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Seasonal and interannual variability in surface energy partitioning and vegetation cover with grazing at shortgrass steppe

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ABSTRACT

We evaluated shortgrass steppe energy budgets based on the Bowen Ratio Energy Balance method for three different grazing intensity treatments at the Central Plains Experimental Range Long-Term Ecological Research (CPER-LTER) site. We tested the correlations between aboveground biomass and surface energy fluxes for three different precipitation years based on continuously measured 20 min interval data.

Grazing has a potential impact on energy partitioning under conditions of higher water availability, but not during dry conditions. Our study confirms that precipitation, not grazing treatment, explains the majority of variation in aboveground biomass at the CPER-LTER site. In addition, we are suggesting effective temperature, not air temperature, as a superior metric to evaluate surface heat change. Effective temperature takes into account humidity as well as air temperature.

1. Introduction

Grazing practices can have a major impact on vegetation production, composition, and structure depending on grazing intensity and type of plant community (Milchunas and Lauenroth, 1993). Annual forage removal in shortgrass steppe (SGS) can range from 40% in moderately grazed to 75% in heavily grazed sites (Morgan et al., 2004). Vegetation plays an important role in determining surface heat content throughout the growing season as it removes moisture from the soil that is lost through transpiration (Lu et al., 2001). During the day, transpiring vegetation converts incoming solar energy into latent heat, thus reducing maximum air temperature. At night, more water vapor above vegetated areas increases minimum air temperatures (Hanamean et al., 2003). Consequently, land-surface processes are increasingly featured in climate system modeling and represented in numerical models of weather and climate (Kabat et al., 2004).

Modeling the partitioning of available energy between sensible and latent heat fluxes on land-surface and accurate simulation of the diurnal, seasonal, and longer-term variations in these fluxes are an essential exercise for understanding how environmental changes may impact land-atmosphere energy exchange. Latent heat contributes water vapor to the atmosphere and tends to increase cloudiness and precipitation while increases in sensible heat tend to increase air temperature in the planetary boundary layer. Water cycling and energy flux partitioning can contribute substantially to the uncertainties of terrestrial ecosystem response to climate change. Climate change and land-use change, in turn, have strong potential to alter ecosystem functioning through their combined effects on both sensible and latent heat fluxes (Chapin et al., 2002; Ferretti et al., 2003).

At the Earth's surface, evapotranspiration (ET) is the connecting link between water and energy budgets. ET is the combination of two processes that lose water to the atmosphere by evaporation from lakes, reservoirs, wetlands, soil and snow cover, and transpiration from plants. Cell walls inside the leaf are covered with a thin film of water which readily evaporates when the stomata open to assimilate carbon for plant photosynthesis. During this trade-off, the ratio water lost to carbon dioxide (CO_2) absorbed can reach 400 (Chapin et al., 2002).

Daily and hourly water loss from a 4-year experiment at the SGS Long-Term Ecological Research (LTER) site was found to be approximately equal to the potential ET rate immediately after large rain events, with a rapid decline up to four days following the event (Parton et al., 1981). Water loss was generally equal to water input while actual water loss was substantially lower than potential ET.

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Lapitan and Parton (1996) found that daily ET rates closely follow seasonal patterns of rainfall and high rates of ET coincide with the presence of green biomass, high solar radiation, and high soil moisture.

In semi-arid areas, energy and water fluxes are strongly influenced by rainfall and grazing. In the SGS, early season rainfall (Lauenroth and Sala, 1992; Ojima et al., 1993a,b, Milchunas et al., 1994) and soil moisture (Knapp et al., 2007) are the main determinants of aboveground biomass production. Semi-arid rainfall patterns are characterized by small events, 80% of which are 0.5 cm or less during any month of the year (Sala and Lauenroth, 1982; Lapitan and Parton, 1996), with high interannual variations. Low vegetation cover and low albedo are typical features of the SGS. The SGS has evolved under grazing by large native herbivores and grazing by livestock is the current primary land use of native rangeland (Milchunas et al., 1988). Herbivores have the potential to affect ET by removing aboveground biomass thus altering microclimate. The recommended grazing practices in SGS allow a stocking rate which removes approximately half of the current season plant production (Klipple and Costello, 1960; Milchunas et al., 1989), although considerable variation in stocking rates exists among ranching enterprises and public lands which permit livestock grazing.

This study evaluates the impact of grazing on microclimate and energy budgets at the SGS-LTER site in a dry (163 mm) and two near-normal (262 and 260 mm) precipitation years. We address how variation in aboveground biomass affects energy budgets and soil and air temperatures and analyze surface heat energy or moist enthalpy (H_e), which accounts not only for surface temperature but for the contribution of water vapor to surface heat content (Pielke et al., 2005) and is a better metric for measuring changes in heat content than surface temperature alone.

Our main hypotheses were:

- In semi-arid grasslands, the main affect of rainfall events on the energy balance is to increase the ratio of latent to sensible heat fluxes for a brief period, seldom exceeding five days. This effect is expected to be more pronounced with increasing in leaf area, and consequently, greatest in ungrazed pastures (UG).
- Since maximum green biomass declines with increasing grazing intensity, heavily grazed (HG) sites will have higher sensible and lower latent heat fluxes compared to moderately grazed (MG) and UG sites.

2. Methods

2.1. Study site and micrometeorological measurements

This experiment was conducted at the CPER (40° 50′ N, 104° 43′ W), which is an LTER site operated by the United States Department of Agriculture – Agricultural Research Service. The CPER is located at the northern limit of the semi-arid SGS grassland on the western edge of the North American Great Plains and is used extensively for livestock grazing (Lauenroth and Milchunas, 1991). Total vegetative basal cover at the site is typically 25–35% (Milchunas et al., 1989), comprised of a mixture of C_3 (e.g., *Stipa comata* [Trin and Rupr.] and *Pascopyrum smithii* [Rybd.]) and C_4 (e.g., *Bouteloua gracilis* [H B K] Lag.) grasses, cacti, forbs, and a sub-frutescent shrub (*Artemesia frigida* [Willd.]). *Bouteloua gracilis* accounts for 90% of the aboveground biomass of grasses and 30% of total aboveground biomass (Sala and Lauenroth, 1982).

Long-term (52 yr) mean annual precipitation averages 321 ± 98 mm (Lauenroth and Sala, 1992), with the majority occurring during May, June, and July. Mean air temperatures are 15.6 °C in summer and 0.6 °C in winter (Singh et al., 1998).

