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Effects of seasonal grazing on soil respiration in alpine meadow on the Tibetan plateau

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Abstract

Little research has been conducted on how to balance plant production and soil respiration (Rs) under seasonal grazing patterns in alpine meadows. Our results from 2009 to 2012 showed that warm season grazing (WG) from June to September significantly increased aboveground net primary production compared with no-grazing (NG), except in 2010, and compared with cold season grazing (CG) except in 2012, while there were no significant differences between NG and CG except in 2009. In both WG and CG treatments, grazing increased root biomass at 0–40 cm depth compared with NG, except in 2011. WG and CG only significantly increased seasonal Rs in 2009. Daily Rs was mainly affected by soil temperature, which explained 40–49% of the variation in daily Rs for all grazing treatments. Seasonal Rs from July to September was significantly influenced by soil temperature and root biomass, which explained 55% of the variation in seasonal Rs for all grazing treatments. Therefore, relative to NG, regardless of WG and CG, moderate grazing significantly increased plant production and had little influence on soil respiration in this alpine region.

Keywords: Seasonal and moderate grazing, plant production, soil respiration, alpine meadow, Tibetan plateau

Introduction

Soil respiration (Rs), which accounts for about 25% of global carbon dioxide exchange (Bouwmann & Germon, 1998), is a major pathway for carbon to move from terrestrial ecosystems to the atmosphere, and even small changes can strongly influence net ecosystem production (Ryan & Law, 2005). Therefore, understanding of soil respiration processes is key to our understanding of the terrestrial carbon cycle (Rustad *et al*., 2000; Schlesinger & Andrews, 2000). Grasslands are one of the major vegetation types, covering about 30% of the world's land surface. Grasslands store about 761 Pg C, of which 10.6% is stored in vegetation and 89.4% in the soil (Atjay *et al*., 1979). Grazing, which is the main land use for grasslands worldwide, can alter carbon emissions from soils to the atmosphere (Ma *et al*., 2006; Lin *et al*., 2009, 2011). Some research has found that grazing decreases Rs (Bremer *et al*., 1998; Cui *et al*., 2000; Johnson & Matchett, 2001; Jia *et al*., 2007), while others have found that grazing increases Rs (Dong *et al*., 2000; Frank, 2002; Zhou *et al*., 2002) or does not affect it (Lecain *et al*., 2000; Li *et al*., 2000). Such discrepancies between results suggest that the response of Rs to grazing may vary with grazing intensity, history, climate and soil types (Lecain *et al*., 2000; Frank, 2002; Jia *et al*., 2005, 2007; Ryan & Law, 2005).

Grassland soils on the Tibetan plateau store a huge amount of organic carbon (C) (33.52 Pg C in the upper 0.75 m of topsoil), which is ca. 2.5% of the global soil C pool (SOC) (Ni, 2002; Wang *et al*., 2002). Thus, minor changes in the SOC pool could significantly alter atmospheric CO_2 concentration and influence the global climate (Bellamy *et al*., 2005; Davidson & Janssens, 2006; Schipper *et al*., 2007; Cui & Graf, 2009). Although the decomposition of organic carbon is limited by cool temperature and therefore a large amount of carbon has accumulated in the soil, long-term overgrazing has resulted in considerable deterioration and even desertification, which may release large quantities of C from the ecosystem to the atmosphere (Wang *et al*., 2002; Zhao, 2011). However,

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compared with temperate grasslands, few studies have been conducted on the effects of grazing on Rs in this alpine region (Cao *et al*., 2004). A better understanding of C turnover and fluxes in alpine meadows under grazing can increase our knowledge of C cycling on the Tibetan plateau and globally.

Society faces the challenge of managing grasslands to provide food and products, while protecting the natural resource base. With increasing human population, demands on grasslands increase, making it even more important to understand the effects of grazing management on grassland ecosystems (Wang *et al*., 2002). Many studies suggest that moderate grazing in semi-arid grasslands with a long history of grazing benefit annual net primary productivity and community composition (Milchunas *et al*., 1988; Milchunas & Lauenroth, 1993; Lecain *et al*., 2000; Wang *et al*., 2003). In comparison with other regions, Rs on the Tibetan plateau is under-studied (Cao *et al*., 2004; Geng *et al*., 2012), and few data are available for alpine meadows. Usually, the alpine meadow is divided into two seasons for grazing, with warm season grazing from June to October and cold season grazing in the other months. This study aimed to understand the effect of seasonal grazing patterns on Rs and to identify the main factors affecting Rs under moderate grazing conditions in the alpine meadow.

