Grazing effects on surface energy fluxes in a desert steppe on the Mongolian Plateau

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Abstract. Quantifying the surface energy fluxes of grazed and ungrazed steppes is essential to understand the roles of grasslands in local and global climate and in land use change. We used paired eddy-covariance towers to investigate the effects of grazing on energy balance (EB) components: net radiation (R_n) , latent heat (LE), sensible heat (H), and soil heat (G) fluxes on adjacent grazed and ungrazed areas in a desert steppe of the Mongolian Plateau for a two-year period (2010–2012). Near 95% of R_n was partitioned as LE and H, whereas the contributions of G and other components of the EB were 5% at an annual scale. H dominated the energy partitioning and shared ~50% of R_n . When comparing the grazed and the ungrazed desert steppe, there was remarkably lower R_n and a lower H, but higher G at the grazed site than at the ungrazed site. Both reduced available energy $(R_n - G)$ and H indicated a "cooling effect" feedback onto the local climate through grazing. Grazing reduced the dry year LE but enhanced the wet year LE. Energy partitioning of LE/R_n was positively correlated with the canopy conductivity, leaf area index, and soil moisture. H/R_n was positively correlated with the vapor pressure deficit but negatively correlated with the soil moisture. Boosted regression tree results showed that LE/R_n was dominated by soil moisture in both years and at both sites, while grazing shifted the H/R_n domination from temperature to soil moisture in the wet year. Grazing not only caused an LE shift between the dry and the wet year, but also triggered a decrease in the H/R_n because of changes in vegetation and soil properties, indicating that the ungrazed area had a greater resistance while the grazed area had a greater sensitivity of EB components to the changing climate.

Key words: available energy; cooling effect; ecosystem function; ecosystem stability; eddy-covariance; energy balance; energy partitioning; land use change; latent heat; net radiation; sensible heat; soil heat.

INTRODUCTION

The energy exchange between the land surface and the atmosphere is influenced by vegetation and may strongly affect the local, regional and global carbon and water cycles and climate change (Aires et al. 2008, Rotenberg and Yakir 2011, Abraha et al. 2016). Grazing is the most ubiquitous land use practice in grasslands, causing substantial changes in the vegetation cover, species composition and their functional type (Klein et al. 2005, Wang et al. 2012). Consequently, the magnitude and dynamics of carbon, water, and energy are altered (Owensby et al. 2006, Polley et al. 2008, Shao et al. 2013), accompanied with changes in aerodynamic characteristics, microclimate, surface resistance to evaporation, and soil water holding capacity (Wan et al. 2002, Hernandez-Ramirez et al. 2010, Paustian et al. 2016).

The European-Asian mid-latitude desert steppe is a transitional type that connects the desert and the typical

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steppe (Han et al. 2009). It is very sensitive to global climate change, especially on the Mongolian Plateau where climate change is occurring at a pronounced pace (Qi et al. 2012, Liu et al. 2013, IPCC 2014, Chen et al. 2015b), with an increases of 0.35°C per 10 years in mean air temperature since 1955 (Lu et al. 2009, John et al. 2016), and a decreasing trend of precipitation frequency and 7% (i.e., 22 mm) in precipitation in central Mongolia (Li et al. 2006, Chen et al. 2013). In this region, grazing coupled with these climate changes have shown already substantial effects on the ecological (e.g., biogeochemical cycling and community dynamics) and hydrological processes (Polley et al. 2008, Groisman et al. 2009, Han et al. 2014, Liu et al. 2014). Quantifying the energy fluxes of grazed and ungrazed desert steppes is therefore an essential step for understanding the role of semiarid temperate grasslands in local-to-global climate and land use changes (Chen et al. 2015a).

Changes in community composition and structure will result in changes of the regime of energy balance (EB) components, including latent heat flux (LE, a measure of evapotranspiration), sensible heat flux (H), net radiation (R_n), and soil heat flux (G) and their partitioning. Grazing could alter plant transpiration (T) and soil evaporation (E) by removing large amounts of vegetation, altering the species composition, modifying soil texture, and modulating the microclimate (Wan et al. 2002, Klein et al. 2005, Zhang et al. 2014). A grazed area usually shows significantly higher G and soil temperature than an ungrazed area due to lowered canopy cover (Shao et al. 2012). Previous studies on the potential effects of grazing on grassland LE showed inconsistent results. Some reported that grazing reduced seasonal LE due to a decrease in above ground biomass and T (Bremer et al. 2001), or an increase in seasonal LE due to an increase in soil exposure and E (Frank 2003), while others found no significant effects (Stewart and Verma 1992, Miao et al. 2009). Limited knowledge also exists on the spatial and temporal variation of grazing effects on the energy fluxes and partitioning (Li et al. 2006, Chen et al. 2009, Shao et al. 2014). Direct effects from grazing on the magnitude, direction, and changes over time in energy fluxes are difficult to measure because of the varying grazing practices across sites (e.g., within the footprint of a flux tower) and lack of comparable sites (e.g., similar soil, microclimate; Owensby et al. 2006). Quantitative knowledge is needed on how disturbance and changing climate can jointly alter energy fluxes on broader spatial scales in order to parameterize regional models for predicting energy fluxes and partitioning.

Here, we report energy fluxes using a unique paired-EC (eddy covariance) system over a grazed and an ungrazed annual grassland ecosystem under the same climate and soil types on the Mongolian Plateau. We hypothesized that (1) grazing reduces LE due to decrease in leaf area, but enhances H due to increase in temperature; (2) soil moisture dominates the LE/R_n change and temperature constrains H/R_n change in this arid desert steppe; and (3) all EB components at the ungrazed area would be more resilient to the changing climate because of a long term protection adapted mechanisms of vegetation. The aims of this study were to investigate the effects of grazing and climate on the individual components of the EB (i.e., R_n , H, LE, and G) and energy partitioning, as well as their biophysical controls. Specifically, our objectives are to (1) evaluate the EB components and partitioning changes in a paired grazed and ungrazed ecosystems from hourly to yearly scales and (2) elucidate the biotic and abiotic factors regulating the energy partitioning across the two ecosystems and across dry and wet years.

METHODOLOGY

Study area

This desert steppe is located near the center of the Mongolian Plateau at the Siziwang Experimental Station of the Inner Mongolia Academy of Agricultural and Animal Husbandry Sciences. The region is characterized by a strong continental climate. The growing season (May– September) is warm and windy, while the non-growing season (October–April) is cold, dry, and windy. The mean annual air temperature is 3.4°C, with the maximum in July (24.0°C) and the minimum in January (-30.5° C). The mean annual precipitation is 180 mm, of which the most falls between June and September. The ungrazed steppe (FS) was fenced in June 2004, and the free-grazed steppe (GS) was grazed with ~1.8 sheep·ha^{-1.}0.5 yr⁻¹ for over 30 years, which represents the average grazing intensity for the region. Both the FS and GS sites had relatively homogenous vegetation and were dominated (area coverage >85%) by perennial bunchgrass (*Stipa breviflora Griseb*). The soil was aridisol (i.e., chestnut soil by FAO classification) with a loamy sand texture.