Grazing treatments were established in 2001 in two adjacent pastures of native SGS vegetation and sampled over three years, 2001–2003. These pastures had previously been grazed by cattle for over 50 years at a moderate intensity (stocked generally from May–October at 0.16 heifers per hectare, which removes approximately 40% annual forage production). One 62-ha pasture remained as an MG pasture. The other 97-ha pasture was divided and converted into a HG pasture (34 ha stocked at a rate of 0.3 heifers per ha, resulting in an average 65% removal of annual forage), and a UG control (63 ha fenced exclosure). Bowen Ratio Energy Balance (BREB) systems (Model 023/CO_2 Bowen ratio system, Campbell Scientific Inc., Logan, UT, USA) were installed near the center of each pasture, resulting in a fetch exceeding 100 m in all cases. MG and HG pastures were stocked with heifers from May 16 to November 1 in 2001 (normal year with 262 mm precipitation, which is close to the long-term average), May 16 to August 9 in 2002 (very dry year-163 mm precipitation) and from May 21 to October 16 in 2003 (normal year-260 mm precipitation). The BREB towers were erected in spring 2000 and operated through the growing season to ensure a uniform baseline before the grazing treatments began.

We followed the methods of Dugas (1993) and Dugas et al. (1999) to calculate evapotranspirational fluxes of water (i.e., latent heat fluxes) from the BREB systems. Temperature and humidity gradients were measured every 2 s from arms mounted on micrometeorological masts positioned at 1 and 2 m height above the canopy to determine the Bowen ratio. The Bowen ratio was, in turn, used with measurements of net radiation (Model Q7 net radiometer, REBS, Seattle, WA, USA), average soil heat flux from two heat flux plates (Model HFT, REBS), and soil temperature to determine sensible heat flux. Turbulent diffusivity was assumed equal for heat and water vapor, and was calculated using 20 min averages of sensible heat flux and air temperatures measured from the two tower arms. When meteorological conditions were not suitable for the BREB method of calculating turbulent diffusivity (approximately 10% of the time occurring primarily at night), we calculated diffusivity according to the method of Dugas et al. (1999) using wind speed, atmospheric stability, and canopy height.

Precipitation was monitored continuously with a tipping bucket rain gauge (model TE-525 mm, Texas Electronics, Dallas, Texas). Depending on the precipitation amount and frequency, water loss is nearly equal to potential ET rate immediately after a rain event and up to four days following the rain event with a rapid decrease thereafter (Parton et al., 1981). Therefore, we defined wet periods as one to four days after each individual rain event, depending on the precipitation intensity and frequency under conditions when net radiation (R_n) exceeded 300 Wm^{-2}. We defined dry periods as having little or no precipitation when the BR was greater than three.

Table 1
Mean and maximum green biomass and leaf area index (LAI) for different grazing treatments.

	Grazing treatments	2001	2002	2003
Green biomass (gm^{-2})	UG (a)	47.5	11.0	55.1
	MG (a)	43.8	7.3	45.6
	HG (a)	36.2	9.2	40.3
	Mean	42.5	9.2	47.0
	Maximum	102.6	23.6	145.3
Leaf Area Index (m^2m^{-2})	UG (a)	0.253	0.093	0.287
	MG (a)	0.237	0.076	0.245
	HG (a)	0.203	0.085	0.221
	Mean	0.231	0.084	0.251
	Maximum	0.495	0.148	0.683

Note: LAI data for 2001 and 2002 are from the measurements except 2003 is converted from the biomass data using the following equation: LAI = Biomass × 0.0044 + 0.044 (R2 = 0.79). UG – ungrazed; MG – moderately grazed; HG – heavily grazed; (a) – statistical significance.

The pastures are not in close proximity with major topographic variation so we assumed R_n and precipitation would not be substantially different among the three pastures. Soil water content on a volume basis was measured by water content reflectometers (model CS615, Campbell Scientific Inc., Logan, UT, USA) at 0–15 cm below the soil surface.

2.2. Aboveground plant biomass and leaf area

Fifteen 30 m × 30 m plots were established on a grid surrounding each of the three BREB towers. During the growing season (April–October) and corresponding with Landsat flyovers (every 32 days), nine of these grids were chosen for Leaf Area Index (LAI) and aboveground biomass measurements. One-meter-square quadrants were randomly located within each of nine grids and LAI was determined by the laser point frame method (Przeszlowska et al., 2006) using 100 points per quadrant. After LAI determination, vegetation in the quadrants was clipped to the crown, oven-dried at 60 °C, and weighed to determine aboveground biomass. Both LAI and biomass samples were classified as green or brown. Necromass, as defined in this study includes standing dead brown biomass but not litter. Leaf Area Index was not measured in 2003; therefore, it was estimated from a linear regression of the prior years' collected biomass versus LAI data using the following equation:

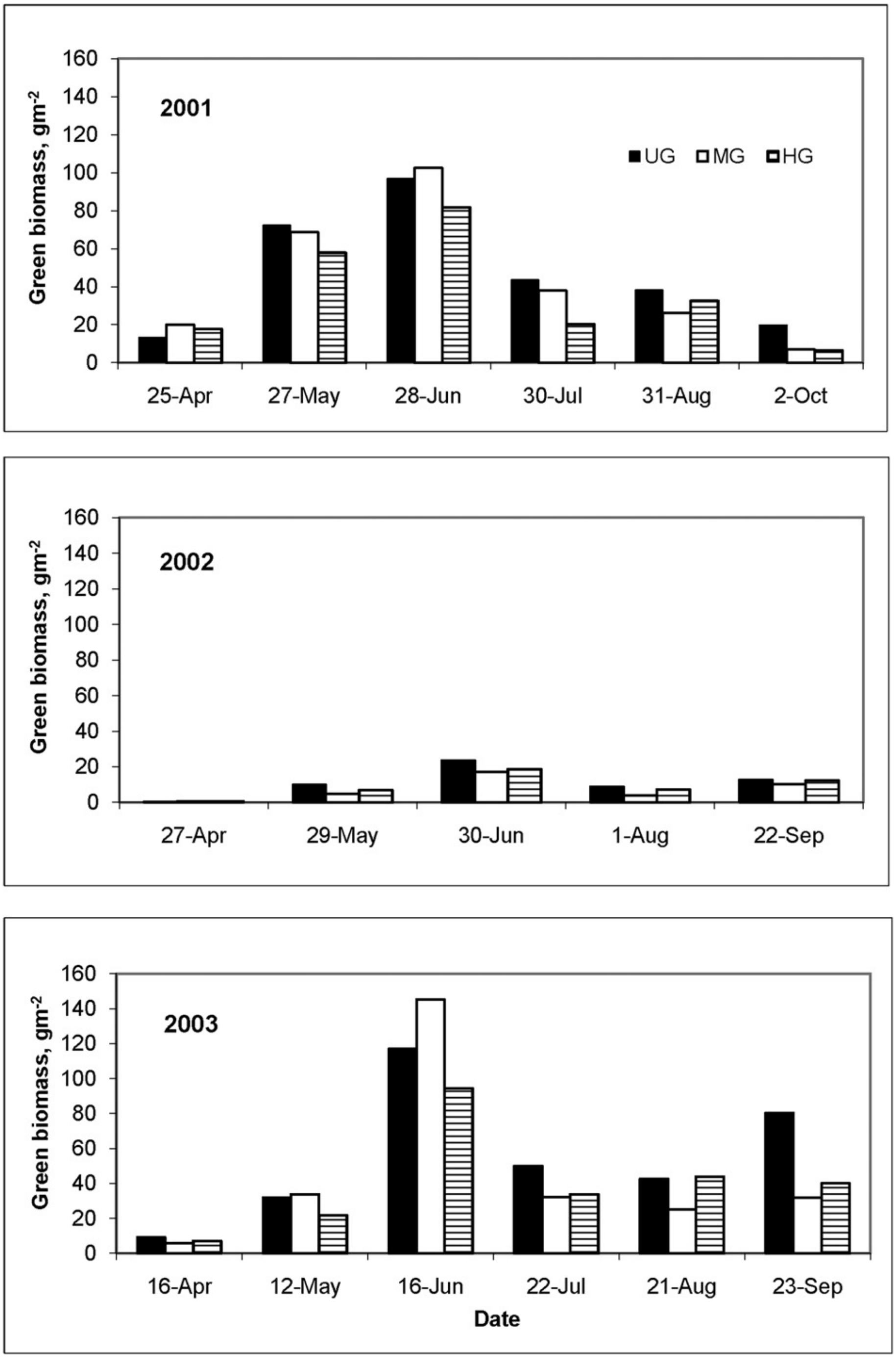

Fig. 1. Seasonal variation of green biomass for each grazing treatment in 2001–2003. UG – ungrazed; MG – moderately grazed; HG – heavily grazed ■ UG; □ MG; = HG.

$$\text{LAI} = \text{Biomass} \times 0.0044 + 0.044 \left(R^2 = 0.79\right)$$

2.3. Research approach

If the effects of photosynthesis and lateral advection can be neglected for simplification, the energy budget of the SGS-LTER is represented as

$$R_n = L_e + H + G_o \quad [1]$$

where R_n is the flux of net incoming radiation, L_e is the flux of latent heat into the atmosphere, H is the flux of sensible heat into the atmosphere and G_o is the flux of heat conducted into the soil, all expressed in W m^{-2}. The ratio of H and L_e is called the Bowen ratio (BR) and expressed in Eq. [2] (Brutsaert, 1982):

$$BR = H/L_e \quad [2]$$

The Bowen ratio ranges from less than 0.1 for tropical oceans to greater than 10 for deserts, indicating that turbulent energy transfer depends on the nature of an ecosystem and the climate (Chapin et al., 2002).

Surface heat energy (H_e), or moist enthalpy, accounts not only for the surface temperature but also for the contribution of water vapor to surface heat content (Pielke et al., 2005) and is expressed as

$$H_e = C_pT + L_vr \quad [3]$$

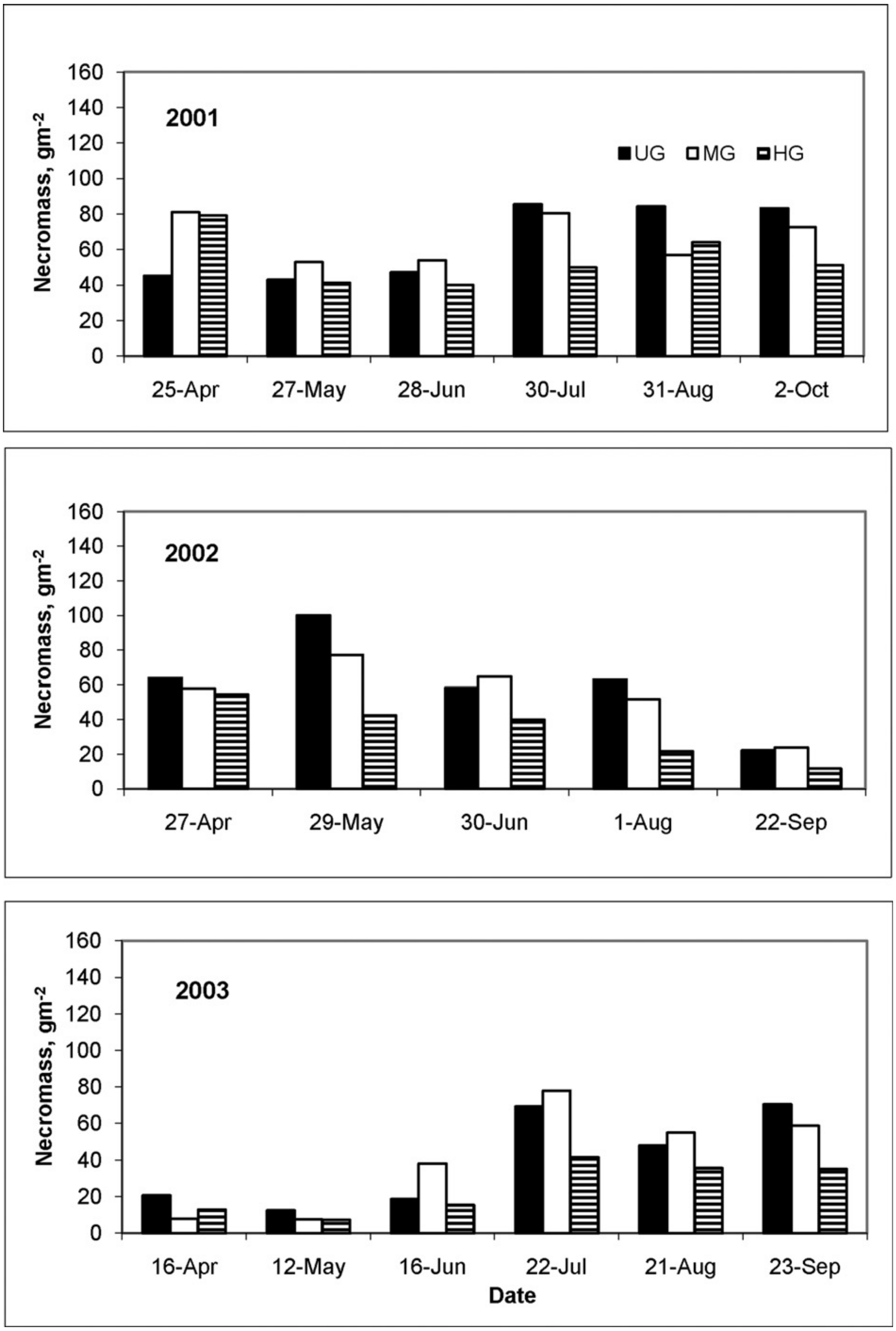

Fig. 2. Seasonal variations of necromass for each grazing treatment in 2001–2003. UG – ungrazed; MG – moderately grazed; HG – heavily grazed ■ UG; □ MG; = HG.