Materials and methods

Experimental site

The experimental site is located at the Haibei Alpine Meadow Ecosystem Research Station (HBAMERS), situated at latitude 37°37′N and longitude 101°12′E. The mean elevation of the valley bottom is 3200 m. A detailed site description can be found in Zhao and Zhou (1999). Mean temperature and total rainfall were 6.8, 7.3, 6.8 and 6.8 °C, and 350.2, 442.6, 339.2 and 325.8 mm during the growing seasons from 1 May to 31 October in 2009, 2010, 2011 and 2012, respectively (Figure 1). Compared with average rainfall during the growing seasons in the region (i.e. 450 mm), these years can be typified as normal in 2010, while there was

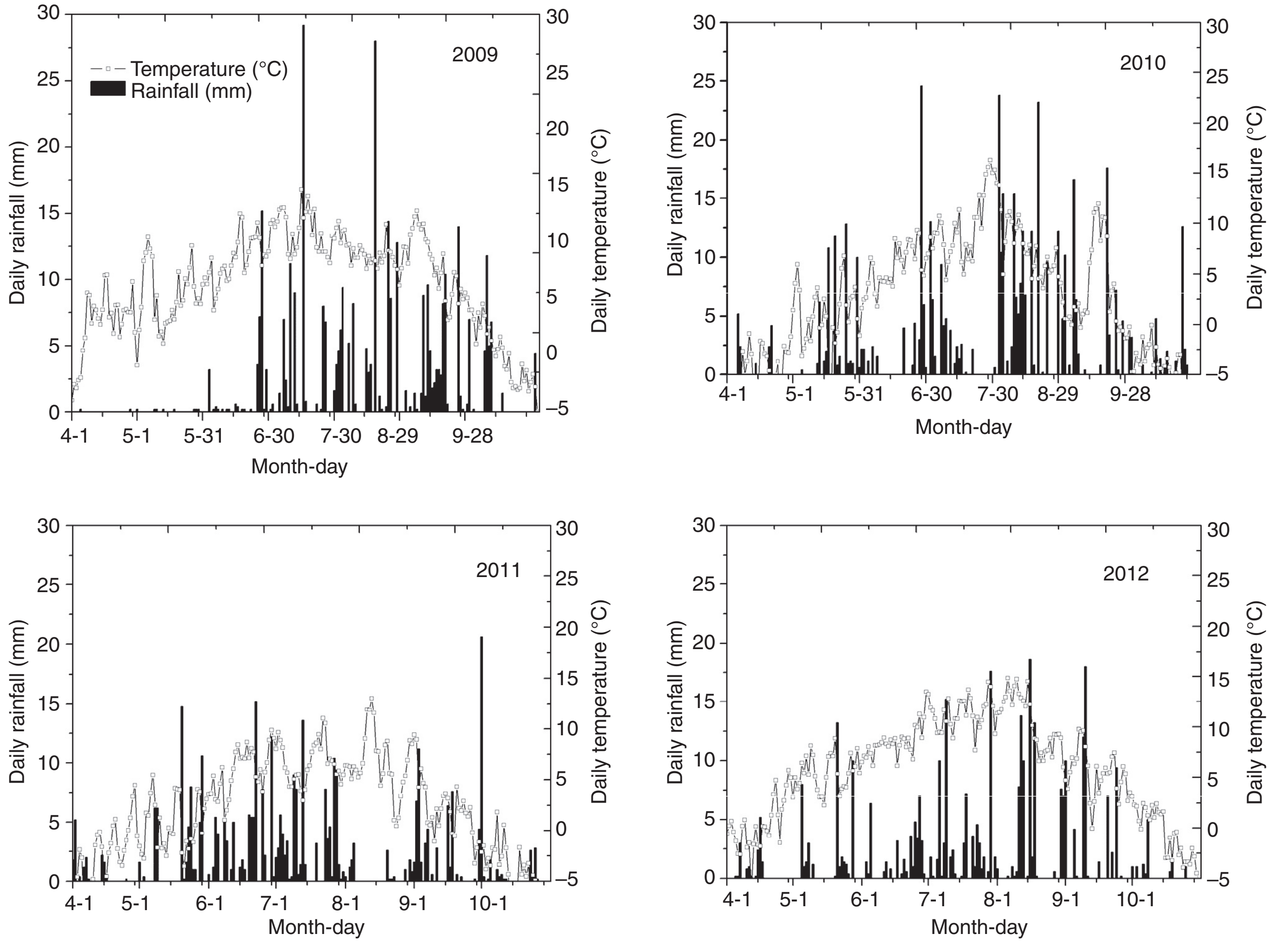

Figure 1 Dynamics of air temperature and precipitation from 2009 to 2012.

slight drought in 2009, 2011 and 2012 (i.e. 22–28% less than long-term average rainfall).

The plant community at the experimental site is dominated by *Kobresia humilis*, *Festuca ovina*, *Elymus nutans*, *Poa pratensis*, *Carex scabrirostris*, *Scripus distigmaticus*, *Gentiana straminea*, *Gentiana farreri*, *Blysmus sinocompressus* and *Potentilla nivea*. The soil is a clay loam with an average thickness of 65 cm, is perennially wet and is classified under Mat Cry-gelic Cambisols according to the Chinese national soil survey classification system (Chinese Soil Taxonomy Research Group, 1995). There were no significant differences among different grazing treatments in average total organic carbon and total nitrogen concentrations, which were 7.6% and 0.55% in 0–10 cm surface soil in 2009.