Flux and micrometeorological measurements

Two open-path EC systems that consisted of an infrared gas analyzer (IRGA, LI-7500; LI-COR, Lincoln, Nebraska, USA) and a CSAT3 three-dimensional sonic anemometer (Campbell Scientific [CSI], Logan, Utah, USA) were deployed at 2.0 m above the ground to measure LE, H, and CO₂ fluxes. The H₂O and CO₂ gas concentrations, wind speed and sonic temperature were sampled at 10 Hz. The IRGAs were prior to calibrating before field setup and routinely calibrated at the beginning of each growing season. Micrometeorological measurements included photosynthetic photon flux density (PPFD; LI-190; LI-COR), net radiation (R_n ; Q7.1; REBS, Seattle, Washington, USA), and relative humidity (RH) and air temperature (T_a ; HMP45C; CSI) at 2.0 m above ground level. The aspirated net radiometers were cross-calibrated before the deployment and new domes were changed every three months. Rainfall was measured with tipping bucket rain gauges (TE-525WS-L; CSI). Soil temperature (T_s) was measured at 0.05 and 0.10 m with four CS107 probes (CSI). The top 0.30 m averaged volumetric soil water content (SWC) was measured using two vertically inserted frequency domain reflectometer (CS616; CSI). Soil heat flux (G) was measured at six locations using heat flux plates (HFT3.1; CSI) at 0.02 m below the ground surface. Instrument maintenance was performed weekly and the online-computed mean halfhourly scalar fluxes and micrometeorological observations along with the 10 Hz raw data were recorded by a CR5000 datalogger (CSI) with a card at each site.

Vegetation measurements

Aboveground net primary production (ANPP), including all green tissues (GNPP), and standing dead and litter biomass, was measured biweekly during the growing seasons over two years by clipping six randomly selected 0.5×0.5 m quadrats. On the highest aboveground biomass period (usually in August–September), the mean canopy height and cover were measured (Table 1). Belowground net primary production (BNPP) was also sampled at peak plant biomass at the same sites using a 1 m deep soil core (0.07 m in diameter) and divided into 0–0.1, 0.1–0.2,

0.2–0.4, 0.4–0.6, and 0.6–1.0 m classes for each of the six replicates. The BNPP, soil bulk density, and soil carbon concentration for each depth were measured using the soil samples. The biomass samples were oven dried at 65°C to a constant mass (\approx 48 h) to obtain biomass estimates. Leaf area index (LAI) was measured by using a LI-3000 (LI-COR) before drying for GNPP. The specific leaf area (SLA) was used only when GNPP was available.

Energy balance closure

Energy balance closure (EBC) was used to evaluate the performance of the EC systems. The EBC was calculated using half-hourly data through a linear regression between the sum of H and LE fluxes and the difference between R_n , and G (HFT measured soil heat flux G_0 plus soil heat storage in upper soil above the HFTs (S_{soil})

$$LE + H = i + k \left(R_n - G \right) \tag{1}$$

where *i* and *k* are the intercept and slope, respectively. The k in 2010 and 2011 were 0.70 and 0.78 for FS, and 0.77 and 0.82 for GS during the growing season, respectively. These are within the normal range in most studies (e.g., Wilson et al. 2002, Foken 2008). The lack of EBC proposed possible errors in the sonic anemometer and a mismatch of source areas between the EB components, etc. (Frank et al. 2013).

QA/QC and gap-filling

The raw data from the EC systems were processed offline using the EC_Processor (available online).⁵ Briefly, raw data quality assurance/quality control (QA/QC) was checked, and spikes were removed according to LI-COR (2004). The diagnostic signals from the CSAT3 and LI7500 were used to flag periods with instrument malfunction. Time lags between measured scalars and vertical velocity were removed, and the planar fit (PF) method was applied to rotate the three velocity components into the mean streamline coordinate system (Wilczak et al. 2001). The PF procedure was performed using the mean wind records of the entire data set. The raw sonic temperature was corrected for fluctuations of water vapor concentration. A 30-min block average without detrending was used (Moncrieff et al. 2004), and a WPL correction was applied (Webb et al. 1980). We used the despiking criteria by setting experiential range checks for each of the physical variables. Data quality was first assessed by atmospheric stability and flux stationarity during periods of well-developed turbulence (Loescher et al. 2006). We also adopted a 7-day moving window in the time series of half-hourly fluxes in order to detect and filter out the erroneous flux (>6 SD of each window). For u^* (friction velocity) criteria, we plotted u^* with the fluxes by month, and found 0.10 m/s was reasonable in our grassland. Both of the LI7500s and CSAT3s' diagnostic value of AGC > 63 data was discarded.

⁵ http://lees.geo.msu.edu/resources/ec_processor.html

A series of data quality controls were conducted through modifications of the EC_Processor and data gap-filling strategy (Noormets et al. 2010, Xie et al. 2016). After the above quality controls were applied, the remaining data was 69% and 65% of the annual coverage for FS and GS in H, respectively, and $\sim 10\%$ less in LE. The data gaps were primarily caused by dew and rainfall, poor fetch direction (e.g., exclusion of data from the $\pm 15^{\circ}$ in lee of the sonic anemometer), and poorly developed turbulence $(u^* < 0.10 \text{ m/s})$. The remaining data were used to compare the differences between FS and GS energy fluxes, or for gap-filling procedures to obtain the cumulative fluxes. To derive a continuous half-hourly time series of energy fluxes, the data gaps of less than 2 h were filled using linear interpolation. The remaining gaps were filled with the marginal distribution sampling (MDS) method (Reichstein et al. 2005, Chu et al. 2015, Shao et al. 2015) by obtaining (1) mean half-hourly values with similar micrometeorological conditions (PPFD, VPD, SWC, and T_a) within a given window size around the gaps, or (2) mean diurnal values from a given window size around the gaps when micrometeorological data were not available (Falge et al. 2001). The size of the window increased from 7, to 14, to 28 days through the iteration of 1 and 2.

Footprint and uncertainties analysis

The fetch of the EC tower was >500 m in all directions for GS, and was 500 × 100 m for FS. Our footprint analysis following Stannard (1997:Eq. 18, p. 382) showed that approximately 98% and 94% of the measured scalar fluxes originated within the fetch area for the FS and GS towers under neutral condition, respectively. The distance between the two towers was ~2 km. Thus, we concluded that our measured fluxes adequately represented the energy exchanges of the two ecosystems.

