Ecosystem responses to mowing manipulations in an arid Inner Mongolia steppe: An energy perspective

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\textbf{ABSTRACT}

Mowing for hay is a widely adopted practice for grasslands utilization and management. However, its effects on energy partitioning have not well been studied. Our primary objective was to examine the role of mowing as a disturbance factor acting on energy partitioning and relationships between community composition/structure and energy fluxes in a typical steppe ecosystem through a long-term field experiment in Inner Mongolia. After four years of annual mowing, dominant species changed from \textit{Stipa krylovii} to \textit{Artemisia frigida}. Mowing decreased hay productivity via the reduction of palatable perennial bunchgrass. During the growing season, soil moisture was 47.5\% lower and soil surface temperature was 7.4 °C higher at midday and 2.2 °C lower at predawn, with a 4.2 °C greater diurnal soil temperature range at 2 cm depth in the heavily mowed plots compared to that in the unmowed plots. Heavily mowing lowered 6\% net radiation and 98 MJ m\textsuperscript{-2} available energy, but elevated 2.1 times soil heat flux. Heavily mowed plots shared higher sensible heat flux, but similar latent heat flux. The absence of mowing might alleviate the stress of high temperature and drought during the hot and dry periods, leading to a high resistance of vegetation to environmental changes.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Energy fluxes distribution in the un-mowed and mowed plots.}
\end{figure}

1. Introduction

Energy fluxes, such as net radiation, soil heat, latent heat and sensible heat, represent the complex functions of long-term interactions between human disturbances, climate and water cycling, and of short-term interactions between plant physiological processes and the development of the atmospheric boundary layer in terrestrial ecosystems (Wilson et al., 2002). Vegetation, as an intermediary, plays a central role in buffering the mass and energy exchanges of land surfaces and the atmosphere (Baldocchi et al., 1988; Beringer et al., 2005). Species composition, structure and distribution of vegetation could be directly affected by the changes in climate and energy partitioning (Kittel et al., 2000), disturbances and management (Schippers and Joenje, 2002). In return, any changes in vegetation composition and structure would further bring significant influences on the heat and water regimes and budgets (Hernandez-Ramirez et al., 2010; Li et al., 2000), causing significant feedbacks to regional and global climate (Beringer et al., 2005; Eugster et al., 2000; Gu et al., 2005; Kellner, 2001).

Mowing for hay is a widely-practiced human disturbance and a pasture management type in grassland ecosystems (Bao et al., 2004; Luo et al., 2001). It resembles the grazing process in terms of canopy biomass removal in grassland ecosystems, causing substantial changes in the canopy structure, species composition and functional type (Poptcheva et al., 2009) and thereby dramatically affects the ecological and hydrological processes, including aerodynamic characteristics, microclimate, surface resistance to evaporation and soil water holding capacity (Chen et al., 2009; Li et al., 2000). It has been documented that mowing can lead to changes in the variability of environmental resources in an ecosystem (Chen et al., 1999, 2004). Changes in community structure could pose direct effects on soil heat flux, which can account for up to one third of the net radiation in arid and semi-arid grasslands (Li et al., 2006; Shao et al., 2008). Wan et al. (2002) found that mowing could increase the growing season soil temperature range by 4.3 °C in a Great Plains tall grass prairie. Klein et al. (2005) reported that mowing increased soil temperature by 1.7 °C and increased the maximum air temperature by 4.0 °C in the Tibetan Plateau rangeland. All of these studies pointed a conclusion that mowing would exacerbate the effects of climatic warming (Luo et al., 2001) and give evidences of near relationships between mowing disturbance and microclimate. However, significantly less effort had been made to examine the underlie processes (i.e.,...
energy fluxes) that determine the microclimatic changes associated with the vegetation change.

The widespread occurrences of changes in microclimate arising from manipulation of terrestrial vegetation require great attention. Climate changes (e.g., temperature increases) caused by extensive land-use alteration may be as substantial at both local and regional scales as the predicted modifications caused by the greenhouse effect (Chen et al., 1999; Schwalm et al., 2010). Despite the important role that grasslands may play in regulating global climate change and the hydrological cycle, manipulative experiments to explore the relationships between energy partitioning and grassland management practices (e.g., mowing) and to reveal the potential contribution of grassland ecosystems to climate change at local scales have been extremely rare in the literature (Rosset et al., 2000).

These kinds of changes in microclimatic measures, such as light input, air temperature and humidity, soil temperature and moisture play important roles in plant growth and community structure, even exotic species invasion. Plant growth is affected directly by temperature change and indirectly by altering the ecosystem’s moisture condition, length of its growing season, etc (Shaver et al., 2000). Each kind of plant has its favorable threshold of germination and death in light, temperature and moisture regimes. If extreme conditions exceed tolerance thresholds for certain species, growth patterns and species compositions will likely be altered (Ma et al., 2010; Wayman and North, 2007). We therefore also put the effort in explore plant species composition and growth with microclimatic change.