Grazing experiment

The experimental site is an overgrazed winter grassland, with all litter removed before the start of the experiment. The common grazing practice in the region is rotational grazing with large numbers of sheep (sometimes > 1000) grazing the grasslands during a few hours in a short-duration, high-intensity grazing pattern. Thus, the grazing experiment was designed to simulate this grazing practice. Nine plots of 5 m × 5 m were fenced in August 2006 and fully randomized throughout the study site. The grazing experiment started in 2007. Three grazing treatments were used with three replicates of each of three treatments: no-grazing (i.e. control-NG), grazing during the warm season (WG) and grazing during the cold season (CG). In the WG treatment, four adult Tibetan sheep grazed for ca. 2–4 h in each grazing plot on 8 July and 25 August 2009, 8 July and 23 August 2010, 22 July and 29 August 2011, and 26 July and 24 August 2012. The first grazing event occurred when canopy height was about 8–10 cm before grazing and ended when canopy height was about 4–5 cm. The second grazing event in late August may reduce the initial canopy height by about half. Cold season grazing events occurred on 13 April and 15 May 2009, 22 April and 15 May 2010, 27 April and 18 May 2011, and 28 April and 15 May 2012, using four Tibetan sheep grazing for 2 h at each grazing event. In both WG and CG treatments, the sheep were removed from the grazing plots when the canopy height was reduced to approximately half of the initial height. The canopy height of the vegetation was measured at 50 points within the plots before and after grazing.

Measurement of aboveground and root biomass

Plant production and utilization were determined using the cage comparison method (Cook & Stubbendieck, 1986). A 50 × 50 cm cage was set up in each plot and clipped inside and outside cages after each grazing event. All samples were oven-dried and weighed to determine plant production and percentage utilization. Sheep intake was calculated using the difference between standing biomass inside and outside the cage after each grazing event. The sum of the standing biomass at the end of grazing period and sheep intake during each grazing period was used as aboveground net primary production (ANPP) (Wang *et al.*, 2012). The annual cumulative forage utilization rates (i.e. total sheep intake as a percentage of ANPP was 53, 62, 45 and 48% for the WG treatment (averaging 52%), and 65, 66, 52, 52% for the CG treatment (averaging 59%) in 2009, 2010, 2011 and 2012, respectively. Because overgrazing always results in degradation of grasslands in China (Wang *et al.*, 2003; Zhao, 2011), we aimed to determine whether moderate grazing can sustain the alpine meadows or not and designed the trials with a forage utilization rate of 50–60% in both WG and CG treatments, which is considered a moderate grazing intensity in the region (Zhao, 2011).

Root biomass was measured using a 4-cm-diameter soil-drill sampler to take 0–10, 10–20 and 20–40 cm soil samples at the end of August each year. These root samples were immediately washed, dried at 80 °C, and weighed. Total root biomass was the sum of the root biomass in each soil layer.

Measurement of soil temperature and soil moisture

Volumetric soil moisture (%) was measured within all treated plots using Time Domain Reflectometry (TDR) (CS615) (Campbell Scientific, Inc.) with four probes (7 cm in length). Soil temperatures at 5 cm depth were measured using digital thermometers when gas samples were collected.

Measurement of Rs

Soil respiration was measured using opaque, static, manual stainless steel chambers described by Lin *et al.* (2011). In brief, the chambers were 40 cm × 40 cm × 40 cm. Soil respirations were measured at intervals of 7–10 days during the experimental period. There were 25, 16, 18 and 18 sampling occasions at the starting dates of 23 April in 2009, 6 July in 2010, 20 June in 2011 and 12 May in 2012, respectively. The Rs between 10:00 a.m. and 12:00 a.m. local time represented 1-day average flux. Chambers were closed for half an hour, and gas samples (100 mL) were collected every 10 min using plastic syringes. Gas samples of CO_2 concentration were analysed with gas chromatography (HP Series 4890D; Hewlett Packard, USA) within 24 h following gas sampling. The method of calculating Rs was the same as that described by Lin *et al.* (2011).

Statistical methods

General linear model-repeated measures define factors (SPSS 16.0; SPSS Inc. Chicago, IL, USA) was used to assess the significance of the impacts of sampling day, treatment and their interactions on Rs in each year due to different sampling times. Significant differences between soil temperature, soil moisture, ANPP and root biomasses and Rs among grazing treatments were assessed by one-way ANOVA and least significance difference. Pearson's correlation was used to test the correlations between daily soil temperature and soil moisture and daily Rs. Stepwise multiple linear regression analysis was performed to test the possible dependency of seasonal Rs on seasonal soil moisture and soil temperature, aboveground and root biomasses. All significances mentioned in the text were at $P \leq 0.05$.