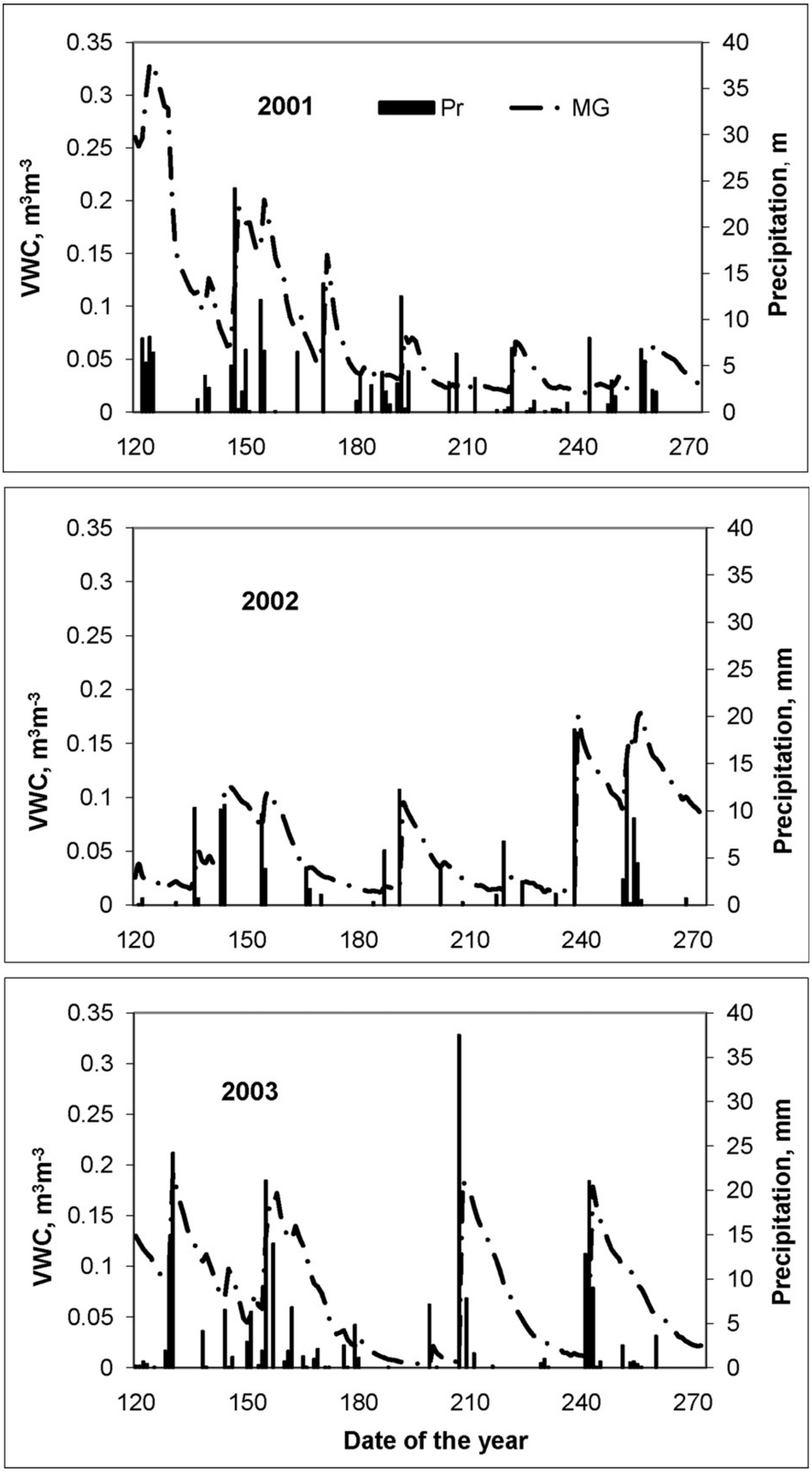

Fig. 3. Volumetric soil water content (VWC) and precipitation (Pr) in the moderately grazed (MG) site for 2001–2003. ▬ Pr; line with ● indicate VWC.

Table 2
Mean net radiation (R_n), soil (G_o), sensible (H), and latent (L_e) heat fluxes for the growing season of 2001–2003 years for each grazing treatment. UG – ungrazed; MG – moderately grazed; HG – heavily grazed; (a,b) –statistical significance.

Energy fluxes	Grazing treatments	2001	2002	2003
R_n Wm^{-2}	UG	285	273	278 (a)
	MG	283	285	289 (a)
	HG	292	276	305 (b)
	Mean	287	278	291
G_o Wm^{-2}	UG	49	52	48 (a)
	MG	59	63	42 (a)
	HG	54	55	48 (a)
	Mean	54(19%R_n)	57(20%R_n)	46(16%R_n)
H, Wm^{-2}.	UG.	125	174	146 (a)
	MG	117	169	137 (a,b)
	HG	124	165	132(b)
	Mean.	122(43%R_n)	169(61%R_n)	138(47%R_n)
L_e Wm^{-2}.	UG	110	48	85 (a)
	MG	106	53	110 (b)
	HG	114	56	126 (b)
	Mean	110(38%R_n)	52(19%R_n)	107(37%R_n)

where C_p is the specific heat content of the air at constant pressure (at 20 °C, $C_p = 1.005$ Jg^{-1}°K^{-1}), T is the observed air temperature at 2 m height in °K, L_v is the latent heat of vaporization (at 20 °C, $L_v = 2450$ Jg^{-1}), r is the mixing ratio or mass of water vapor to the mass of dry air (g g^{-1}).

To express enthalpy in degrees for comparison to air temperature we use the term effective temperature (T_e), expressed as

$$T_e = H_e/C_p = T + L_v r/C_p \quad [4]$$

where T_e is the effective temperature that accounts for specific humidity of the air; therefore it has contributions from both sensible and latent heat (Pielke et al., 2004,2005).

2.4. Data quality check and processing

We focused on daytime (7 am–7 pm Mountain Standard Time) energy fluxes to avoid the prevalence of large errors in nighttime measurements due to small values in the available energy (i.e., R_n–G_o). The Bowen Ratio method closes the energy balance. Therefore, in order to detect possible errors, we summed sensible, latent, and soil heat fluxes and checked the total against net radiation data (formula 1). Differences greater than 50 Wm^{-2} were considered errors and were removed from the data. We removed 2–5% of the total data from each grazing treatment.

We averaged the energy fluxes and summed precipitation on a daily basis for the growing season for each of three different grazing treatments: HG, MG, and UG. Differences among treatments were determined using one-way ANOVA statistical test (Spss, Inc. SPSS, 2004).

