



## Stocking Rate and Grazing Season Modify Soil Respiration on the Loess Plateau, China<sup>☆</sup>



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### ARTICLE INFO

#### Keywords:

CO<sub>2</sub> efflux  
rotational grazing  
typical steppe  
root biomass  
path analysis

### ABSTRACT

The influence of sheep grazing on carbon cycling in the midarid steppe of the Loess Plateau, Gansu, China, was investigated by measuring the CO<sub>2</sub> exchange rate in pastures with a 7-year history of zero, light, moderate, and heavy grazing. Farming systems in the area are characterized by heavy grazing pressure and low vegetation productivity. The effect of stocking rate on soil respiration (Rs) was determined using field trials to investigate factors influencing spatial and temporal variation in Rs in August 2008 on two sites: summer grazed and winter grazed. Soil respiration is an important component of the carbon cycle in rangeland. Measurements included daily Rs, soil temperature, soil moisture, and root biomass. Daily Rs was also measured in late April and middle December 2008. The response of Rs to increasing stocking rate in August 2008 differed with site; on the summer-grazed site increased stocking rates reduced Rs ( $P < 0.02$ ), whereas on the winter-grazed site, stocking rate had little effect on Rs. Path analysis revealed that on the summer-grazed site, soil moisture had the greatest influence on Rs, whereas on the winter site soil temperature was the most important factor; stocking rate had the least influence on Rs at both sites. The results highlight the importance of environmental variability in determining the effects of grazing on Rs.

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### Introduction

Rangeland covers 40% of the earth's terrestrial surface and traditionally supports domestic livestock grazing in extensive agricultural grazing systems (Morgan et al., 2007). The Loess Plateau in northern China, one of the most distinctive natural-cultural regions on earth, is situated in the middle reaches of the Yellow River, occupies an area of 650,000 km<sup>2</sup>, and is characterized by loess deposits that can reach up to several hundred meters thick (Sun et al., 2001). About 54% of China's Loess Plateau is utilized for grazing livestock, providing the main source of income for the local population (c. 16 million) (Hou and Nan, 2006). During the past century there have been many changes in livestock grazing practices with respect to the

environment, social systems, and policy. Long-standing overgrazing has resulted in many problems including soil erosion and reduced productivity. Livestock grazing on rangelands has received a great deal of attention because there is often disagreement about the impacts of grazing on ecosystem sustainability (Briske et al., 2011). Grazing systems in the area evaluated in the present study are typically dominated by mixtures of cropping and rangeland sheep production (Hou et al., 2008).

Evidence of climate change due to elevated CO<sub>2</sub> levels is already known (Boone et al., 1998); the possibility of further changes and the increasing scale of potential climate impacts have given urgency to adapting grazing systems to help prevent adverse effects from climate change. These adaptations include the use of appropriate stocking rates, grazing frequencies, and grazing times (Hou and Nan, 2006).

The effects of grazing management on the ecosystem processes that control carbon (C) cycling and distribution have not yet been sufficiently recognized in evaluating native grassland ecosystems. Current literature suggests that there is no clear relationship between grazing management and C sequestration (Reeder and Schuman, 2002). A number of studies have been conducted to evaluate grazing-mediated changes in Rs in grasslands (Li et al., 2013; Fu

<sup>☆</sup> Research was supported by the National Key Project of Scientific and Technical Supporting Programs (2014CB138706), National Natural Science Foundation of China (No. 31172249), and Program for Changjiang Scholars and Innovative Research Team in University (IRT13019).

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et al., 2014). Some reported that grazing reduced Rs (Chen et al., 2008), while others reported that grazing accelerated Rs due to disturbance of the physical and chemical properties of soil (Cao et al., 2004; Owensby et al., 2006) or that grazing had no effect on Rs (Risch and Frank, 2006; Li et al., 2013; Fu et al., 2014).

Environmental factors, particularly soil temperature (Wang et al., 2011b) and soil moisture (Chen et al., 2008), and management factors including grazing (Owensby et al. 2006) can all influence Rs. Identifying a causal mechanism through which grazing may affect Rs is complicated by the interactions between these factors (Chen et al., 2008). An insight into the mechanisms and relative importance of different factors influencing Rs can be achieved through path analysis (Wang et al., 2011a, 2011b); this study utilized path analysis to model the direct and indirect effects of important environmental and management factors, including grazing, on soil respiration.

In the Loess Plateau rangeland ecosystem, long-term overgrazing has resulted in considerable deterioration and even desertification, which may result in the release of considerable quantities of C to the atmosphere through loss of biodiversity and biomass (Hou and Nan, 2006; Neely et al., 2009). Grazing intensity is one of the major factors controlling the C budget of rangeland ecosystems. However, there is little information available regarding the effect of grazing intensity on the C budget of rangeland on the Loess Plateau because most research is based on nonquantitative grazing plots rather than quantitatively designed grazing experiments. Consequently, we investigated the influence of grazing on Rs in a long-term study. The objectives of this research were to 1) identify the effects of stocking rate on Rs under different grazing periods in rangeland of the Loess Plateau and 2) quantify the response of Rs to environmental and management factors.