Results

Soil temperature and soil moisture and biomass

There were no significant differences in soil temperature and soil moisture, although there was a trend in soil temperature increase (i.e. 0.5 °C) for WG and CG treatments (Figure S1). WG significantly increased ANPP compared with NG except in 2010 and compared with CG except in 2012, and there were no significant differences between NG and CG except in 2009 (Figure 2a). In both the WG and CG treatments, compared with NG grazing increased root biomass at 0–40 cm depth except in 2011 (Figure 2b).

Soil respiration (Rs)

Although there were no significant differences in daily and monthly Rs among the three treatments (Figures 3–6), both WG and CG significantly increased seasonal Rs in 2009 (Figure 3c). Peaks of daily and monthly Rs were in July and/or August for all treatments during the experimental period, except in 2011, which was in June. The average Rs from July to September was lowest in 2012 (i.e. 326.6 mg $CO_2/m^2/h$), followed by 2011 (i.e. 368.3 mg $CO_2/m^2/h$) and 2009 (i.e. 405.6 mg $CO_2/m^2/$ h), and was greatest in 2010 (i.e. 419.6 mg $CO_2/m^2/h$).

Factors affecting Rs

Daily Rs was mainly affected by soil temperature, which can explain 40–49% of the variation in daily Rs for all grazing treatments (Figure 7), and there were no significant correlations between daily Rs and soil moisture (data not shown). Temperature sensitivity of Rs to soil temperature was greatest in CG compared with other treatments (Figure 7). Seasonal Rs from July to September was significantly influenced by soil temperature, root biomass and soil moisture (Figure 8). Stepwise regression analysis showed that seasonal Rs = 11.254 + 28.890Ts + 0.026 RB ($r^2 = 0.55$, $n = 36$, $P < 0.001$), where Ts is seasonal soil temperature from July to September and RB is root biomass.

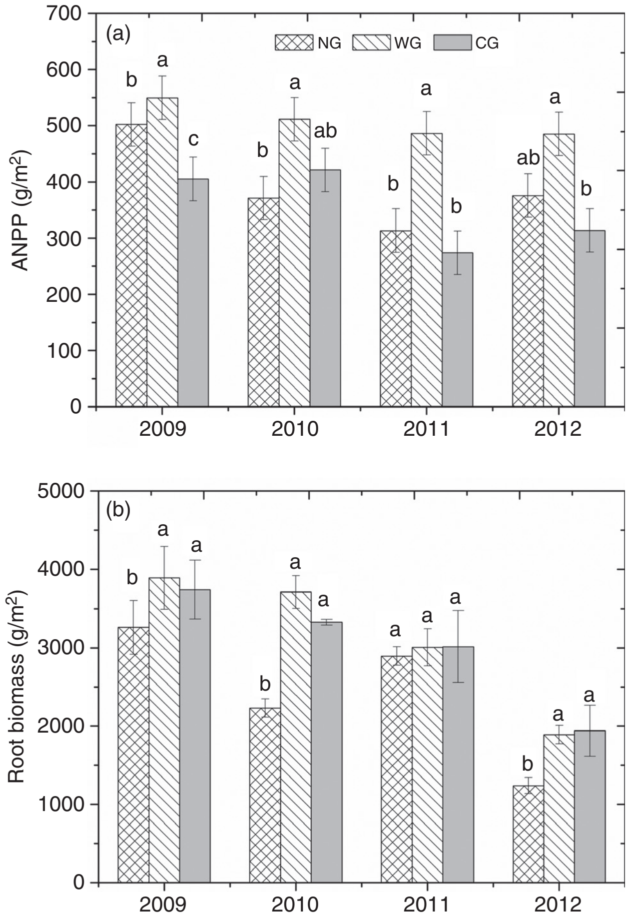

Figure 2 Aboveground net primary production (ANPP) and root biomass for NG, WG and CG from 2009 to 2012. NG, no-grazing; WG, warm season grazing; CG, cold season grazing. Bars indicate mean ± 1 SE. Different letters indicate significant difference at $P = 0.05$ level.