Uncertainties of fluxes generated from the flux calculation, gap-filling processes, and u^* criterion selection were estimated following Aurela et al. (2002). Briefly, the random error for each half-hourly flux was estimated following Richardson and Hollinger (2005). The errors were propagated through the gap-filling processes and incorporated into the uncertainties of the gap-filling data. The Monte Carlo analysis was performed (1000 repetitions) and the standard deviation of the resulting annual sums was used as a measure for the uncertainty due to random measurement error (Chu et al. 2015). The uncertainties of the u^* criterion selection were estimated by the sensitivity analysis of applying different u* criteria. Finally, the halfhourly uncertainties were integrated into annual sums. All the flux uncertainties were reported at 95% confidence intervals.

Data analysis

 $R_{\rm n}$ was partitioned into LE, H, and G (i.e., $G_0 + S_{\rm soil}$)

$$R_n = \mathrm{LE} + H + G \tag{2}$$

 S_{soil} (W/m) was calculated as (Shao et al. 2008)

$$S_{\text{soil}} = (\rho_{\text{b}}c_{\text{d}} + \theta\rho_{\text{w}}c_{\text{w}})\frac{\Delta T}{\Delta t}z$$
(3)

where ρ_b (kg/m) is the soil bulk density, ρ_w is the density of water, c_d (890 J·kg⁻¹·K⁻¹) and c_w (4190 J·kg⁻¹·K⁻¹) is the specific heat capacities of the dry mineral soil and the soil water, and θ is the volumetric soil water content (%). $\Delta T/\Delta t$ (K/s) is the mean soil temperature change at the time t interval (1800 s), and z is the measurement depth. We used the 0.05 m depth soil temperature change and 0.30 m θ to estimate the heat storage above the HFTs.

Canopy surface conductance (g_c) was calculated using the inverted form of the Penman-Monteith equation (Monteith and Unsworth 1990)

$$g_{\rm c} = \frac{1}{\rho c_{\rm p} / \gamma (\rm VPD/LE) + [(\Delta/\gamma)\beta - 1](1/g_{\rm a})}$$
(4)

where LE is latent heat, ρ (kg/m³) is air density, c_p (J·kg⁻¹·K⁻¹) is the specific heat of the air, γ is the psychrometric constant (kPa/°C), β is the Bowen ratio (*H*/LE), Δ is the slope of the saturation water vapor pressure curve with respect to air temperature (kPa/°C), VPD (kPa) is the vapor pressure deficit of air, and g_a (m/s) is the aerodynamic conductance of the air layer between the canopy and the flux measurement height. The parameter g_a was calculated after Gu et al. (2005)

$$g_{\rm a} = \frac{1}{(u/u^{*2}) + 6.2u^{*-0.67}} \tag{5}$$

To isolate the vegetation effects on energy fluxes and by year, we divided the data set into two years: the first year (Year 1) from May 2010 to April 2011, and the second year (Year 2) from May 2011 to April 2012. This included two growing seasons (May-September in 2010 and 2011) and two non-growing seasons (October 2010-April 2011 and October 2011–April 2012). To estimate the diurnal changes in energy fluxes and their ratios (Figs. 3 and 4), FS and GS data with the same timestamp but without gap-filled data that passed quality control were combined into 30-min averages at growing seasonal scale. This was made in effort to reduce the sampling error associated with individual flux measurements that were resulted from the intermittent turbulence caused by horizontal transport across large sunny and shaded patches (Baldocchi et al. 2000, Ouyang et al. 2014). We used an R (version 3.0.0; R Development Core Team 2013) dismo package to derive boosted regression tree models (Elith and Leathwick 2016) to demonstrate the relative importance of abiotic variables by different site and year. For the comparisons between FS and GS, paired-sampled *t*-test (two-tailed) was used to compare the variables, and generalized linear model was used to compare the linear regression slopes (Fig. 8 and 9) (SPSS v22, IBM, New York, New York, USA). All the other statistical analyses and the flux data processing were performed in SAS 9.0 (SAS Institute, Cary, North Carolina, USA).

RESULTS

Microclimatic and biotic environment

The $T_{\rm a}$, $T_{\rm s}$, PPFD, and VPD showed a classical unimodal shape at both FS and GS at an annual scale, with significant differences (P < 0.05) between the two sites and the two years (Fig. 1, Table 2). In the 2010 growing season, the daily mean T_s at 10 cm depth was 17.72° and 18.15°C, with 18.50° and 19.41°C during the daytime, and 16.95° and 16.88°C at night in FS and GS, respectively. This resulted in a 0.98°C greater diurnal different soil temperature range (i.e., daily maximum-minimum temperature, DTR) at GS than at FS, and the 2-yr DTR cumulatively linear fitting with days slope was 26% greater at GS than FS. The VPD was higher at FS than that at GS (1.16 and 1.11 kPa, respectively) with a 15% difference in July 2010 (Fig. 1d). In 2011, the annual mean T_s was 6.68° and 6.60°C, and the mean daily T_a was 3.30° and 3.04°C at FS and GS, respectively. The SWC was lower at FS than GS, with 10.2% and 12.1% at FS and GS, respectively. The rainfall was similar at the two sites in the first year (260 mm) was higher while the second year was lower (174 mm) than the long-term annual rainfall (180 mm). Therefore the first year is described as a wet year and the second year as a dry year.

The changes in LAI at FS and GS appeared bimodal for both years (Fig. 2). In 2010, the maximum LAI was 0.70 ± 0.07 (mean \pm SD) for FS in early September and

 0.62 ± 0.06 for GS in mid-September. The specific leaf area (SLA) was $0.0059 \pm 0.0026 \text{ m}^2/\text{g}$ for FS and $0.0076 \pm 0.0033 \text{ m}^2/\text{g}$ for GS. The canopy height and cover, and the standing dead and litter biomass of the FS during the peak growing period was significantly greater (P < 0.05), nearly three-fold and two-fold, than that of GS (Table 1). The soil bulk density showed no significant difference between the two sites (Table 1). The belowground biomass at 0-0.2 m depth was greater in FS than in GS. No roots were found below 0.4 m at either site. In late August 2011, the maximum LAI was 0.38 ± 0.04 for FS and 0.21 \pm 0.05 for GS, significantly less (P < 0.05) than that in 2010, especially in GS, likely due to the extreme drought. The 0-1 m soil organic carbon concentration (g C per kg) was significantly greater (P < 0.05) in FS (9.58 ± 4.16) than in GS (8.99 ± 4.19) .

