et al., 2017). A consensus from all of these studies is that grazing-induced temperature changes are highly correlated with ecosystem productivity that is coupled with the corresponding canopy cover and litter layers. In low-productivity areas (e.g., the desert steppe in western Inner Mongolia), the sparse, small plants provide low interception of incoming/outgoing radiation (Shao et al., 2017), yielding a relatively small change in soil temperature with grazing (Zhao et al., 2011; Odriozola et al., 2014; Shao et al., 2017). Our meadow steppe, in contrast, has the highest productivity of all grasslands in northern China because of the favorable soil nutrient and precipitation conditions (Tang et al., 2016), resulting in high canopy cover (68.6%) and AGB of 386 g m^{-2} in the ungrazed plots (Table 1). The thick, deep vegetation column serves as a powerful insulator for G and consequently soil temperature. The LG, MG and HG treatments removed 41%, 65% and 75% of the AGB, respectively, relative to the UG treatment (Table 1). Consequently, a significantly different soil temperature was created depending on the grazing intensity (Fig. 4).

It is worth noting that snow, accompanied by wind, is common in the winters at our study sites, where vegetation cover can affect the redistribution of wind-driven snow (Naeth and Chanasyk, 1996). During this study, we recorded a significantly greater decrease in accumulated snow of 23.5–11.0 cm under HG (unpublished data). This is consistent with Willms and Chanasyk (2006) who reported the annual average snow accumulation at heavily and moderately grazed sites as 42% and 20% lower, respectively, than that at the ungrazed site in rough fescue grasslands of southwestern Alberta, Canada. Although we did not explore the heat transfer between the air and soil under different snow cover/depth, we reason that the mechanism by which grazing intensity influences soil temperature in the cold season may be a result of differences in the cover of both above-ground vegetation and snow.

4.2. Effect of grazing on soil moisture

The changes in soil water in our study ecosystem appeared to be governed primarily by snowmelt and rainfall (Fig. 6). A sharp increase in soil moisture coincided with the spring snow melting in all treatments (Fig. 6). This result implies that snow accumulation throughout the winter plays a critical role in the spring hydrology in the ecosystem (Naeth and Chanasyk, 1996). The increased amount of wind-blown snow captured by the dense vegetation in the ungrazed and LG treatments might be responsible for the high snow accumulation that contributed to the high soil water content in these plots, especially in the EGS (Fig. 7). Therefore, grazing can be predicted to decrease productivity (i.e., canopy cover and litter accumulations) due to the lower amount of soil water storage in the EGS (Yuan and Zhou, 2005). However, compared with the grazing treatments, the ungrazed plots did not exhibit a significantly higher soil water content in the MGS and LGS in 2015–2016, except in the deep soil layer (100 cm), which had a high soil water content due to delayed soil thawing at this depth (Fig. 7). We speculate that higher plant transpiration in the ungrazed plots may have been offset by the higher soil evaporation under grazing in the growing season, resulting in the slight difference in soil water content among the different grazing intensities (Aalto et al., 2013; Han et al., 2014; Shao et al., 2017) (Fig. 7).

We also detected different depths of soil infiltration during snowmelt and rainfall events (Fig. 6). Snow melting influenced the deep soil layer (100 cm), primarily through lowering air temperature and subsequently lowering evaporation in the EGS when plants are small. These conditions are optimal for the complete infiltration of snowmelt. Thus, our results indicate that higher snow accumulation and better conditions for infiltration are responsible for the significantly greater water storage in the ungrazed plots in the EGS, especially in the deeper soil layer. However, rainfall events only influenced the soil water in the shallow layer (< 40 cm) because rainfall mainly occurs in the season of high water consumption to support the requirements of plant growth and evaporation (Fig. 6).

4.3. Long-term feedback of soil temperature and moisture

Grazing-induced changes in soil temperature and moisture will likely accelerate the warming and drying process in grasslands under a changing climate. Organisms must adapt to environmental changes via physiological adaptation or shifts in community structure (Li and Zhao, 2005; Stark et al., 2015). Compared with the ungrazed treatment, the proportion of *Leymus chinensis* has been shown to decrease in response to HG while *Carex duriuscula* increased (Yan et al., 2015). Increases in soil temperature caused by grazing could benefit exotic (Eldridge et al., 2017) invasive species at the expense of indigenous C3 grasses (Williams et al., 2007). Meanwhile, ungrazed plots may be more resistant to invasion by exotics because of the relatively mild changes in microclimate. Stark et al. (2015) indicated that tundra soil microorganisms might be better adapted to cold under low grazing intensity than high. In addition, altered soil temperature and moisture will have long term feedbacks on ecosystem structure and function, such as reductions in productivity due to decreased soil water storage (particularly in the spring), and increased wind erosion and desertification resulting from greater soil warming and drying (Li and Zhao, 2005). Clearly, the long-term feedback of soil warming and drying to ecosystem functions from grazing would be an important mechanism in understanding the dynamics of future grasslands. Scientific efforts in maintaining a long term study on changes in soil microclimate, ecosystem responses, as well as the coupled underlying mechanisms are needed as follow ups of this study.