Discussion

Our study did not find significant effects of moderate grazing on seasonal average Rs, except in 2009. Similarly, when all measurements were averaged over the entire season, there was no difference in CO_2 fluxes between heavily grazed, lightly grazed and ungrazed pastures (Lecain *et al*., 2000). Our study showed that the soil temperature at 5 cm was the main factor affecting daily and seasonal change in soil respiration. Soil temperature and water content are known to have a pronounced influence on the seasonal dynamics of soil respiration (Fang & Moncrieff, 2001; Reichstein *et al*., 2003; Ryan & Law, 2005; Jia *et al*., 2007). However, soil moisture did not affect daily and seasonal Rs in our study, because soil moisture is not a limiting factor for microbial activity in the region (Lin *et al*., 2011). A number of studies have shown that soil water content has a limited impact on soil respiration rate except at the extremes of saturation or

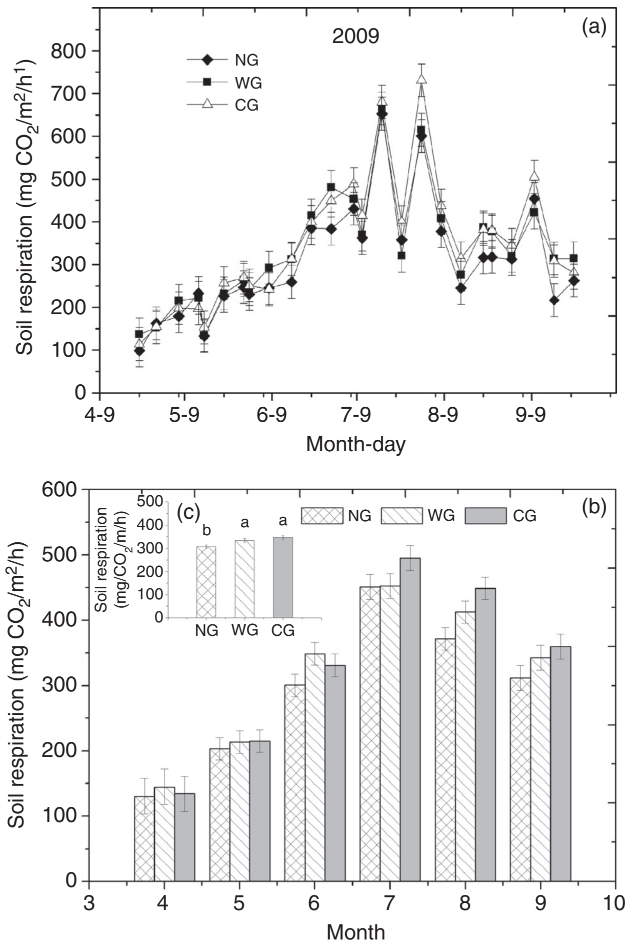

Figure 3 Daily values of soil respiration (Rs) under different seasonal grazing treatments in 2009 (a) and monthly means (b); the panel is the seasonal average Rs (c). NG, no-grazing; WG, warm season grazing; CG, cold season grazing. Bars indicate mean ± 1SE. Different letters indicate significant difference at P = 0.05 level.

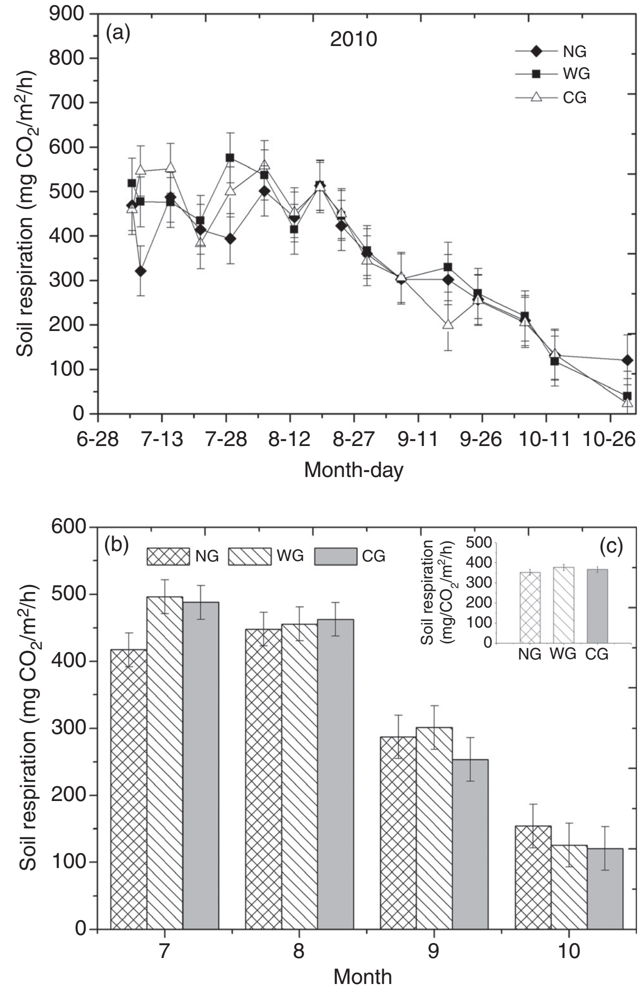

Figure 4 Daily values in soil respiration (Rs) under different seasonal grazing treatments in 2010 (a) and monthly means (b); the panel is the seasonal average Rs (c). NG, no-grazing; WG, warm season grazing; CG, cold season grazing. Bars indicate mean ± 1SE. Different letters indicate significant difference at P = 0.05 level.

water deficit (Edwards, 1975; Hanson *et al.*, 1993; Jia *et al.*, 2005). Soil temperature can explain 40–49% and 32% of the variation in daily and seasonal Rs in our study, which is lower than previous reports (i.e. 65% of CO_2 efflux variability) (Frank, 2002). Similar results have also been reported for research conducted in alpine meadow on the Tibetan plateau (Cao *et al.*, 2004). However, Geng *et al.* (2012) found root biomass and soil moisture, but not soil temperature, best explain large-scale patterns in Rs.