Our objectives then are to examine the effects of mowing as a disturbance agent on energy partitioning and to explore the relationships between different heat fluxes and community composition and structure characteristics at the long-term field experimental site of CAS, located in the Inner Mongolian Autonomous Region of northern China. We hypothesized that mowing would lead to significant changes in energy partitioning, including an increase in soil heat, sensible heat and latent heat fluxes but with a decrease in net radiation due to lowered canopy buffering capacity that can be expressed in canopy architecture and community composition. We further hypothesized that the removal of biomass by mowing would facilitate and maintain plant coexistence and diversity by changing the surface environments.

2. Methods

2.1. Study site

The study was conducted during the 2007 growing season at the mowing plots of the long-term experimental of the Duolun Restoration Ecology Research Station (42° 50’ N, 116° 18’ E, elevation 1380 m asl, Fig. 1). The area belongs to a semi-arid agro-pastoral transitional region in southeastern Inner Mongolia, with a typical continental climate. The mean annual temperature is around 3.3 °C, with a mean monthly temperature ranging from −15.9 °C in January to 19.9 °C in July. The mean annual precipitation is ~400 mm (375 mm in the study year), which falls primarily from May to October. The mean annual relative humidity is about 61%. Summers are damp and warm while winters are cold, dry and windy (5.2 m s⁻¹ in winter and 2.6 m s⁻¹ in summer in the study year). The study site was flat with relatively homogenous vegetation of a typical steppe ecosystem dominated by a perennial bunchgrass – Stipa krylovii Roshev. Other common species include Artemisia frigida Willd., Potentilla acaulis Linn., Cleistogenes squarrosa Trin., and Allium bidentatum Fisch. Ex Prokh.&Ilkonn.—Gal. Soil is classified as chestnut soil (Chinese classification) or Haplic Calcisols according to the FAO classification, with 62.75 ± 0.04% sand, 20.3 ± 0.01% silt and 16.95 ± 0.01% clay. Mean bulk density is about 1.31 g cm⁻³ and pH is around 7.12 ± 0.07. The site has been fenced since 2001 to exclude large herbivores such as cattle and sheep, which had been previously grazed for several decades.

2.2. Experimental design

The experiment was designed using a single-factor with five mowing intensities aiming at maintaining post-harvest heights of 2 cm [R₁₀], 5 cm [R₂], 10 cm [R₅], 15 cm [R₁₅], and no mowing [Rₐ, control], with five replications for each treatment. Usually farmers

![Fig. 1. Our study sites are located in a typical steppe grassland region of Inner Mongolia, China. R₁₀, R₅, and Rₐ represent three mowing treatments where the steppe was trimmed once a year to a height of 2 cm and 10 cm, or no mowing (i.e., control), respectively.](image-url)
in the study region in Inner Mongolia typical steppe mow pasture at the height of 5–7 cm once per year, depending on rainfall. A total of 25 10 × 20 m² plots were established at the study site with 4 m gaps between the adjacent plots. Mowing (using a push mower, Yard-man 160CC, USA) and biomass removal began in 2003 and took place once per year in late August, after which plants were allowed to grow until the next mowing.

2.3. Measurements of available energy and other micrometeorological variables

An automatic microclimate measuring system consisting of nine monitoring stations was employed to measure energy fluxes and micrometeorological variables. Each station was deployed at three randomly selected plots from five replicates of R2, R10, and Rc treatments (i.e., nine out of 25 plots, representing heavy mowing, suitable mowing, and without mowing control) due to a limited number of channels on the datalogger for recording. These stations were deployed in a way to avoid edge effects (Chen et al., 1992) in the selected plots. Each station was equipped with one Q7.1 net radiometer (Radiation Energy Balance System (REBS), Seattle, WA, USA) mounted at 0.50 m above the canopy for net radiation (Rn), two heat flux transducer HFT3.1s (REBS) buried at 8 cm soil depth to measure soil heat flux (Gs), two custom-made T-type copper-constantan thermocouples to measure soil temperature at 2 (T_{soil}), and 6 cm (T_{6cm}) soil depth, and a E-type chromel-constantan thermocouple to measure soil surface temperature (T_{s}). Soil volume water content (θ) at 2.5 cm (upper pole) under the soil surface was recorded with water content reflectometers (CS616, Campbell Scientific Inc. (CSI)). Soil bulk density (ρb, at 0–5 cm depth) was measured with four replicates at each plot. T_{2cm}, T_{6cm}, θ, and ρb were used to calculate the soil layer heat storage flux (∆S) above the HFT3.1 plates (Shao et al., 2008). The sum of Gs and S is soil heat flux (G). An additional E-type thermocouple and a 3-Cup-Anemometer (CSI) were used to determine the air temperature (T_a) and the wind speed (u) at the height of 2.0 m. All meteorological data were collected at 10-s intervals and compiled as 30-min averages with a CR10X (CSI) datalogger. Canopy surface temperature (T_c) was measured using a hand infrared thermometer (IRT, Fluke63, Raytex Inc, USA) with an emissivity of 0.95. Rainfall data were derived from a nearby weather station about 1000 m north of our experimental site. Continuous measurements of micrometeorological variables began on 3 June (DOY 154), 2007.