Diurnal changes in energy partitioning

The ensemble averaged diurnal trends in R_n , LE, H, and G in GS and FS also showed a classical unimodal shape (Fig. 3). Comparing the FS and GS, there were markedly lower R_n and H, but higher G in GS than those in FS during the daytime; LE showed different relationships between GS and FS, i.e., LE in GS was higher during the wet year but lower during the dry year (Fig. 3b vs. f). During the peak times (9:00–15:00), R_n decreased in the GS by 7% and 2% but G increased by 34% and 31% in Year



FIG. 1. (a) Mean daily air temperature at 2 m height (T_a), (b) soil temperature at 0.05 m depth (T_s), (c) soil volumetric water content at 0–0.3 m depth (SWC), (d) vapor pressure deficit (VPD), (e) photosynthetic photon flux density (PPFD) at 2 m height, and (f) precipitation (PPT) at the grazed and ungrazed desert steppes in Siziwang on the Mongolian Plateau desert steppe from 2010 through 2012.

	Growing season (May-Sep)				Non-growing season (Oct-Apr)				Entire year			
	2010		2011		2010-2011		2011-2012		2010-2011		2011-2012	
Items	GS	FS	GS	FS	GS	FS	GS	FS	GS	FS	GS	FS
T _a (°C)	17.84 ^a	18.18 ^b	16.04 ^a	16.22 ^b	-6.54 ^a	-6.22 ^b	-6.97 ^a	-6.47 ^b	3.11 ^a	3.44 ^b	2.65 ^a	3.02 ^b
$T_{\rm s}$ (°C)	20.84 ^a	20.62 ^b	19.06 ^a	19.11 ^b	-3.56 ^a	-2.86 ^b	-3.66 ^a	-3.57 ^b	6.10 ^a	6.44 ^b	5.84 ^a	5.91 ^b
SWC (%)	15.03 ^a	13.13 ^b	12.51 ^a	10.24 ^b	11.65 ^a	10.05 ^b	10.42 ^a	8.42 ^b	12.99 ^a	11.27 ^b	11.29 ^a	9.18 ^b
VPD (kPa)	1.26 ^a	1.31 ^b	1.19 ^a	1.21 ^b	0.29 ^a	0.30 ^b	0.28 ^a	0.29 ^b	0.68 ^a	0.70 ^b	0.66 ^a	0.68 ^b
Rainfall sum(mm)	257	257	144	144	3	3	30	30	260	260	174	174
$R_{\rm n} ({\rm MJ}\cdot{\rm m}^{-2}\cdot{\rm d}^{-1})$	9.66 ^a	10.60 ^b	9.90 ^a	10.42 ^b	2.63 ^a	3.28 ^b	3.29 ^a	3.82 ^b	5.13 ^a	6.18 ^b	6.05 ^a	6.58 ^b
$LE (MJ \cdot m^{-2} \cdot d^{-1})$	3.31 ^a	2.98 ^b	3.36 ^a	3.81 ^b	1.26	1.29	1.25 ^a	1.12 ^b	2.07 ^a	1.96 ^b	2.13 ^a	2.24 ^b
$H(\mathrm{MJ}\cdot\mathrm{m}^{-2}\cdot\mathrm{d}^{-1})$	3.90 ^a	4.22 ^b	4.67 ^a	5.00 ^b	1.73 ^a	2.08 ^b	1.74	1.86	2.59 ^a	2.93 ^b	2.96 ^a	3.17 ^b
$G_0 (MJ \cdot m^{-2} \cdot d^{-1})$	0.56	0.54	0.76 ^a	0.65 ^b	-0.25	-0.30	-0.04	-0.02	0.13	0.11	0.35 ^a	0.30 ^b
$S_{\text{soil}} (\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1})$	0.19	0.18	0.25 ^a	0.22 ^b	-0.08	-0.10	-0.01	-0.01	0.04	0.04	0.12 ^a	0.10 ^b
EBR	0.90 ^a	0.75 ^b	0.92	0.93	1.01	0.92	0.89 ^a	0.77 ^b	0.96	0.88	0.99	0.93
β	1.18 ^a	1.42 ^b	1.39 ^a	1.31 ^b	1.37 ^a	1.61 ^b	1.39 ^a	1.66 ^b	1.25 ^a	1.49 ^b	1.39 ^a	1.42 ^b
g _c (mm/s) GNPP (g/m ²)	4.97 ^a 81.31 ^a	4.40 ^b 117.91 ^b	3.52 ^a 27.62 ^a	3.86 ^b 64.59 ^b	4.43	4.46	4.76	4.78	4.71 ^a	4.43 ^b	4.11 ^a	4.30 ^b

TABLE 2. Energy balance components and major biological and meteorological factors at the grazed steppe (GS) and ungrazed fenced steppe (FS).

Notes: T_a , mean daily air temperature; T_s , soil temperature at 0.05 m depth; SWC, soil volumetric water content at 0–0.3 m depth; VPD, vapor pressure deficit; R_n , net radiation; LE, latent heat flux; H, sensible heat flux; G_0 , soil heat flux; S_{soil} , soil heat storage; G summed G_0 and S_{soil} . *EBR*, mean midday energy balance ratio; β , Bowen ratio; g_c , canopy surface conductance; GNPP, peak season green biomass. Midday was defined as 10:00–15:00. Significant differences between GS and FS are indicated by different letters at P = 0.05.

1 and 2, respectively; LE increased by 7% in wet Year 1 but decreased by 5% in dry Year 2, and *H* decreased by 7% in both years when compared to FS. The maximum *G* was nearly the same as the maximum LE (Fig. 3b, f vs. d, h).

At both FS and GS, *H* dominated in daytime energy partitioning $(H/R_n, \text{Fig. 4b}, \text{g})$ while LE/R_n (evapotranspiration fraction) was relatively small (Fig. 4a, f). LE/R_n showed a reversed-bell change with time during

8:00–18:00, while H/R_n and the EBC (Fig. 4e, j) showed an increasing trend. During the day, LE/R_n for FS and GS was higher in the early morning, and decreased over time until 12:00; varying little with 0.20 and 0.22 in 2010, 0.25 and 0.24 in 2011, respectively, during 9:00–15:00. The change at nighttime was stable and small, with about -0.20 in 2010 and -0.30 in 2011 at both FS and GS. The daytime Bowen ratio (β , H/LE) showed that a unimodal



FIG. 2. Seasonal variations of leaf area index (LAI) at the grazed and ungrazed desert steppes during (a) 2010 and (b) 2011. Bars indicate ± 1 SD.



FIG. 3. Daily net radiation (R_n) , latent heat (LE), sensible heat (H), and soil heat flux (G) at the grazed and ungrazed desert steppes over the entire growing season (May–September) of 2010 and 2011.

daily shape averaged over the growing season, with a maximum value of 2.0 at both FS and GS. The β was significantly greater (P < 0.05) in FS than that in GS (Fig. 4d, i).