Soil respiration originates mainly from root and microbial activities, and partitioning root and microbial contributions to soil respiration is important for calculating the carbon budgets of vegetation and the turnover rate of soil organic matter, as well as for understanding sources and sinks of carbon in terrestrial ecosystems under global climate change (Jia *et al.*, 2006). In our study, both WG and CG increased root biomass, which may result from changes in plant species composition induced by grazing (Wang *et al.*, 2012). For example, grazing increased the proportion of forbs in the community, which are deep rooted in the study site (unpublished data). Raich and Tufekcioglu (2000) reported that root contribution to soil respiration was 17–40% in grasslands and 50–93% in arctic tundra. The proportions of root respiration to soil respiration by the inferred method were 40% in unbroken tallgrass prairie (Kucera & Kirkham, 1971), 14–39% in temperate grassland (Li *et al.*, 2002; Jia *et al.*, 2006), and 42% (Gupta & Singh, 1981) and 36.4% (Upadhyaya & Singh, 1981) in tropical grassland. For the inferred approach (Kucera & Kirkham, 1971), the key assumption that the CO_2 efflux rate from root respiration is proportional to root biomass has to be valid. In our study, due to drought in 2011 and 2012, root biomass of all treatments decreased over the study period. As Figure S2

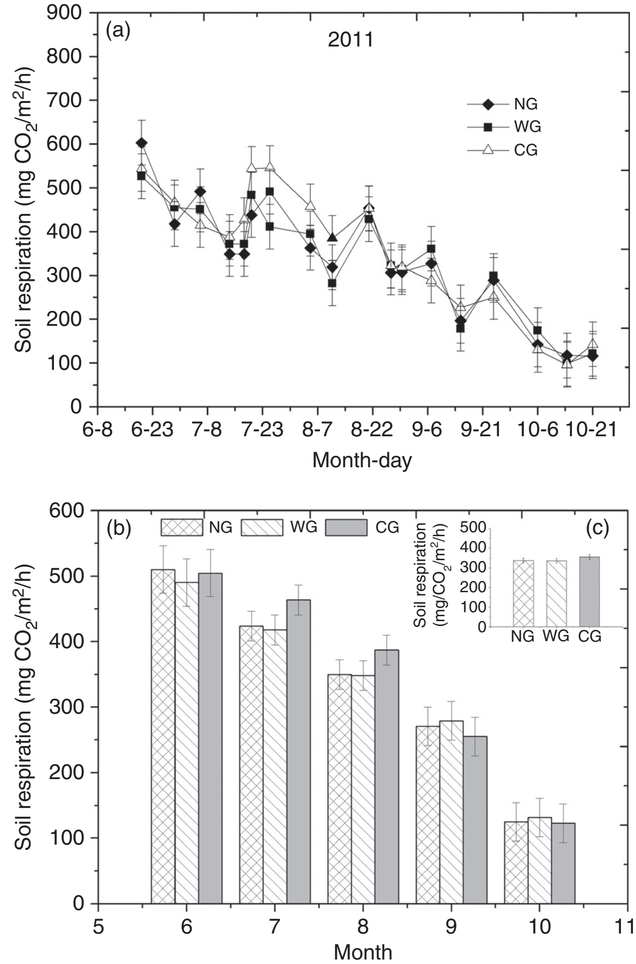

Figure 5 Daily values in soil respiration (Rs) under different seasonal grazing treatments in 2011 (a) and monthly means (b); the panel is the seasonal average Rs (c). NG, no-grazing; WG, warm season grazing; CG, cold season grazing. Bars indicate mean ± 1SE. Different letters indicate significant difference at $P = 0.05$ level.