2.4. Calculations of turbulence energy

Sensible heat flux (H) was determined following the method of Triggs et al. (2004):

\[ H = \rho_0 c_p (T_s - T_a) / \rho_a \]  

where \( \rho_0 \) is air density (kg m⁻³), \( c_p \) is the heat capacity of air (J kg⁻¹ K⁻¹), \( T_s \) is the canopy surface temperature (K), \( T_a \) is the air temperature (K), \( \rho_a \) is the aerodynamic resistance (s m⁻¹). We used the method of Triggs et al. (2004; page 69) to calculate the \( \rho_a \). Eqs (15), (13), (14) and (5) were used, in turn. Latent heat flux (LE) was quantified by a residual energy balance approach:

\[ LE = R_n - G - H - Q \]  

where LE is the latent heat flux, \( R_n \) is the net radiation, G is the soil heat flux, H is the sensible heat flux, and Q is the sum of other heat fluxes on the surface (e.g., in plants, water, etc.) with a small fraction converted to chemical energy through photosynthesis. In grasslands, Q is relatively minor due to low vegetation mass and is ignored in this study.

2.5. Measurements of community indexes

One picture of a 1 × 1 m² quadrat enclosed by a sampling square was taken vertically at each plot with a digital camera (Canon DS6041, Japan) mounted at a height of 2 m in mid-August. Community coverage was calculated using Adobe Photoshop 7.0 software (Adobe Systems, Inc., USA). Canopy height in each plot was measured manually and percentage coverage of each species was assessed visually in each quarter. The density of individuals/ clusters for each species was also recorded. Species frequencies were measured through a quadrat (1 × 1 m²) with 100 sub-quadrats by recording the presence amount for a given species. These data were finally sorted by functional types. Plant abundance, species richness, evenness (Pielou index), and the Shannon-Wiener index were calculated to describe the diversity characteristics of the plant community (see Zhou et al., 2006).

We also measured live canopy biomass, including all green tissues for herbs and current-year twigs for shrubs (Jobbagy and Sala, 2000). For biomass estimation, all the aboveground living plant tissues, dead stand plant tissues and plant litter were collected in 0.5 × 0.5 m² quadrats, with three replications for each treatment, at two-week intervals during the growth season and stored in an icebox. Clippings were then sorted with green and dead stand by each species. After the leaf area index (LAI) was measured (LI-3000, LI-COR Biosciences, Inc., Lincoln, NE), the samples were oven-dried at 65 °C to constant weight (≈ 48 h) to obtain biomass estimates.

2.6. Data analysis

We analyzed most of the data using a one-way ANOVA (SPSS 11.0 software) unless stated otherwise. The significance of detected differences was determined using Duncan’s multiple comparison tests. Data sets determined to be abnormal were either log-transformed or square-root transformed to achieve normality and homogeneity of variances. Data were back-transformed to report the results. We conducted repeated-measures ANOVA where ‘date’ was the repeated measure and ‘mowing level’ was the main factor in canopy temperature analysis (SAS software). For all ANOVAs, the reported results are significant at P < 0.05 unless stated otherwise. A one-tailed Pearson correlation was used to verify the relationship between community indexes and energy fluxes.

3. Results

3.1. Community characteristics

Changes in green canopy biomass with mowing intensity showed clear seasonal patterns and were highly consistent with that in the accumulated rainfall (Fig. 2). The total vegetation coverage was comparable among the three mowing treatments. However, the percent cover of different individual species differed greatly in response to the mowing treatments, with significant decrease of A. krylovii, obvious increase of A. frigida, and no significant change of P. acaulis with increasing mowing intensities (Fig. 3a). The total LAI decreased with mowing intensity and was significantly higher (P < 0.05) in the Rc plots than that in the mowed plots (Fig. 3b). LAI of S. krylovii also decreased significantly with increasing mowing intensity while no significant difference was detected for A. frigida. Among the three treatments, LAI of P. acaulis was highest in the R0 plots and lowest in the Rc plots (P < 0.05). Among the three dominant species, the highest LAI in R2 was A. frigida, in R10 was P. acaulis, while in Rc was S. krylovii (Fig. 3b). The same trends to those of LAI were found for the green canopy biomass of both the total and individual species measures.
Interestingly, opposite trends in the relative biomass were found between *A. frigida* and *S. krylovii* (data not shown). Mowing affected biodiversity and green biomass in opposite ways (Fig. 3; Tables 1 and 2). That is, the values of green biomass decreased while plant abundance, Pielou and Shannon-Wiener indices, and species richness increased with mowing intensity. Significantly higher plant abundance, Shannon-Wiener indices, and species richness were found in both mowing treatments (*R*2 and *R*10) relative to the unmowed reference plots, *R*0 (*P* < 0.05, Table 2). The mean green biomass (g m⁻² year⁻¹) was 112 ± 7, 76 ± 10 and 66 ± 8 in *R*c, *R*10 and *R*2, respectively. Hay harvest (the sum of green biomass and dead stand, t ha⁻¹ year⁻¹) was 9.1 ± 1.2, 10.0 ± 1.0 and 28.9 ± 2.0. *R*2 had the highest plant abundance but the least green biomass, i.e., the plant sizes in these plots were smaller than in those of the other treatments.