Seasonal changes in energy fluxes

The seasonal changes in R_n , LE, H, and G were similar between the FS and GS at the daily (Fig. 5) and monthly (Fig. 6a–d) scales. All four energy flux components were low (close to zero for LE and with negative values for R_n , H, and G) during the snow cover period (i.e., December–February). After February in 2011 and 2012, R_n increased to a positive value, reaching the maximum in July before decreasing. The annual variation of LE showed a similar peak curve with the change of R_n . The maximum daily LE appeared in June for the GS (7.3 MJ·m⁻²·d⁻¹ in 2010 and 9.9 MJ·m⁻²·d⁻¹ in 2011) and for the FS (7.7 $MJ \cdot m^{-2} \cdot d^{-1}$ in 2010 and 9.3 $MJ \cdot m^{-2} \cdot d^{-1}$ in 2011). LE decreased after mid-August and became extremely low when the soil froze after late October (Fig. 6, Table 2).

The seasonal change in H was different from that of LE (Fig. 5b, c). H increased significantly with an increase in R_n from late March in both years, but decreased in May, while R_n continued increasing. Then H gradually decreased with other small peaks in August or October, reaching its minimum near January. This suggested that H reached its maximum in May, which was earlier than either R_n or LE. For EBC, ~95% of R_n was partitioned into H and LE, whereas the contributions of G and other energy flux components were ~5% at annual scale (Table 2).

Seasonal differences in energy fluxes between FS and GS also existed. The R_n and H were markedly lower in GS than those in FS during the growing season, while LE was higher and lower before and after June, respectively,



FIG. 4. Diurnal changes of the ratio of energy partition (latent heat flux [LE], sensible heat flux [H], and soil heat flux [G] to net radiation $[R_n]$), Bowen ratio (β , H/LE), and energy balance closure (EBC, $(H + LE)/(R_n - G)$) at the grazed and ungrazed desert steppes over the whole growing season (May to September) of 2010 and 2011.

in GS than that in FS in both years; and in GS the G differences remained smaller due to the greater absorption in daytime and release at nighttime (Fig. 6). Over the growing season, R_n decreased significantly (P < 0.05) at GS by 10% in 2010 and 5% in 2011 compared with FS (Fig. 6e). Monthly negative R_n appeared in December and January for both years at both sites, indicating that

the available energy used for the partitioning mainly came from the ground (Fig. 6a). The total LE was 506 (489–523, CI, 95%) and 456 (434–478) in 2010, 514 (496–532) and 583 (563–603) MJ/m² in 2011 for GS and FS, respectively, i.e., LE increased in GS by 11% in 2010 and decreased 13% in 2011 compared to FS. The highest LE month was found in July or August (Fig. 6b). The highest



FIG. 5. Seasonal changes of energy fluxes moving average with a period of 5 days at the grazed and ungrazed desert steppes from May 2010 through April 2012.

H month found in 2010 was July and in 2011 was April– June (Fig. 6c). *H* at GS decreased by 8% in 2010 and 7% in 2011 compared to FS. GS, meanwhile, increased *G* by 4% in 2010 and 22% in 2011 compared with FS (Fig. 6d, h).

At a monthly scale, the normalized energy fluxes LE/R_n was <0.4 for both years at both sites (Fig. 7a), while the H/R_n was >0.4 for most of the months (Fig. 7b). During the growing season, the maximum LE/R_n (>0.3) occurred in August for 2010 and in July for 2011 (Fig. 7a), both before reaching the months with maximum LAI, while the minimum LE/R_n (<0.25) occurred in July of 2010, the driest month during the two growing seasons. LE/R_n in GS was significantly greater (P < 0.05) in the first year, but lower in the second year than those in FS (P < 0.05 in May and June, Fig. 7d), while the H/R_n in GS was significantly (P < 0.05) lower in both growing seasons than that in FS (Fig. 7e). As a result, the seasonal β in GS was significantly lower (P < 0.05) than that in FS in Year 1 (Fig. 7f).

Energy partitioning and the biophysical regulations

The LE/ R_n appeared to be primarily controlled by g_c , LAI, and SWC (Fig. 8). There were significantly (P < 0.05) positive relationships between LE/ R_n and g_c in all four site-years. FS had significant smaller response slopes than that in GS's growing season in both years (Fig. 8a, b). The seasonal changes of midday mean g_c for the rain-free periods appeared to have significant



FIG. 6. (a–d) Monthly sum and (e–h) seasonal/yearly mean of energy fluxes at the grazed and ungrazed desert steppes from May 2010 through April 2012, including net radiation (R_n), latent heat (LE), sensible heat (H), and soil heat flux (G). Year1, May 2010 to April 2011; Year2, May 2011 to April 2012; grow1, May to September 2010; grow2, May to September 2011; non1, October 2010 to April 2011; non2, October 2011 to April 2012, respectively. Bars indicate +1 SE; and the significant differences between grazed and ungrazed are indicated by different letters at P = 0.05.

(P < 0.05) differences between the two sites during the growing season with significantly (P < 0.05) greater g_c during the first growing season for GS, but greater during the second growing season for FS (Table 2). These differences are consistent with the changes in LE. Significantly (P < 0.05) positive relationships were found between SWC and LE/ R_n at both GS and FS (Fig. 8d), and between LAI and LE/ R_n at GS (Fig. 8c). The regression tree results based on the growing season passed QC 10:00–15:00 data (i.e., half-hourly LE/ R_n) in both years against the potential drivers, suggesting that SWC dominated the changes in both years and sites. It also showed that PPFD contributed more on LE/ R_n variations in the second dry season than in the first wet season in both sites (Table 3).

There was also a significantly (P < 0.01) negative relationship between SWC and H/R_n (Fig. 9c, d), but a postive relationship between VPD and H/R_n at both GS and FS for both growing seasons (Fig. 9a, b). The regression tree results showed that SWC dominated the changes in H/R_n in the first wet season, while temperature was the primary variable responsible for the second dry season in GS and for both years in FS (Table 3).

DISCUSSION

Grazing reduced net radiation but enhanced soil heat flux

A 5–10% lower R_n in GS than that in FS was observed (Table 2). Grazing caused plant height and vegetation cover to decrease and albedo to increase. Thus, the ratio of R_n to incident solar radiation decreased with grazing, and significant linear negative relationships were found between LAI and albedo (Li et al. 2006). Therefore, the FS absorbed incoming solar radiation more efficiently because of higher LAI (i.e., decreased albedo) than GS (Fig. 2). The lowered R_n due to increased albedo at GS would contribute to the partitioning of LE and H within the near surface boundary layer. This reduction in R_n energy input by grazing has important implications for global warming

FIG. 7. (a–d) Monthly ratio and (e–h) seasonal/yearly ratio of energy fluxes at the grazed and ungrazed desert steppes from May 2010 through April 2012. Bars indicate +1 SE and the significant differences between the land-use types are indicated by different letters at P = 0.05.

studies and ecosystem modeling, as it can reduce annual mean temperature by up to 10% (Lee et al. 2011).