5. Conclusions

Through a controlled experiment, we examined and modeled the effects of grazing on soil temperature and moisture over a three-year study period. Grazing increased the surface soil temperature (10 cm) by an average of 2.6 °C in the warm season (April to October), which is 3.7 times the rate of global warming. Exponential and linear models accurately fit the changes of soil temperature with grazing intensity in the warm and cold seasons, respectively. Grazing also decreased the soil water storage in the EGS by approximately 44%, which is likely due to the decreased snow accumulation in the winter. Altogether, grazing produced significant warming and drying effects on the soil by altering the vegetation cover and redistributing snow. Our study provides an important piece of evidence for understanding the influences of grazing practices on ecosystems under the influence of climate change. Potential approaches for decreasing the consumption of AGB during the growing season and thereby reducing soil warming and increasing soil water storage in grasslands include the conversion from grazing to mowing and the establishment of alternating sections of ungrazed and grazed lands.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agrformet.2018.07.011.

References

Aalto, J., Roux, P.C.L., Luoto, M., 2013. Vegetation mediates soil temperature and moisture in arctic-alpine environments. Arct. Antarct. Alp. Res. 45, 429–439.

Altesor, A., Oesterheld, M., Leoni, E., Lezama, F., Rodríguez, C., 2005. Effect of grazing on community structure and productivity of a Uruguayan grassland. Plant Ecol. 179, 83–91.

Asbjornsen, H., Goldsmith, G.R., Alvarado-Barrientos, M.S., Rebel, K., Van Osch, F.P., Rietkerk, M., Chen, J., Gotsch, S., Tobón, C., Geissert, D.R., Gómez-Tagle, A., Vache, K., Dawson, T.E., 2011. Ecohydrological advances and applications in plant–water relations research: a review. J. Plant Ecol. 4, 3–22.

Bao, S., 2000. Soil Agrochemical Analysis. China Agriculture Press, Beijing.

Blok, D., Heijmans, M.M.P.D., Schaepman-Strub, G., Kononov, A.V., Maximov, T.C., Berendse, F., 2010. Shrub expansion may reduce summer permafrost thaw in Siberian tundra. Glob. Change Biol. 16, 1296–1305.

Campbell, G.S., Norman, J.M., 1998. An Introduction to Environmental Biophysics. Springer, New York, NY.

Chen, J., Saunders, S., Crow, T., Naiman, R., Brosofske, K., Mroz, G., Brookshire, B., Franklin, J., 1999. Microclimate in forest ecosystem and landscape ecology. BioScience 49, 288–297.

Chen, J., Wan, S., Henebry, G., Qi, J., Gutman, G., Sun, G., Kappas, M. (Eds.), 2013. Dryland East Asia (DEA): Land Dynamics Amid Social And Climate Change. HEP and De Gruyter 467pp.

Cheng, H., Wang, G., Hu, H., Wang, Y., 2008. The variation of soil temperature and water content of seasonal frozen soil with different vegetation coverage in the headwater region of the Yellow river, China. Environ. Geol. 54, 1755–1762.

D'Odorico, P., Caylor, K., Okin, G.S., Scanlon, T.M., 2007. On soil moisture–vegetation feedbacks and their possible effects on the dynamics of dryland ecosystems. J. Geophys. Res. Biogeosci. 112, G04010.

Eldridge, D.J., Poore, A.G.B., Ruiz-Colmenero, M., Letnic, M., Soliveres, S., 2016. Ecosystem structure, function, and composition in rangelands are negatively affected by livestock grazing. Ecol. Appl. 26, 1273–1283.

Eldridge, D.J., Delgado-Baquerizo, M., Travers, S.K., Val, J., Oliver, I., Dorrough, J.W., Soliveres, S., 2017. Livestock activity increases exotic plant richness, but wildlife increases native richness, with stronger effects under low productivity. J. Appl. Ecol. https://doi.org/10.1111/1365-2664.12995.

Geiger, R., 1965. The Climate Near the Ground. Harvard University Press, Cambridge (MA.

Gornall, J.L., Woodin, S.J., Jonsdottir, I.S., Van der Wal, R., 2009. Herbivore impacts to the moss layer determine tundra ecosystem response to grazing and warming. Oecologia 161, 747–758.

Han, J., Chen, J., Han, G., Shao, C., Sun, H., Li, L., 2014. Legacy effects from historical grazing enhanced carbon sequestration in a desert steppe. J. Arid Environ. 107, 1–9.

Hirsch, A.L., Pitman, A.J., Kala, J., 2014. The role of land cover change in modulating the soil moisture-temperature land-atmosphere coupling strength over Australia. Geophys. Res. Lett. 41, 5883–5890.

Horton, J.L., Hart, S.C., 1998. Hydraulic lift: a potentially important ecosystem process. Trends Ecol. Evol. 13, 232–235.