3. Results

3.1. Green biomass and necromass

Differences in grazing intensity did not significantly impact green biomass amount harvested during the 2001–2003 growing seasons (Table 1). Observations did, however, tend to follow the expected pattern of higher green biomass in the UG pasture and lower green biomass in the HG pasture (Table 1, Fig. 1). Peak green biomass occurred in June, and was greatest in the MG pasture (Fig. 1), which was consistent with Holecheck et al. (2006) findings that managed grazing resulted in slightly higher biomass production than in the UG site. The UG pasture, as would be expected, showed a consistent pattern of higher necromass at the end of the season than the grazed pastures with the exception of the 2002, due to substantially lower-than-normal precipitation (Fig. 2).

As is common in semi-arid grasslands (Sala and Lauenroth, 1982; Ojima et al., 1993a,b, Milchunas et al., 1994; Knapp et al., 2007), there was substantial interannual variability in the amount of green biomass (Table 1). Consequently, maximum standing green biomass was only 24 gm^{-2} in the dry year 2002, compared to 103 and 145 gm^{-2} measured in the more normal precipitation years 2001 and 2003. Maximum necromass greatly exceeded maximum green biomass (100 gm^{-2} vs. 24 gm^{-2}) in the very low precipitation year (2002; Figs. 1 and 2). Precipitation events led to predictable increases in volumetric soil water (data from MG shown in Fig. 3).

3.2. Near-surface energy fluxes

Mean H values were higher than L_e in all years and grazing treatments, expressing the impacts of ground cover, biomass, and LAI in semi-arid grasslands (Tables 1 and 2). As would be expected, there was a relative increase in H and G_o with respect to R_n in a dry year (Table 2), indicating that, because of the low water levels, the energy tended to be used to heat the air and soil first, and

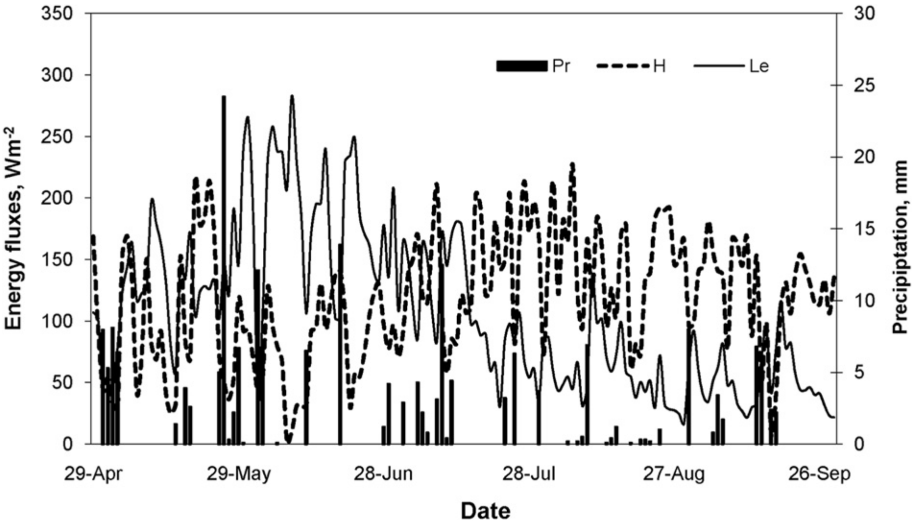

Fig. 4. Latent (L_e) and sensible (H) heat energy fluxes and precipitation (Pr) for moderately grazed site in 2001. ▬ Pr; –– H; ── L_e

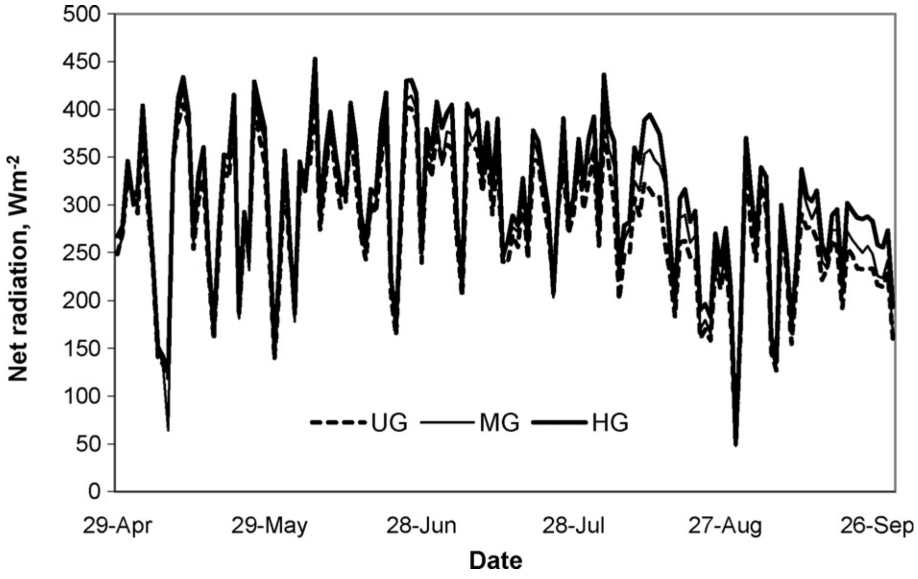

Fig. 5. Net radiation for all grazing treatments in 2003. UG – ungrazed; MG – moderately grazed; HG – heavily grazed; _ _ _ UG; ____ MG; ▬ HG.

what remained was available for evaporation and transpiration. The general seasonal trends of H and L_e are shown in Fig. 4 for the MG pasture in 2001. Soil heat flux showed no trend and was relatively low throughout the study period, averaging 52 Wm^{-2}. About 45% of incoming R_n went to H, 38% to L_e and 18% to G_o during the normal years versus 61% of R_n to H, 19% to L_e and 20% to G_o during the dry year (Table 2).

Overall seasonal totals of energy fluxes followed the expected relationships with precipitation and soil moisture: L_e was higher at the beginning of the season when the rainfall amount was relatively high, and decreased as the soil dried out in late summer (Fig. 4).

With the exception of 2003, grazing treatments did not result in detectable differences in H, L_e and R_n. In 2003, R_n was greater in the HG treatment compared to the UG ($p < 0.001$) and MG ($p < 0.048$) treatments (Fig. 5 and Table 2). These treatment differences in R_n became more evident later in the season (Fig. 5) as necromass increased (Fig. 2). Furthermore, H was greater in the UG treatment than the HG treatment ($p < 0.025$), while L_e was lower in the UG treatment compared to the MG ($p < 0.001$) and HG ($p < 0.001$) treatments (Table 2), all of which did not follow expected patterns.

3.3. The impact of green biomass on energy variables for wet and dry periods

3.3.1. Wet periods

Wet periods were selected for this analysis as one to four days after the rain events when R_n exceeded 300 Wm^{-2}. In 2001, 2002, and 2003 there were 30, 13, and 26 days, respectively, which qualified as wet periods.