There was remarkably higher G during the day but lower G at night in GS than that in FS (Fig. 3d, h). This difference was more pronounced at a short time scale, but less obvious at broader time scales. For example, there is a 45% greater G in GS than that in FS in the peak of day, while there is 13% higher G in GS during the two growing seasons. Although a higher G during the day and lower G at night might counteract the difference between GS and FS in the daily and longer temporal scales, the increasing T_s and DTR (0.98°C) caused by G in GS needs attention (Shao et al. 2012). For example, this increased T_s could do harm to mainly distributed local C₃ photosynthetic pathway species in grasslands (Williams et al. 2007), indicating that G changes play an important role in plant growth and community structure in GS. On a daily scale, G was mostly positive from early March to late September except on rainy or cloudy days (Fig. 5d). An obviously greater G was observed in GS than in FS in 2011, suggesting that grazing enhanced more G in a dry year than in a wet year. Caused by the decreased R_n and elevated G by grazing, the growing season available energy $(R_n - G)$ at GS was 13.9% less than at FS. From this point of view, grazing may also decrease the surface air temperature and H, causing a "local cooling effect" in response to the decreased surface available energy from grazing.

The elevated G/R_n in GS compared to FS (0.60 at night and 0.20 during daytime; Fig. 4c, h) agreed well with our earlier study in a different grassland (Shao et al. 2008), where G/R_n was 0.70 at night and 0.20 during the day. This finding was also similar (i.e., 0.25) to that at midday during drought conditions in the North American grasslands (Meyers 2001) and similar to those at a Eurasian grazing steppe where G/R_n was overwhelmingly dominant at night (Li et al. 2006). Although G/R_n showed large seasonal fluctuations and was even dominating H/R_n and LE/ R_n in some months, the G/R_n was reduced to 0.05 on an annual basis (Table 2). Theoretically, G should be zero on an annual basis if there is no annual trend in soil temperature. However, the results of G at both sites were positive with a mean value of ~0.05. One of the reasons might be due to the spatial variation of G(Shao et al. 2008), which could be examined in future EB research through controlled experiments.

Grazing reduced the dry year LE but enhanced the wet year LE

Grazing decreased the growing season LE by 11% in the dry year (Fig. 6b) but increased LE by 13% in the wet year, regardless of a consistently greater LAI in FS than in GS. During the two growing seasons, LAI was 37% and 50% lower at GS than that at FS in Year 1 and 2, respectively (Fig. 2a). Grazing affected LE through

FIG. 8. Relationships between daytime LE/ R_n and canopy surface conductance (g_c) for (a) 2010 and (b) 2011 growing season, and (c) leaf area index (LAI) and (d) 0–0.3 m soil volumetric water content (SWC) at the grazed (GS) and ungrazed (FS) desert steppes during two growing seasons (May–September both in 2010 and 2011). LE/ R_n data are averaged with SWC bins of 1%. Bars indicate ±1 SE. The regression slopes comparison between FS and GS was (a) P < 0.001, (b) P = 0.013, (c) P = 0.007, (d) P < 0.001.

TABLE 3. The relative importance of each variable in the boosted regression tree model.

Variable, year, and site	$T_{\rm a}$	$T_{\rm s}$	SWC	VPD	PPFD
$\overline{\text{LE}/R_{n}}$					
2010 (wet)					
GS	8.87	7.99	66.90†	2.50	13.74
FS	5.63	3.19	78.28†	1.61	11.28
2011 (dry)					
GS	14.93	9.02	36.80†	15.25	24.01
FS	12.27	6.67	28.98	21.61	30.46†
$H/R_{\rm n}$					
2010 (wet)					
GS	13.13	19.15	40.07†	12.86	14.78
FS	45.09†	17.13	26.22	5.53	6.03
2011 (dry)					
GS	12.30	36.12†	28.02	6.30	17.26
FS	14.91	35.19†	23.17	10.57	16.16

Notes: Boosted regression tree modeling (Elith and Leathwick 2016, family = gaussian, tree.complexity = 5, learning. rate = 0.01, bag.fraction = 1) was between LE/ R_n and H/R_n with midday 30-min air temperature at 2 m height (T_a , °C), soil temperature at 0.05 m depth (T_s , °C), soil volumetric water content at 0–0.3 m depth (SWC, %), vapor pressure deficit (VPD, kPa), photosynthetic photon flux density (PPFD, mol·m⁻²·d⁻¹) at 2 m height at the grazed steppe (GS) and ungrazed fenced steppe (FS) using the growing season passed quality control data in 2010 and in 2011 (df = 642). Midday was defined as 10:00 through 15:00 local standard time.

†Marked the first dominate variable.

FIG. 9. Relationships between daytime H/R_n and (a, b) vapor pressure deficit (VPD) and (c, d) 0–0.3 m soil volumetric water content (SWC) at the grazed and ungrazed desert steppes during the 2010 (left) and 2011 (right) growing season (May to September). H/R_n data were averaged with VPD bins of 0.2 kPa, and SWC bins of 1%. Bars indicate ±1 SE. The regression slopes comparison between FS and GS were P < 0.001 in a, b, c, and d.

removal of LAI via several mechanisms. It enhanced E and reduced T by altering the partitioning of energy between the soil and the canopy. Reduced LAI increased both soil temperature and E via increased soil surface irradiance. On the other hand, grazing decreased T because of the reduced amount of irradiance intercepted by the canopy and decreased amount of energy partitioned to leaves. In our study, the reduced LAI in GS limited transpiration from the vegetation, and the belownormal precipitation limited E in the dry year of 2011, resulting in a reduced LE at GS. This concurred with Frank (2003) that grazed prairie had 7% less LE than ungrazed prairie in an arid region in North Dakota, USA. Similarly, Bremer et al. (2001) found that a grazed site had 28% less LE than an ungrazed site when the LAI was 78% lower during a dry period on tallgrass prairie sites in northeastern Kansas, USA. In all, grazing usually reduced LE in dry years.