IPCC, 2013. Climate Change: The Physical Science Basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Li, X.-Y., Zhang, S.-Y., Peng, H.-Y., Hu, X., Ma, Y.-J., 2013. Soil water and temperature dynamics in shrub-encroached grasslands and climatic implications: results from Inner Mongolia steppe ecosystem of north China. Agric. For. Meteorol. 171–172, 20–30.

Li, Y., Zhao, J., 2005. Effects of overgrazing on ecological and environmental construction and measurement. J. Desert Res. 25, 404–408.

Naeth, M.A., Chanasyk, D.S., 1996. Runoff and sediment yield under grazing in foothills fescue grasslands of Albert. J. Am. Water Resour. Assoc. 32, 89–95.

Naeth, M., Chanasyk, D., Rothwell, R., Bailey, A., 1991. Grazing impacts on soil water in mixed prairie and fescue grassland ecosystems of Alberta. Can. J. Soil Sci. 71, 313–325.

Odriozola, I., García-Baquero, G., Laskurain, N.A., Aldezabal, A., 2014. Livestock grazing modifies the effect of environmental factors on soil temperature and water content in a temperate grassland. Geoderma 235–236, 347–354.

Olofsson, J., Stark, S., Oksanen, L., 2004. Reindeer influence on ecosystem processes in the tundra. Oikos 105, 386–396.

Özkan, U., Gökbulak, F., 2017. Effect of vegetation change from forest to herbaceous vegetation cover on soil moisture and temperature regimes and soil water chemistry. Catena 149, 158–166.

Porada, P., Ekici, A., Beer, C., 2016. Effects of bryophyte and lichen cover on permafrost soil temperature at large scale. Cryosphere 10, 2291–2315.

Qi, J.G., Xin, X.P., John, R., Groisman, P. Pavel., Chen, J.Q., 2017. Understanding livestock production and sustainability of grassland ecosystems in the Asian Dryland Belt. Ecol. Proc. 6 (1), 22.

Savva, Y., Szlavecz, K., Pouyat, R.V., Groffman, P.M., Heisler, G., 2010. Effects of land use and vegetation cover on soil temperature in an urban ecosystem. Soil Sci. Soc. Am. J. 74, 469–480.

Shao, C., Li, L., Dong, G., Chen, J., 2014. Spatial variation of net radiation and its contribution to energy balance closures in grassland ecosystems. Ecol. Proc. 3, 1–11.

Shao, C., Chen, J., Li, L., Dong, G., Han, J., Abraha, M., John, R., 2017. Grazing effects on surface energy fluxes in a desert steppe on the Mongolian Plateau. Ecol. Appl. 27, 485–502.

Stark, S., Männistö, M.K., Ganzert, L., Tiirola, M., Häggblom, M.M., 2015. Grazing intensity in subarctic tundra affects the temperature adaptation of soil microbial communities. Soil Biol. Biochem. 84, 147–157.

Tang, H.J., Xin, X.P., Li, L.H., Wang, D.L., Yan, Y.C., Zhou, Y.L., Wang, M.J., Zhou, D.W., Cui, G.W., Li, X.L., Yan, R.R., Chen, B.R., Xu, L.J., Wang, X., 2016. North meadow degraded grassland treatment technology and demonstration. Acta Ecol. Sin. 36, 7034–7039.

Tian, L., Chen, J., Zhang, Y., 2017. Growing season carries stronger contributions to to albedo albedo dynamics on the Tibetan plateau. PLoS One 12 (9), e0180559. https://doi.org/10.1371/journal.pone.0180559.

Vandandorj, S., Eldridge, D.J., Travers, S.K., Val, J., Oliver, I., 2017. Microsite and grazing intensity drive infiltration in a semi-arid woodland. Ecohydrology 10, e1831. https://doi.org/10.1002/eco.1831.

Williams, D.W., Jackson, L.L., Smith, D.D., 2007. Effects of frequent mowing on survival and persistence of forbs seeded into a species-poor grassland. Restor. Ecol. 15, 24–33.

Willms, W.D., Chanasyk, D.S., 2006. Grazing effects on snow accumulation on rough fescue grasslands. Rangel. Ecol. Manag. 59, 400–405.

Yan, R., Xin, X., Yan, Y., Wang, X., Zhang, B., Yang, G., Liu, S., Deng, Y., Li, L., 2015. Impacts of differing grazing rates on canopy structure and species composition in Hulunber meadow steppe. Rangel. Ecol. Manag. 68, 54–64.

Yuan, W., Zhou, G., 2005. Responses of three *Stipa* communities net primary productivity along Northeast China Transect to seasonal distribution of precipitation. Chin. J. Appl. Ecol. 16, 605–660.

Zhao, Y., Peth, S., Reszkowska, A., Gan, L., Krümmelbein, J., Peng, X., Horn, R., 2011. Response of soil moisture and temperature to grazing intensity in a *Leymus chinensis* steppe, Inner Mongolia. Plant Soil 340, 89–102.