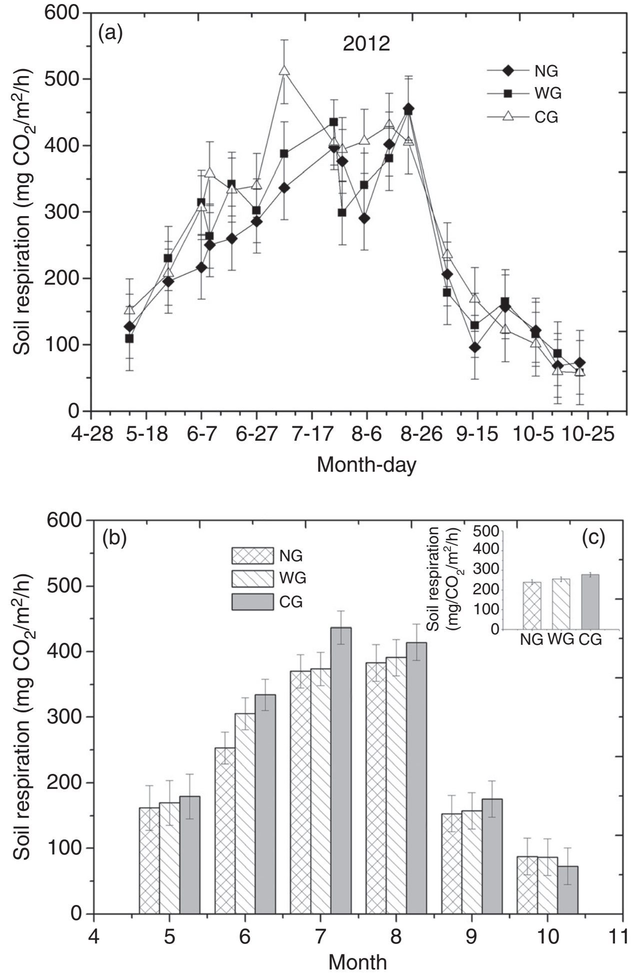

Figure 6 Daily values in soil respiration (Rs) under different seasonal grazing treatments in 2012 (a) and monthly means (b); the panel is the seasonal average Rs (c). NG, no-grazing; WG, warm season grazing; CG, cold season grazing. Bars indicate mean ± 1SE. Different letters indicate significant difference at $P = 0.05$ level.

shows, the correlation coefficients (r^2) between Rs rate and root biomass were 0.16 for NG ($P = 0.200$), 0.37 for WG ($P = 0.037$) and 0.47 for CG ($P = 0.014$). Thus, these models could significantly explain about 37–47% of variation in soil respiration rates for WG and CG, and mean inferred proportions of root respiration to soil respiration were 57.4 and 65.3% from July to September for WG and CG, respectively. These results are similar with the report by Raich and Tufekcioglu (2000) in the arctic tundra.

Some studies have reported that soil compaction decreased Rs (Linn & Doran, 1984; Torbert & Wood, 1992) because soil compaction shifts soil conditions to an anaerobic state, resulting in reduced aerobic microbial activity due to a reduction in O2 diffusion through soil (Cannell, 1977). In our study, although we did not measure the effects of grazing on soil bulk density, these effects could be relevant because the WG and CG treatments involved moderate stocking rates and two grazing events each year.

Conclusions

In both warm and cold season grazing treatments, moderate grazing did not decrease plant production, and even increased aboveground biomass for WG and root biomass for both WG and CG compared with NG, whereas there were no significant differences in Rs for all grazing treatments, except in 2009. Root biomass and/or soil temperature were the main factors affecting daily and seasonal Rs in the alpine meadow. Therefore, relative to NG, moderate grazing is preferred for local farmers because it enables a balance between livestock production and environmental protection in the alpine region.