As mowing intensity increased, species frequency trends showed an increase in *A. frigida* and a decrease in *S. krylovii*. Altogether, we recorded 26, 25 and 25 species in *R*2, *R*10 and *R*c, respectively (Table 1). Most of these species were perennial forbs. Compared with *R*c, *R*2 and *R*10 were characterized by a greater frequency of Liliaceous species (*A. bidentatum*, *Allium nerini* and *C. squarrosa*). *R*10 had significantly higher (*P* < 0.05) frequency of *Carex duriuscula* than the other two treatments. *Leymus chinesis*, one of palatable species for the livestock, was found exclusively in *R*c with relatively high frequency. Like percent coverage, no differences were found in frequency of *P. acaulis* among the three treatments.

Other community structural features were also altered by mowing manipulations (Fig. 4). Litter weight in the mowed plots was consistently lower than in the unmowed plots (*R*c), with litter coverage at least 4 cm thicker in the *R*c plots. Dead stand and stem weight were also significantly lower in the mowed plots than in the reference plots, with weights nine times higher in *R*c than in *R*2 and *R*10. Vegetation height decreased significantly (*P* < 0.05) with mowing intensity. *S. krylovii* biomass per cluster in mowed plots was significantly (*P* < 0.05) lower than in the unmowed plots, although the number of plants or clusters showed no significant difference among the three treatments (18 ± 8, 21 ± 11 and 24 ± 6 (mean ± 1 SD) for *R*c, *R*10 and *R*2, respectively).

### 3.2. Soil moisture

There were substantial fluctuations in soil moisture (θ) in both the control and the mowed plots. Temporal changes in θ in the three treatments followed similar trajectories, and exhibited obvious differences between different treatments, with a consistent trend in daily θ of *R*c > *R*10 > *R*2 throughout the growing season (Fig. 5). Significant differences in the seasonal mean θ were also found between the three treatments, with the mean θ being 47.5 and 20.5% lower (*P* < 0.05) in the *R*2 and *R*10 plots, respectively, than in the unmowed plots (Fig. 5, inserted panel).

### 3.3. Soil temperature

With increasing mowing intensity, soil surface temperature (*T*ₘ₀) increased during the daytime, but decreased at night.
Table 1
Plant species frequency (%) in three different mowing treatments in a semi-arid grassland ecosystem of Inner Mongolia, northern China. Data (mean ± 1 SE) with the same letter was not significantly different in Duncan’s multiple tests reported from one-way ANOVA (P > 0.05).