We observed a clear pattern of higher L_e with higher green biomass (Fig. 6). Moreover, during these wet periods, latent heat fluxes (evaporation and transpiration) for the HG treatment were generally higher than for the UG and MG treatments and this difference increased as green biomass increased. Observations of H, were highly variable and did not correlate with grazing intensity or green biomass. There were no significant differences observed for G_o (not shown).

To evaluate near-surface energy flow, we looked at the gradient in air temperature between 1 m and 2 m. During wet periods, the air temperature gradient decreased as green biomass increased

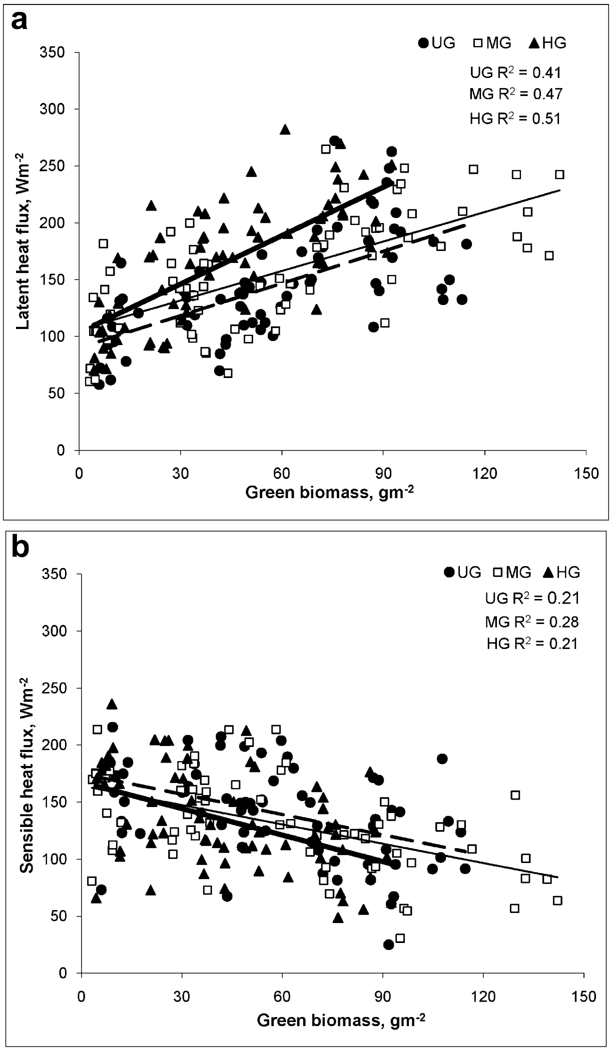

Fig. 6. Latent (a) and sensible (b) heat fluxes versus green biomass for wet days (for all years). UG – ungrazed; MG – moderately grazed; HG – heavily grazed ● UG; _ _ _ UG linear trend; □ MG; ____ MG linear trend; ▲ HG; ▬ HG linear trend.

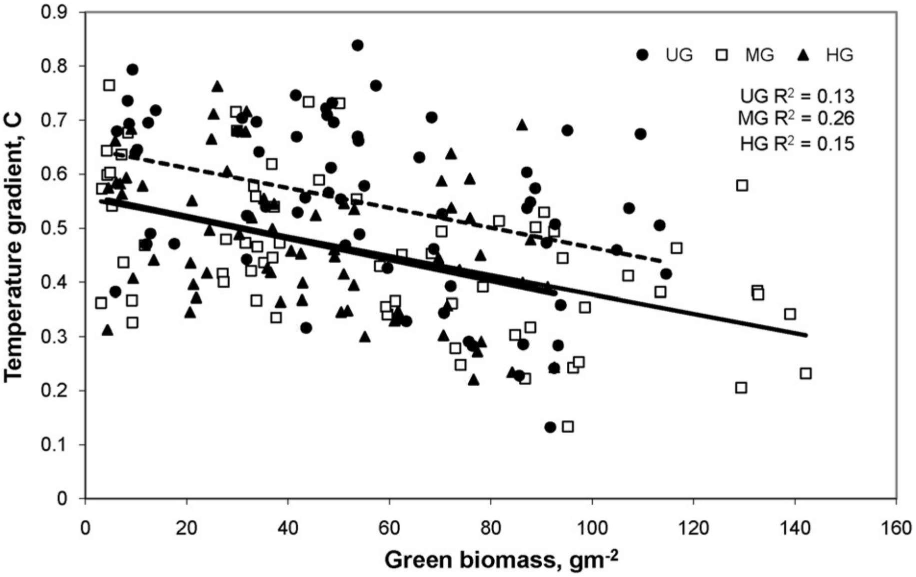

Fig. 7. Air temperature gradient versus green biomass for wet days and for all grazing treatments. UG – ungrazed; MG – moderately grazed; HG – heavily grazed; ● UG; _ _ _ UG linear trend; □ MG; ____ MG linear trend; ▲ HG; ▬ HG linear trend.

but there were no apparent differences due to grazing treatment (Fig.7). This could be due to the fact that with higher green biomass there would be higher transpiration reducing the air temperature increase; therefore, the air temperature gradient is decreased.

3.3.2. *Dry periods*

We defined dry periods as periods with little or no precipitation when the *BR* was greater than three. In 2001, 2002, and 2003 there were 23, 80, and 18 days classified as dry periods. No clear relationship was observed between energy fluxes (Fig. 8) or air temperature gradients (not shown) and amount of green biomass during those dry periods. Values of L_e were always lower than H in dry periods with green biomass higher than 20 gm^{-2} (Fig. 8).

3.4. *Surface energy and temperature*

On a seasonal basis, grazing treatment did not impact interannual differences in mean, maximum, or minimum air temperatures for the study period. Therefore, air temperatures were averaged for all treatments (Table 3).

Under low wintertime humidity, there was no significant difference between T and T_e (Fig. 9). When the humidity was higher during the growing season, differences between T and T_e increased (Fig. 9). During the dry year (2002) T_e has lower values than the years (2001 and 2003) with relatively normal precipitation levels (Table 3). No grazing treatment differences were found for T_e.

4. Discussion

Short-term changes in grazing intensity had little impact on this semi-arid grassland which is characterized by relatively low production and standing biomass. Our results confirm the findings of Lauenroth and Sala (1992), Milchunas et al. (1994), and Ojima et al. (1993a,b) that variability of forage production may be explained primarily by precipitation and soil moisture (Knapp et al., 2007), and the magnitude of that variability in forage production was more sensitive to annual fluctuations in precipitation than to short-term differences in grazing intensity. The lack of early-season rainfall in 2002 led to extremely low biomass production despite late-season precipitation events.