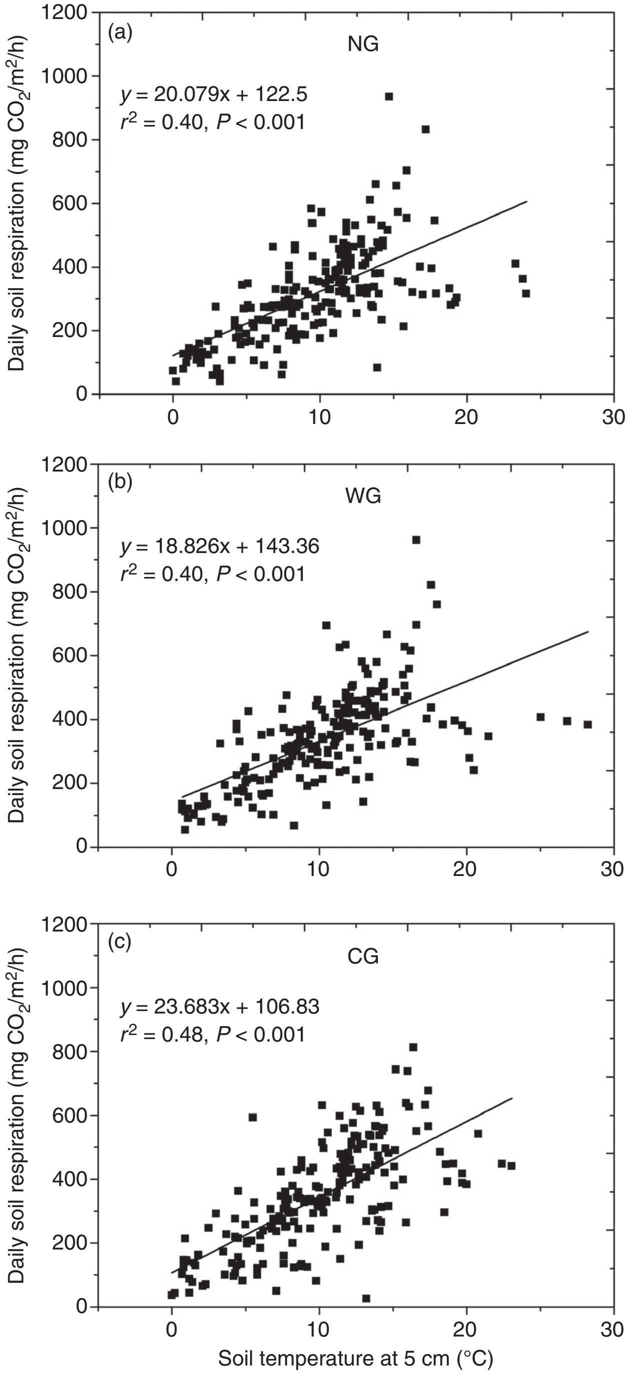

Figure 7 Relationships between daily soil respiration and soil temperature at 5 cm soil depth for NG (a), WG (b) and CG (c). NG, no-grazing; WG, warm season grazing; CG, cold season grazing.

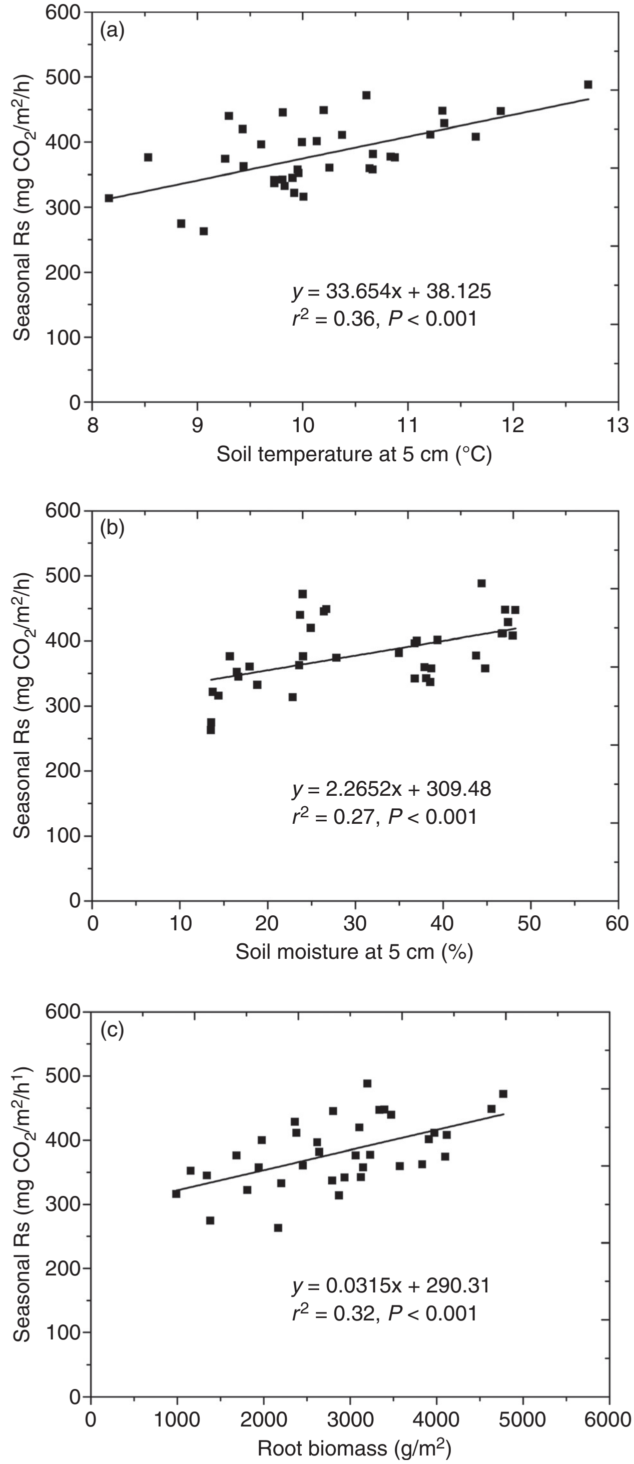

Figure 8 Relationships between seasonal soil respiration and soil temperature at 5 cm soil depth (a), soil moisture at 5 cm soil depth (b) and root biomass (c) across all treatments.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Fig S1. Mean soil temperature (A) and mean soil moisture (B) at 5 cm depth under different seasonal grazing treatments from 2009 to 2012.

Fig S2. Relationships between seasonal soil respiration and root biomass for NG (A), WG (B) and CG (C).