<table>
<thead>
<tr>
<th>Plant functional group</th>
<th>Species</th>
<th>Mowing intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R2</td>
</tr>
<tr>
<td>Annual and biennial</td>
<td>Salsola collina</td>
<td>1 ± 1</td>
</tr>
<tr>
<td></td>
<td>Fagopyrum tataricum</td>
<td>0a</td>
</tr>
<tr>
<td></td>
<td>Gentiana squarrosa</td>
<td>1 ± 1</td>
</tr>
<tr>
<td></td>
<td>Artemisia annua</td>
<td>0a</td>
</tr>
<tr>
<td>Perennial rhizome</td>
<td>Agropyron michnoe</td>
<td>15 ± 8a</td>
</tr>
<tr>
<td>grass</td>
<td>Leymus chinesis</td>
<td>0a</td>
</tr>
<tr>
<td>Perennial</td>
<td>Cleistogenes squarrosa</td>
<td>19 ± 3a</td>
</tr>
<tr>
<td>bunchgrass</td>
<td>Stipa krylovii</td>
<td>59 ± 7a</td>
</tr>
<tr>
<td></td>
<td>Poa angustifolia</td>
<td>0a</td>
</tr>
<tr>
<td></td>
<td>Koeleria cristata</td>
<td>1 ± 1a</td>
</tr>
<tr>
<td>Perennial forb</td>
<td>Carex duriuscula</td>
<td>10 ± 3a</td>
</tr>
<tr>
<td></td>
<td>Melilotus ruthenic</td>
<td>1 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Astragalus scaberrimus</td>
<td>3 ± 2a</td>
</tr>
<tr>
<td></td>
<td>Astragalus galactites</td>
<td>2 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Heteropappus alticus</td>
<td>2 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Potentilla acutil</td>
<td>40 ± 12a</td>
</tr>
<tr>
<td></td>
<td>Potentilla bifurca</td>
<td>5 ± 2a</td>
</tr>
<tr>
<td></td>
<td>Potentilla tanacetifolia</td>
<td>1 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Potentilla betonicaefolia</td>
<td>1 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Potentilla multifida</td>
<td>0a</td>
</tr>
<tr>
<td></td>
<td>Allium bidentatum</td>
<td>40 ± 6a</td>
</tr>
<tr>
<td></td>
<td>Allium tenuissimum</td>
<td>1 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Allium neriiflorum</td>
<td>9 ± 6a</td>
</tr>
<tr>
<td></td>
<td>Allium ramosum</td>
<td>0a</td>
</tr>
<tr>
<td></td>
<td>Allium senescens</td>
<td>2 ± 2a</td>
</tr>
<tr>
<td></td>
<td>Iris tenuifolia</td>
<td>1 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Thalictrum pseudotetumidum</td>
<td>0a</td>
</tr>
<tr>
<td></td>
<td>Dianthus amurensis</td>
<td>1 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Androsace umbellata</td>
<td>1 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Scorzoneria mongolica</td>
<td>0a</td>
</tr>
<tr>
<td>Shrub and semi-shrub</td>
<td>Cymbalaria dahurica</td>
<td>1 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Artemisia capillaris</td>
<td>1 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Artemisia frigida</td>
<td>98 ± 1a</td>
</tr>
<tr>
<td></td>
<td>Thymus serphyllum</td>
<td>1 ± 1a</td>
</tr>
</tbody>
</table>

a. Following the species name means data with skewed probability of occurrence were log-transformed for the analysis. Data less than 0.5 but not 0 marked with 1.

R2, R10, and Rc represent mowing once per year to a height of 2 cm, to a height of 10 cm, and no mowing, respectively.

(Fig. 6a). The growing season averages of T$_{sur}$ were 7.4 and 4.8 °C higher at midday and 2.2 and 1.2 °C lower at predawn for R2 and R10, respectively, as compared to the values for the Rc. Daytime averages (6:30–18:00 h) were 24.2, 26.5 and 28.2 °C while nighttime (18:30–6:00 h) averages were 12.1, 11.2 and 10.2 °C for R2, R10 and Rc in the growing season from 3 Jun to 31 Oct, 2007, respectively. Daily averages of T$_{sur}$ over the growing season were 1.2 and 0.8 °C higher in R2 and R10, respectively, than in Rc. The diurnal T$_{sur}$ range (DTR, the difference between the daily maximum and minimum temperature) also became higher in the mowed plots (Fig. 6a), with increases in the diurnal T$_{sur}$ range by mowing being 9.0 (R2) and 5.9 (R10) °C over that of Rc.

Similar to those for T$_{sur}$, soil temperatures at 2 cm depth were 3.4 and 2.9 °C higher at midday and 0.9 and 0.5 °C lower at predawn for R2 and R10, respectively, than Rc. The growing season averages of soil temperature were 19.5, 21.0 and 21.2 °C during the daytime (6:30–18:00 h) and 14.4, 14.2 and 13.9 °C at night (18:30–6:00 h) for R2, R10 and Rc, respectively. Mowing increased the growing season soil temperature by 0.7 °C for R2 and R10 over Rc. Soil DTR was also higher in the mowed vs. unmowed plots (Fig. 6b).

Mowing elevated the diurnal soil temperature ranges of 4.2 and 3.4 °C over Rc by R2 and R10, respectively.

3.4. Available energy

Diurnal changes in available energy showed an obvious lowered trend in Rc with increasing mowing intensity during the daytime (Fig. 7A). By average, the midday R$_y$ over the growing season were 413, 395 and 388 W m$^{-2}$ for R2, R10 and Rc, respectively. Rc was nearly 6.0% lower in the R$_y$ treatment than that in Rc both at midday and on a daily base. Over the growing season, the total R$_y$ were 1409, 1331 and 1328 MJ m$^{-2}$ for R2, R10 and Rc, respectively, i.e., in the heavily mowed treatment (R2) decreased by 6% (or about 81 MJ m$^{-2}$) compared with the reference.

Soil heat flux (G) increased with mowing intensity during the daytime (Fig. 7B). On a typical sunny day (14 August), G values at

Table 2
Values (mean ± 1 SE) of diversity indices in three different mowing treatments in a semi-arid steppe ecosystem of northern China.