Interestingly, LE was higher at GS than at FS in the wet year and during several periods despite the significantly lower LAI. In the wet year, the maximum daily LE in GS was 41% greater (i.e., 2.66 MJ·m⁻²·d⁻¹ greater,

Fig. 5b) than that of FS. In July 2011, we also observed a greater LE in GS (Fig. 6b). These periods coincided with several major rain events (Fig. 1f). We speculate that this might be because the mature leaves in FS have a protection mechanism for losing less water from their long-term adaption in the desert steppe. To explore the contributions of E and T for LE in GS with groundwater infiltration (Loik et al. 2004), we selected three typical rain events to examine the changes of soil moisture after each event. The soil dried slower in GS than in FS within the 5 days after the rains. The slightly more soil compaction and interception at the GS soil surface, the water loss in deeper soil layers by greater roots in FS than in GS might be another reasons. Meanwhile, younger leaves on the GS site were slower to senesce (Shao et al. 2013), which might have caused a greater LE than that at the FS site during the late growing season of the year. Greater LE on the GS site after 9 August for the first growing season was likely a consequence of younger leaves with higher transpiration rates (i.e., lower 18.9% of stomatal resistance), although increased E may also have contributed to the elevations in LE on the GS site after the

rain. This finding is consistent with our previous studies on the carbon assimilation ability in GS than that in FS during the active growth period (e.g., 9 August-6 September; Shao et al. 2013). As a result, there was a greater LE in GS than in FS in the wet year of 2010. This is in agreement with the results based on the Bowen ratio method that grazing increased LE when the soil was wet (Bremer et al. 2001). In addition, our results here showed that E might be less in GS than FS due to the observed higher SWC in GS. The recent isotope researches (Hu et al. 2014, Kool et al. 2014, Wang et al. 2015) concluded that T shared $\sim 80\%$ of ET in grasslands. Thus, the increased LE in GS during the wet year should mainly be from the increase in T, which was consistent with the active leaves and longer growth period in GS. In conclusion, T, not E, seemed more responsible for the LE differences between GS and FS.

A significantly greater (P < 0.05) LE/ R_n at GS than that at FS was recorded in the first growing season because grazing clearly increased LE and decreased R_n (Fig. 7d). The partitioning of available energy appeared to be related to variations in g_c , which not only regulated plant water loss but also carbon gain. The regression coefficient between g_c and LE/ R_n was relatively high in GS during the first growing season when the soil was moist (Fig. 8a). An increase in g_c directly elevated LE (Yang and Zhou 2011), and thus LE/R_n . The role of stomatal regulations of LE/R_n differed as a function of soil moisture conditions (Hunt et al. 2002, Aires et al. 2008). At our sites, the energy partitioning was significantly (P < 0.05) related to the dynamics of the top 0.3 m of the soil layer moisture in both GS and FS (Fig. 8d). This is because the surface soil layer received the most precipitation and returned it to the atmosphere through E(Agam and Berliner 2004) and T, which affected plant growth strongly since most of the grass roots measured were distributed within the top layers of the soil (0-0.2 m over 85%, Table 1).

Grazing reduced sensible heat flux consistently in both dry and wet years

H was consistently lower in GS than in FS at both short-time (Fig. 3c, g) and long-time scales (Fig. 6c), despite the high variation in LE. Theoretically, the exposure of soil surface and reduction in LAI would cause a greater H in GS. Contrary to this, we found a greater H in FS in both years, which means our hypothesis that grazing enhances H was rejected. These changes in Year 1 could be explained by the increased available energy $(R_n - G)$ and reduced LE (mostly T not E), resulting in a greater H in FS than in GS (Eq. 2 and Table 2). In Year 2, if the increase intensity was greater in $(R_n - G)$ than that in LE at FS, a higher H would still be expected because both $(R_n - G)$ and LE increased. This is confirmed because the second growing season $(R_n - G)$ increased by 102 MJ/m², while the LE increased only by 69 MJ/m².

A significantly higher (P < 0.05) H/R_n in FS than that in GS was observed consistently during the two growing seasons, suggesting that the increase in H was greater than the increase in R_n in FS (Fig. 7e). H dominated in the daytime and the entire growing season energy partitioning, with the seasonal H/R_n reaching 52% in FS and 48% in GS. The daytime H/R_n increasing from 8:00 to 18:00 (Fig. 4a, f) coincided closely with the daytime changes in VPD. The highest H/R_n was observed in July 2010 and from April to June 2011 during the growing season (Fig. 7b). During the leaf-out period, variation in H traced the variation in R_n very well. In contrast, H in the leaf-on period decreased despite an increasing $R_{\rm n}$ from the influence of both ecophysiological activities of the plants and rain events, which reduced H/R_n . During or immediately after the rain events, H/R_n was remarkably low.

Both EB components and its partitioning varied sharply in GS than in FS under different biophysical conditions or across the dry and wet years. For example, although the LE/ R_n increased, H/R_n decreased linearly with increasing in SWC, both with the slope in GS roughly twice than in FS (Figs. 8d and 9c). This suggests that LE/R_n and H/R_n under grazing were more sensitive to the soil water regime changes. In other words, LE/R_n in FS was relatively stable, i.e., the FS has a greater resistance to the changing climate, which means our hypothesis 3 was accepted. The seasonal changes of g_c during the rain-free periods appeared to be different between GS and FS during the growing season (Fig. 8). The low g_c at FS in the wet year or at GS in the dry year was related to high VPD (Table 2), low SWC, and low photosynthetic capacity at this nutrient poor site. The lasting drought conditions might be the reason for the stomatal closure that reduced the photosynthetic activity at this desert steppe (Yang and Zhou 2011, Lei et al. 2015). During the growing season in the wet year, VPD in GS was lower (Table 2), promoting the stomatal exchange (Pejam et al. 2006). As a result, the increase in LE and the decrease in R_n caused a significantly (P < 0.05) higher LE/R_n in GS than in FS during the wet season of Year 1 (Fig. 7d). In both years, VPD was positively correlated with H/R_n (Fig. 9a, b), i.e., a higher VPD (Table 2) resulted in a higher H/R_n in GS than in FS (Fig. 7e). In addition, when comparing the wet and dry years, LE variation was increased in GS, and the changes of R_n , H, and G in GS was 1.3, 1.3, and 1.1 times, respectively, greater than those in FS. Only for GS but not for FS, the boosted regression tree results showed that the dominate control variables on H/R_n changed between the dry and wet year. All of these evidences also supported a conclusion that the GS is more sensitive, while the FS is more resistant to the changing climate.

Energy fluxes and partitioning in global grasslands

To place our findings in a global context, we compiled energy fluxes and partitions in other grasslands and