We found clear seasonal and interannual variability that followed expectations for most response variables. The UG pasture tended to have more green biomass than the grazed pastures although no statistically significant (Fig. 1). The necromass followed the same pattern later in the growing season during years with near-normal precipitation (Fig. 2). Although we did not find major green biomass differences between grazing treatments at the SGS-LTER site, differences in total annual precipitation resulted in significant differences in green biomass (Table 1). The seasonal distribution of precipitation was a major determinant of plant growth in SGS-LTER site. At global scale, aboveground biomass is more sensitive to ecosystem-environmental variables than grazing and grazing at the SGS-LTER site has unusually small impacts relative to grasslands elsewhere in the world (Milchunas and Lauenroth, 1993).

We did not find major differences among grazing treatments in aboveground biomass or energy fluxes. This follows findings by LeCain et al. (2000,2002), showing mostly minor impacts of grazing treatments on seasonal and short-term CO_2 exchange. The general lack of major differences in near-surface fluxes between grazing treatments (Table 2) may be due to higher soil temperatures at the grazed sites possibly causing greater emissions of near-surface longwave radiation, as suggested by Bremer et al. (2001). Also grazing treatment resulted in more uniform horizontal distribution of aboveground biomass (Milchunas et al., 1989). Grazing did not significantly influence crown biomass but there was a tendency for the relative contribution of crown material to total plant biomass to increase with grazing in SGS (Sims et al., 1978). In 2003, however, R_n was consistently and statistically significantly higher at the HG site than at the UG and MG sites throughout the growing season (Fig. 5). Contrary to our expectations, we found the lowest H and the highest L_e in the HG treatment (Table 2). This relationship was somewhat amplified later in the growing season, possibly due to necromass accumulation, more uniform crown cover, and a resultant decrease in albedo. Therefore, we suggest that further measurements of albedo are necessary to better understand the amount of absorbed incoming radiation.

Overall, seasonal patterns of energy fluxes; higher L_e and lower H during the first half of the growing season and higher H and

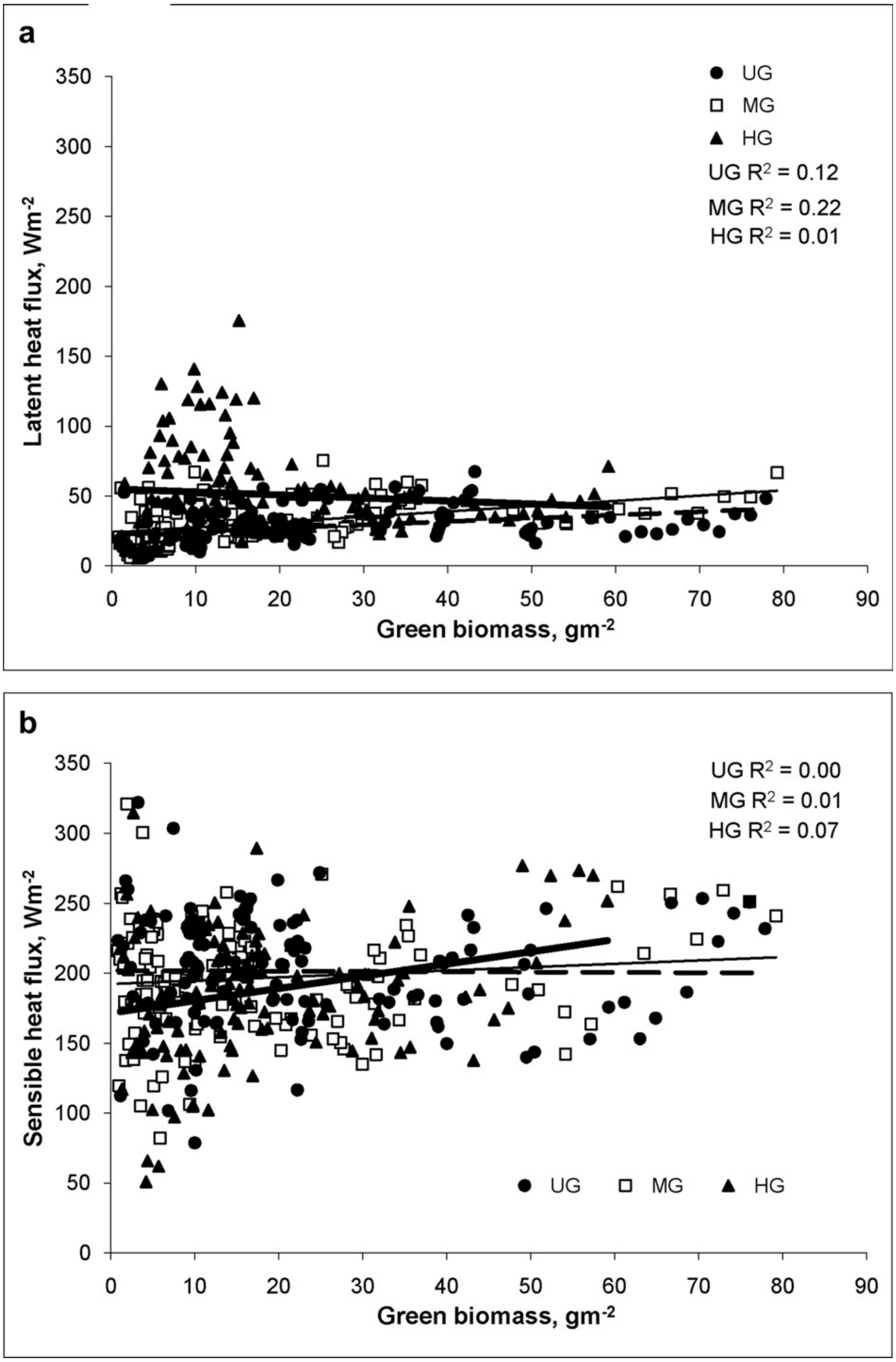

Fig. 8. Latent (a) and sensible (b) heat fluxes versus green biomass for dry days (for all years). UG – ungrazed; MG – moderately grazed; HG – heavily grazed; ● UG; _ _ _ UG linear trend; □ MG; ____ MG linear trend; ▲ HG; ▬ HG linear trend.

lower L_e during the second half of the season, and spikes in fluxes with each precipitation event (Fig. 4) were as expected. We clearly observed that green biomass increased with increasing latent heat flux and decreasing sensible heat flux during the wet periods (Fig. 6) but not during the dry periods (Fig. 8). It is likely that years with higher production would better illustrate these relationships (Milchunas and Lauenroth, 1993). The low water level in dry periods always resulted in lower L_e and higher H when the biomass were higher than 20 gm^{-2}. L_e was close to H when the biomass was less than 20 gm^{-2} only in a heavily grazed site (Fig. 8), possibly due to L_e being mainly influenced by bare ground evaporation.