<table>
<thead>
<tr>
<th>Mowing intensity (m$^{-2}$)</th>
<th>Plant abundance</th>
<th>Petiol index</th>
<th>Shannon-Wiener index</th>
<th>Species richness</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2</td>
<td>1319 ± 66a</td>
<td>0.46 ± 0.01a</td>
<td>1.25 ± 0.01a</td>
<td>15.3 ± 0.33a</td>
</tr>
<tr>
<td>R10</td>
<td>1036 ± 111a</td>
<td>0.44 ± 0.04ab</td>
<td>1.16 ± 0.08a</td>
<td>14.3 ± 1.45a</td>
</tr>
<tr>
<td>Rc</td>
<td>447 ± 84b</td>
<td>0.35 ± 0.03b</td>
<td>0.86 ± 0.07b</td>
<td>11.7 ± 0.33b</td>
</tr>
</tbody>
</table>

a. Kruskal–Wallis ANOVA used for analysis as variances were not homogenous; parametric ANOVAs were used for the other analyses. See Table 1 for notes and abbreviations.

Fig. 4. Community structural measures in the two mowing treatments plus control on 28 Aug, 2007. Kruskal–Wallis ANOVA was used for analysis of dead standing plant and stalk weight and parametric ANOVAs were used for the other analyses; community height and Stipa krylovii biomass data were transformed with square root. See Fig. 1 for notes and abbreviations.

Fig. 5. Daily (bottom panel) and seasonal mean (top panel) soil moisture (θ, volumetric water content) in the two mowing treatments plus control. See Fig. 1 for notes and abbreviations.
midday were 75, 85 and 105 W m\(^{-2}\) for \(R_c\), \(R_{10}\) and \(R_2\), respectively, i.e., 40 and 13% higher in \(R_2\) and \(R_{10}\) relative to \(R_c\). Over the growing season, the total \(G\) were 0.11, 0.21 and 0.25 MJ m\(^{-2}\) d\(^{-1}\) for \(R_c\), \(R_{10}\) and \(R_2\), respectively, i.e., 2.1 and 1.8 times higher in \(R_2\) and \(R_{10}\) relative to \(R_c\).

Available energy (\(R_n - G\)) decreased with mowing intensity during the daytime and increased in \(R_2\) but changed little in \(R_{10}\) at night (Fig. 7C). By average, that midday (\(R_n - G\)) over the growing season were 371, 354 and 334 W m\(^{-2}\) for \(R_c\), \(R_{10}\) and \(R_2\), respectively. Over the growing season, the total available energy in \(R_2\) decreased by 7.0% approximately 98 MJ m\(^{-2}\) relative to \(R_c\).

3.5. Turbulent energy

There were clear relationships between the community structure and the energy fluxes in response to mowing treatment (Fig. 8). Negative relationships were found between community biomass (Pearson \(r \approx -0.77, P < 0.007\)) or LAI (\(r \approx -0.92, P < 0.001\)) and the midday soil heat flux to net radiation ratio (\(G/\Delta R_n\)), and between biomass (\(r \approx -0.67, P = 0.024\)) or LAI (\(r \approx -0.80, P = 0.005\)) and the Bowen ratio (\(H/LE\)). Canopy temperature was significantly higher (\(F_{2, 27} = 4.98, P = 0.014\)) in the mowed plots than that in the unmowed plots when measured in late morning on sunny days. Significantly higher (\(P < 0.05\)) sensible and soil heat fluxes were observed in the heavily mowed plots (\(R_2\)) than in the unmowed plots, whereas there were no significant differences in latent heat flux among the three mowing treatments (Fig. 9).

4. Discussion

4.1. Effects of mowing on vegetation

Inner Mongolia has the largest grasslands in China, where there are ~0.55 million ha of grasslands for grazing and ~4.8 million ha
for fenced mowing management up until 2009 (Government News, 2009). Understanding how mowing affects the vegetation and environment is an urgent issue for developing future management strategies. The results learned from this study have direct implications for both practices. Mowing had significantly altered species composition and community structure. After four years of continuous mowing, the most dominant species shifted from the tall and dense bunchgrass *S. krylovii* to the short-stature — semi-shrub *A. frigida* (Tables 1 and 2; Figs. 3 and 4), demonstrating a compensatory effect that is similar to the findings of Antonsen and Olsson (2005). The major reason might be that these two species responded differently to the mowing disturbance because of their differences in morphological characteristics, although both exhibited the same clonal regeneration strategy. The leaves of *S. krylovii* are generally about 10 cm above the ground, suggesting that mowing at a height lower than this would remove most of the aboveground parts in the late growth stage of each year. *A. frigida*, on the other hand, having many tillers coming off a spreading stolon, is more likely to exhibit a short-stature phenotype, allowing it to survive and opportunistically occupy the niche vacated by *S. krylovii* when the latter is removed by mowing. The perennial loose bunchgrass (*C. squarrosa*), which had both high frequency of occurrence and high biomass in the *R*$_1$, *R*$_2$ and *R*$_{10}$ treatments, has most of its leaves growing at the base of the plant, suggesting that mowing would influence them less than grasses with their leaves located higher (e.g., *S. krylovii*). *P. acuillis* showed little response to mowing, except for becoming slightly lower and with smaller leaves in mowed plots. As a result, mowing reduced the hay quality via the decrease in palatable perennial bunchgrass of *S. krylovii* for the livestock, as modeled by Schippers and Joenje (2002). Clearly, species responded to the mowing treatments differently and through different biophysical mechanisms.