	Daily							
Grassland type	Latitude (°N)	Maximum LAI	R _n	LE	Н	G	Maximum LE	Source
Meadow steppe (dry), F	44.60	2.9	n.a.	4.66	n.a.	n.a.	12.74	Dong et al. (2011)
Meadow Steppe (wet), F	44.60	3.1	n.a.	5.39	n.a.	n.a.	13.72	Qu et al. (2016)
C ₄ short-grass prairie (dry), F	31.59	2.5	n.a.	4.51	n.a.	n.a.	7.72	Krishnan et al. (2012)
C ₄ short-grass prairie (wet), F	31.59	2.5	n.a.	5.24	n.a.	n.a.	8.82	Krishnan et al. (2012)
C_3/C_4 grassland (dry), F	31.74	1.0	n.a.	3.33	n.a.	n.a.	7.23	Krishnan et al. (2012)
C_3/C_4 grassland (wet), F	31.74	1.0	n.a.	4.07	n.a.	n.a.	8.33	Krishnan et al. (2012)
Typical steppe (wet), F	42.05	1.0	5.52	2.91	2.75	0.37	13.96	Chen et al. (2009)
Typical steppe (normal), F	43.55	0.5	n.a.	n.a.	n.a.	n.a.	8.59	Miao et al. (2009)
Typical steppe (normal), G	43.55	0.4	4.79	1.89	2.24	0.28	9.04	Miao et al. (2009)
C_3/C_4 grassland (dry), G	38.47	0.4	5.81	2.12	3.19	0.11	6.86	Aires et al. (2008)
C_3/C_4 grassland (normal), G	38.47	2.5	7.16	3.23	2.50	0.36	11.03	Aires et al. (2008)
Typical steppe, G	47.02	0.6	4.29	1.11	2.42	0.23	6.93	Li et al. (2006)
Desert steppe, F	32.60	n.a.	n.a.	2.01	n.a.	n.a.	5.15	Mielnick et al. (2005)
Desert steppe, F	44.08	0.4	n.a.	2.21	n.a.	n.a.	9.31	Yang and Zhou (2011)
Desert steppe (dry to wet), F	41.79	0.7	6.18	1.96	2.93	0.15	7.69	This study
Desert steppe (dry to wet), G	41.79	0.6	5.13	2.07	2.59	0.17	6.99	This study
Desert steppe (dry), F	41.79	0.4	6.58	2.24	3.17	0.40	9.91	This study
Desert steppe (dry), G	41.79	0.2	6.05	2.13	2.96	0.47	9.31	This study

TABLE 4. Comparison of energy fluxes and partitioning of yearly eddy-covariance measurements on grasslands.

Notes: LAI, leaf area index; F, fenced ungrazed; G, grazed. Daily energy flux unit: MJ·m⁻²·d⁻¹. n.a., data not available.

compared them with our results (Table 4). Daily mean LE varied from 1.11 MJ·m^{-2·d⁻¹ to 5.39 MJ·m^{-2·d⁻¹ and the}} maximum LE varied from 5.15 MJ·m⁻²·d⁻¹ to 13.96 MJ·m⁻²·d⁻¹ over the range of arid desert steppes to wet meadow steppes and prairie grasslands. Notably, H and G varied less than LE. The daily mean LE $(2.24 \text{ MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1} \text{ in FS and } 2.13 \text{ MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1} \text{ in GS},$ respectively) of our desert steppe was at the lower end within the range of global grassland ecosystems. For this moderately grazed desert steppe, the daily LE of GS (LAI 0.2–0.4) was 2.07–2.13 MJ·m^{-2·d⁻¹, which is relatively} higher than the heavily grazed typical steppes with LE of 1.89 $MJ \cdot m^{-2} \cdot d^{-1}$ (Chen et al. 2009, peak LAI 0.4) or 1.11 MJ·m⁻²·d⁻¹ (Li et al. 2006; peak LAI 0.6) on the Mongolian Plateau. However, our LE in GS was lower than that of a C₃/C₄ grassland in Portugal $(3.23 \text{ MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1})$ where there is a greater LAI of 2.5 (Aires et al. 2008). The daily LE of FS (1.96-2.24 MJ·m⁻²·d⁻¹) with an LAI of 0.4-0.7 was very close to the result from an ungrazed desert steppe of 2.21 MJ·m⁻²·d⁻¹ with an LAI of 0.4 on the Mongolian Plateau (Yang and Zhou 2011), while they were much lower than an ungrazed typical steppe (Chen et al. 2009) or meadow steppe (e.g., Dong et al. 2011). The differences in LE among grassland ecosystems seemed to be related to differences in LAI that depended directly on precipitation (Aires et al. 2008, Li et al. 2012, Xiao et al. 2013).

The global annual LE/ R_n varied from 0.26–0.53, the H/R_n varied from 0.35–0.56, and the G/R_n varied from 0.02–0.08 from these arid desert steppes to wet meadow steppes and prairie grasslands. At our site, the annual bulk LE/ R_n ratio averaged at 0.33 in FS and 0.38 in GS, the H/R_n ratio averaged at 0.48 in FS and 0.59 in GS, while the G/R_n ratio was ~0.05. The Mongolian desert steppe had a low LE/ R_n compared to a Mediterranean

 C_3/C_4 grassland (Aires et al. 2008) or to a typical steppe in the same area (Chen et al. 2009). The significantly positive relationships between g_c and LE/R_n at both the study sites suggested that a lack of precipitation coupled with high VPD conduced remarkable decreases of g_c , which could decrease the LE/R_n in this semiarid ecosystem. A lower LE/R_n and higher H/R_n might be one of the major characteristics of the Mongolian desert steppe due to their low LE vegetation adaption (Mulroy and Rundel 1977), sparse vegetation cover, and arid climate.

Management applications

Our results suggest that in a semiarid to arid desert steppe, proper grazing conserves soil water in dry years, but not in wet years. This is demonstrated by year-to-year variations in climate that affect LE between GS and FS. The GS substantially reduced LE by 11% in the dry year mainly caused by the reductions in T by defoliation, combined with minimal contribution of E from the soil. This reduction in LE may conserve soil water, which could be available later in the growing season (Day and Detling 1994). In contrast, GS enhanced LE by 13% in the wet year, which was caused by longer daily and seasonally regrowth of younger leaves with lower stomatal resistance and, therefore, higher transpiration per unit leaf area compared to FS. Under grazing, lower LE in the drier years and higher LE in the wet years has important implications for the hydrologic cycle in this arid environment, although further research is required to check other components of the water balance besides LE and rainfall (e.g., deep percolation and runoff).

The effects of grazing on LE also have implications for the carbon balance of the steppe, because H_2O and C are always coupled through the stomata (Tuzet et al. 2003). Therefore, the decrease in photosynthetic rates after defoliation in GS may be offset by improved water relations during dry periods (Bremer et al. 2001). In another mixed-grass prairie, grazing increased both photosynthetic rates, soil carbon and nitrogen (Schuman et al. 1999), suggesting that LE also had been impacted by grazing and vice versa.

Both reduced available energy and sensible heat flux through grazing indicated a cooling effect feedback onto the local climate, which further means a negative feedback to global warming. As a result, the surface air temperature is lower in a grazed area than in a nearby ungrazed area triggered by increases in surface albedo (Davin and Noblet-Ducoudré 2010). Here, we demonstrated that the one-tenth reduction in energy fluxes by grazing should be considered in climate models as a driver of land management for climate mitigation due to the large land use changes on the Mongolian Plateau. More generally, our study supports that a better understanding of ecological controls can mitigate the adverse ecological consequences of global change through management strategies (Bobbink et al. 2010, Beck et al. 2015).

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DATA AVAILABILITY

Data associated with this paper have been deposited in Dryad: https://doi.org/10.5061/dryad.fk2rm