Table 3
Mean (T_{air}) and effective (T_e) temperatures and moist enthalpy (H_e) for the growing season of 2001–2003 years averaged for all grazing treatments.

Variables		2001	2002	2003
T_{air}, °C	Mean	16	16	16
	Maximum	36	38	38
	Minimum	−12	−14	−16
T_e, °C	Mean	28	27	27
	Maximum	61	56	59
	Minimum	−9	−11	−13
H_e, J kg^{-1}	Mean	317	313	315

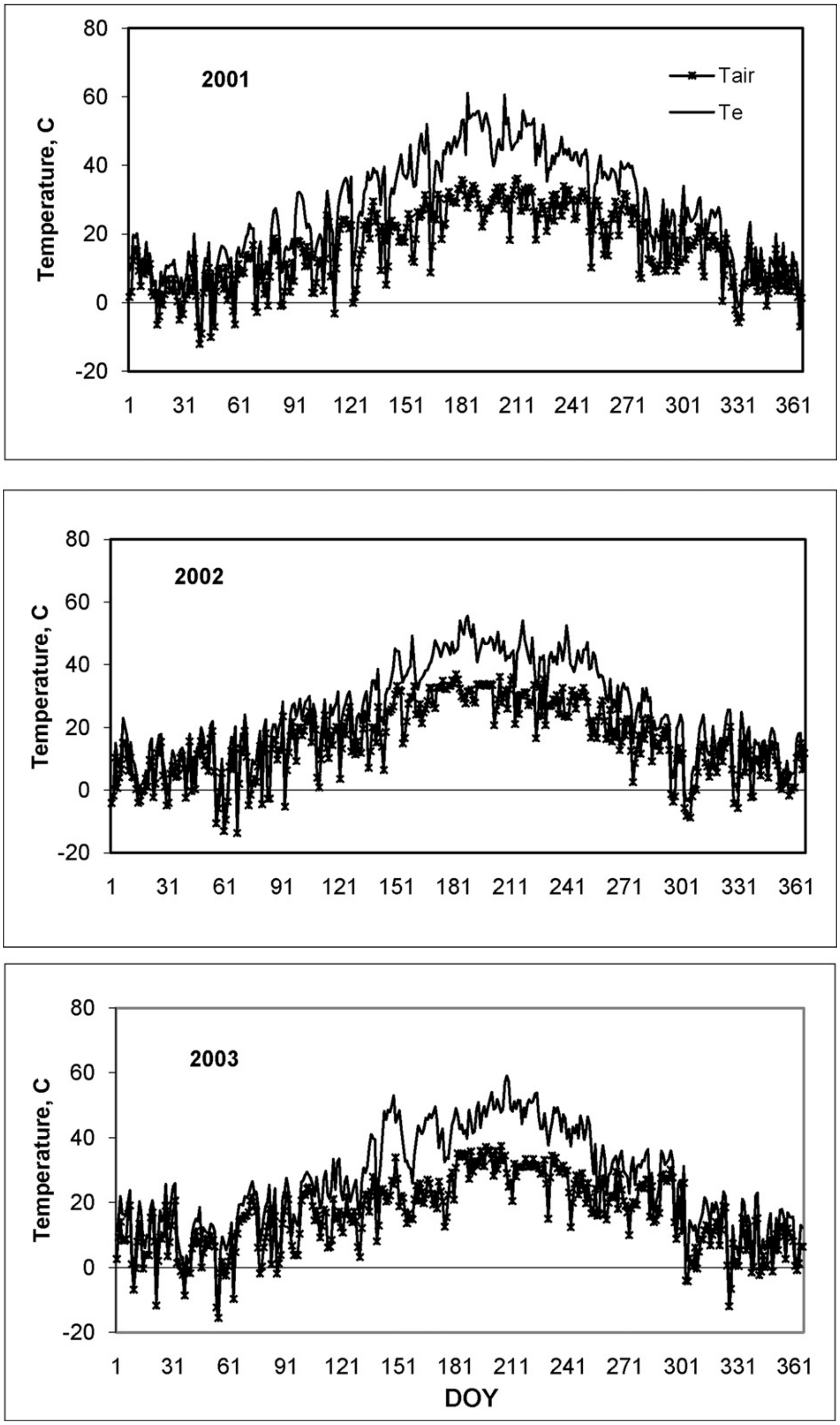

Fig. 9. Air (line with x) and effective (line) temperatures (°C) averaged for all grazing treatments at 14:00 Mountain Standard Time: 2001–2003 years. DOY- Day of year.

We did not find any significant grazing treatment effects on air temperature. Most of the time, however, the grazed pastures had higher soil mean and maximum temperature than the UG pasture, as was suggested by Milchunas et al. (1989) and Parton (1984). Also we did not find major grazing treatment effects on surface heat energy and effective temperature. This is due to a lack of clear response of the energy budget to grazing treatments, and no responses of humidity with sufficient magnitude between grazing treatments (Fig. 9). As is typical of many ecosystem responses in this strongly water-limited grassland system, interannual and seasonal variations in humidity have greater influence on the ecosystem than the comparatively subtle effects of grazing.

There were no major difference in green and total biomass among the three levels of grazing, making it difficult to detect treatment effects. Given that "the energy balance will not close perfectly at every timescale all the time even in the very best dataset from an ideal experimental site" (Kabat et al., 2004), measurements of biomass performed with greater frequency may have yielded measurable responses to grazing. This is something to consider in future studies of this semi-arid system, one that is characterized by seasonally- and annually-important responses to short-term events of relatively small magnitude.

5. Recommendations

We clearly observed a pattern of higher latent heat flux with higher biomass during wet periods. This suggests a potential impact of grazing on energy budgets if grazing treatments had led to a measurable difference on green biomass. We recommend further testing of the assumption that grazing treatments should have an impact on the surface energy budget when green biomass is significantly impacted. Similar studies could be performed in long-term heavily grazed sites to better assess differences on the measured variables.

Measurements of albedo are necessary to investigate the amount of absorbed incoming radiation for different grazing treatments. In addition, it would be useful to have separate estimates of water loss via evaporation and transpiration to be able to distinguish water loss from the soil surface versus the vegetation. Metrics of leaf area index, vegetation greenness, and albedo using remote sensing technology would help in the study of surface energy budgets because of more continuous data availability.

Our results can help to further thorough investigation of compound effects of grazing and precipitation to better understand the semi-arid zones' land-atmosphere interactions under current climate change conditions. Grasslands, including semi-arid and arid SGS exist in every continent, covering almost half of the earth's terrestrial surface (Suttie et al., 2005). The sensitivity of global change is expected to be high at these arid lands. Therefore our study will also help to gain understanding through modeling how grazing management and precipitation would impact the energy budget partitioning on these semi-arid and arid lands in the context of global climate change.

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