Our findings are consistent with the conclusion that increased productivity can reduce species richness (Foster and Gross, 1998) in grasslands by reducing the probability of establishment of different species (Fig. 3b and c; Table 2). Increased competitive dominance, especially for light (*G* as an indicator), in the unmowed plots reduced local diversity through high local production (Collins et al., 1998; Foster and Gross, 1998; Parker et al., 2005). Seed germination might occur in many locations, but survival of seedlings is generally restricted to larger canopy gaps due to the elevated availability of physical space, light, temperature, moisture, and nutrients (Williams et al., 2007). Another reason for reduced species richness in the unmowed plots is the rapid accumulation of ground litter which limited species establishment (Fig. 4). A number studies have found that a dense litter layer can limit the diversity of productive habitats by inhibiting species establishment through a variety of mechanisms including physical impediment and shading (Weltzin et al., 2005).

Litter plays an important role in determining relationships between ecosystem biodiversity and stability (Wardle et al., 1997). The standing crop of plant litter in the mowed plots amounted to only one third of that found in the unmowed plots (Fig. 4). This should be due not only to the reduction in aboveground biomass, but also to the lowered resistance to wind erosion in the mowed plots. Intensive mowing resulted in reduced LAI and plant height (both living and dead), making it easier for litter being blown away — a characteristic element of the local climate (see site description). The decrease in the amount of litter had caused a decrease in soil moisture (Fig. 5) and organic matter, which results in unfavorable conditions for those organisms vital for the incorporation of the humus into the soil (Weltzin et al., 2005; Xie and Wittig, 2004). At the same time, degradation of the vegetation would expose the soil surface directly to wind and water erosion, leading to losses of the fertile top soil and its contents of nutrients and desertification (Li et al., 2000).

The change we found in *S. krylovii* tillers could also have implications for resistance to environmental variation (Figs. 4–6). Mowing at certain heights could stimulate vegetative growth and the development of tillers by reducing the influences of apical dominance and the related changes in the microclimate. However, severe mowing reduced total basal area and tiller numbers, similar...
to the findings of Olson and Richards (1988) who reported similar effects in a grazing experiment. By reducing nutrient accumulation in belowground organs, mowing consequently limits tiller growth in the following spring. In fact, we found more seedlings than clonal plants in R2, showing that the seedlings from the preceding year did not grow well in the next year. In R0, however, we found plants from the previous year with tillers. Aside from the effects from mowing, microclimate also contributed to the number of tillers through changes in the light component (Evers et al., 2006; Wan and Sosebee, 1998). We did not find differences in S. krylovii abundance among the three treatments, although the number of tillers and biomass per cluster showed significant difference.

4.2. Link between microclimate and energy fluxes with vegetation

Changes in the community structure by mowing manipulations resulted in the changes in soil temperature and other microclimatic measures which also posed a feedback effect on the community dynamics in the present study. Chen et al. (1999) reported a strong negative correlation between canopy structure and surface temperature. We also found that the abundance of dead standing plant materials and ground litter had substantial effects on the canopy, surface and soil temperatures, although the total vegetation coverage remained unchanged under the three mowing intensities (Fig. 3a). The heavy mowing plots increased the growing season soil temperature and DTR at 2 cm soil depth by 0.7 and 4.2 °C, respectively (Fig. 6). This is very close to the 0.6 and 4.3 °C increases at a depth of 2.5 cm reported by Wan et al. (2002), who removed 85% of the aboveground biomass in a Great Plains tall grass prairie. Klein et al. (2005) reported that clipping mimics grazing and increased soil temperature by 1.7 °C at a depth of 12 cm and increased the maximum by air temperature 4.0 °C in the Tibetan Plateau rangeland. All these studies converged to the conclusion that mowing would exacerbate the effects of climatic changing (Luo et al., 2001), as evidenced by the elevated soil heat fluxes (Fig. 8a). This change in temperature plays an important role in plant growth and community structure. If more extreme conditions, such as hotter temperatures in the daytime (or summer months) and cooler temperatures in the nighttime (or winter months), exceed these thresholds, the growth of these species would be affected. For example, Lobell (2007) found a clear negative response of crop growth and yield to increased DTR from a long-term data set (1961–2002). Moreover, if extreme conditions exceed tolerance thresholds for certain species, growth patterns and species compositions will likely be altered (Ma et al., 2010; Wayman and North, 2007).

The widespread implications of changes in microclimate from the manipulation of grasslands and community structure require serious attention. Field studies suggested that increases in soil surface temperatures caused by mowing (i.e., increases of 7.4 °C at midday and 1.2 °C daily average) are of similar magnitude to some predictions of the increased temperatures associated with increased atmospheric CO2 and other greenhouse gases within this century (IPCC, 2007). Thus, climate changes (e.g., temperature increases) caused by extensive land-use alteration may have similar effects on the regime of energy fluxes and their partitioning in an ecosystem (Fig. 7). Heavily mowed plots in this study had a significantly higher sensible heat flux (P < 0.05) than unmowed plots during the observation time (Fig. 9), likely attributed to the higher wind speed and/or surface temperatures, which occur often in the mowed plots (Li et al., 2000). The loss of soil moisture in the mowed plots would decrease latent heat flux leading to more energy dissipated as sensible heat (air and soil warming; Wan et al., 2002). Mowed plots had lower LAI and stand biomass with seasonal maximums only around one third of those of unmowed plots. The soil heat flux was 2.1 times higher in R2 than that in R0. Consequently, it is not surprising that the ground heat flux in mowed plots would consume a much larger fraction of net radiation than unmowed plots with a dense canopy (Fig. 8a). The changes in H and G would increase the local air and soil temperatures, and would further affect the community composition and structure. Lower G (Fig. 7b), H (Fig. 9) and canopy temperature (not shown) suggested that unmowed plots could resist more droughts (Fig. 5). Negative relationships were found between the soil heat flux to net radiation ratio (CHF) and the green biomass and leaf area index (Fig. 8), which are as examples to the studies of energy balance and the water cycle and quantify the relationship between Rn and G (e.g., the FAO56 PET model).

We did not find a significant difference in LE (i.e., evapotranspiration or ET) among treatments in the semi-arid grassland during the sunny measurement period (Fig. 9). This is because mowing may reduce plant transpiration due to lower LAI but may increase evaporation from the soil surface owing to decreased plant litter, shading and boundary-layer resistance (Bremer et al., 2001; Frank, 2003) and increases in soil heat flux. An obvious reduction in soil moisture was found on or shortly after rainy days in the mowed plots (Fig. 5) which demonstrated that energy provided by radiation was partially dissipated as latent heat, resulting in more evaporation and decreased soil moisture than that in unmowed plots. The variances of ET between disturbed (e.g., grazing/mowing) and undisturbed locations are still debated, with some studies supporting that a decrease in aboveground biomass reduced seasonal ET (Bremer et al., 2001; Frank, 2003), some demonstrating an increase in seasonal ET (Ewers et al., 2000), and others reporting no significant effect (Stewart and Verma, 1992). More attentions should be put into the differences in weather conditions, disturbed intensities, vegetation characteristics and soil physical properties (Miao et al., 2009). One point is clear at our study site — unmowed plots maintained higher soil moisture than the mowed plots. The litter and community structure in unmowed plots forms a practically impermeable barrier to evaporation under enough energy but deficient water conditions, thereby representing a means for high water retention. We emphasize here that maintaining an undisturbed community structure could reduce soil evaporation and increase ecosystem resistance to drought at our semi-arid grassland site.

5. Conclusions

This study provides insight into energy fluxes and relationships with community composition, structure, and function using results from an experimental field study of mowing effects in a semi-arid grassland. With four years of annual mowing, community species composition was altered significantly, accompanied by changes in community structure. Heavily mowing reduced the hay productivity via the decrease in palatable herb (S. krylovii). Our study...
indicated that the unmowed plots could better alleviate the stress of high temperatures and drought during the hot dry season and reduce the daily temperature variation compared to mowed plots. In other words, unmowed plots had higher ecosystem resistance to adverse temperatures and soil moistures during the hot dry season as well as reducing soil erosion during the rainy season. Greater aboveground biomass and dense ground litter were key factors in soil temperature buffering and high soil moisture maintenance. Overall, the plots’ productivity and resistance decreased but plant diversity increased with increased mowing intensity during the study year.

The mowed plots received lower net radiation due to scarce litter and high reflectance but shared higher soil heat flux and tended to heat and cool more quickly than the unmowed plots. Heavily mowed plots shared a significantly higher sensible heat flux than unmowed plots, but were not significantly different in latent heat flux. Changes in dominant species would profoundly affect the community and microclimate as well as their interactions. Consequently, structural changes caused by mowing resulted in changes in soil temperature and other microclimatic measures could further feedback to community dynamics. Even mowing the plots to 10 cm height once per year could cause significant deterioration of the vegetation and soil properties in semi-arid steppe systems. In order to avoid sustained damage, the intensity and frequency of mowing should not be too severe but the plots cannot remain unmowed every year. Attempts to restore ecosystem function and stability in degraded grasslands are therefore unlikely to succeed without repairing the vegetation community structure that resulted in the microclimatic changes.

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