## Methods

### Site Description

This study is part of a larger long-term research project begun in 2001 and has previously been described (Chen et al., 2010). Briefly, the study site is located in Huanxian County, eastern Gansu Province, northwest China (37.14°N, 106.84°E) in the Loess Plateau Ravine. The study site is at about 1650 m altitude with a mean daily air temperature of 7.1°C, a mean annual precipitation of 360 mm, and mean annual potential evaporation of 1993 mm; more than 70% of the total rainfall occurs from July to September. Spring and autumn in the study area are typically short; summer is hot and humid; and winter is long and cold. The soil is classified as sandy, free-draining loess and the rangeland a typical temperate steppe (Cooperative Research Group on Chinese Soil Taxonomy, 2001). The dominant species are *Stipa bungeana*, *Lespedeza davurica*, *Pennisetum flaccidum*, *Artemisia capillaries*, and *Setaria viridis* (Hou et al., 2002).

### Experimental Design

A simulated grazing system was established in spring 2001 using 18-month-old Tan wethers, a traditional breed in the region, purchased in May each year at an average 20 kg live weight and sold 7 months later at an average 35 kg live weight. Two flatland areas, about 200 m apart, were selected for summer grazing and early winter grazing. Each was divided into 9 plots comprising three replicates of three stocking rates: 2.7, 5.3, and 8.7 sheep · ha<sup>-1</sup> in a spatial design. Two enclosure plots (0 sheep · ha<sup>-1</sup>) were also maintained in the summer grazed area. The area of each plot was 0.5 ha for the grazing treatments and slightly less than this for the enclosure plots. Summer grazing duration was 90 days, from early June to early September each year (10 days per replicate, three rotations) and winter grazing

duration 48 days, from late October to mid-December (8 days per replicate, two rotations).

### Sampling and Measurements

All sampling and measurements were conducted in early August 2008, when the aboveground biomass of the rangeland typically peaks (Chen et al., 2010), during the second rotation for the summer grazed site. A LI-COR 6400 portable photosynthesis system attached to a 6400-09 soil efflux chamber (LI-COR, Lincoln, NE, USA) was used to measure Rs following the standard procedures recommended by LI-COR (Dornbush and Raich, 2006). Soil respiration was measured at 01:00 hours and every 2 hours from 06:00 hours to 20:00 hours during the first 2 wk of August. Daily total Rs was estimated by integrating the periodic CO<sub>2</sub> efflux rates over a 24-hour period. Mean daily Rs efflux rate was also estimated in late April (early stage of herbage growth) and mid-December (non-growth period of rangeland) by measuring Rs from 09:30 hours to 10:30 hours and from 15:30 hours to 16:30 hours on clear days (Mosier and Delgado, 1997; Kessavalou et al., 1998).

In each plot, three parallel 50-m transects 30–40 m apart were randomly established, two sites were randomly set along each 50-m sampling transect, and thus six sites were selected for measuring Rs. Aboveground live biomass was removed 1–2 days before insertion of tubes (PVC: 11.0 cm diameter, 5.0 cm height) to a depth of 2–3 cm, to enable Rs measurements.

Soil temperature (°C) at 2-cm and 5-cm depth was measured adjacent to each Rs core site (c. 10.0 cm) using a thermocouple probe connected to the LI-COR 6400 at the time of Rs measurement (Davidson et al., 1998). Gravimetric soil moisture content in the top 10.0 cm was measured within 1 day of Rs sampling (Haferkamp and MacNeil, 2004).

The relationship between Rs and soil temperature can be described using the exponential function  $R_s = a e^{bST}$ , where  $R_s$  is the soil respiration,  $a$  represents the intercept for Rs at 0°C,  $b$  represents the sensitivity of Rs to temperature, and  $ST$  is soil temperature (Luo et al., 2001). To evaluate the sensitivity of diurnal and seasonal Rs to temperature, we calculated the Rs quotient  $Q_{10} (= e^{10b})$ .

Root dry matter (DM) was measured adjacent to the Rs sample points by collecting and washing soil cores (10.0-cm depth, 10.0-cm diameter) to a depth of 100.0 cm in 10.0-cm increments (Lamb, 2008). Soil was removed from the roots by washing soil cores over a 2.0mm mesh sieve (McNaughton et al., 1998), after which the dry mass of roots was determined by oven-drying at 65°C until a constant weight was obtained. Results are reported as total root DM (g · m<sup>-2</sup>) to a depth of 1 m. Aboveground DM was measured by cutting all vegetation in 1.0-m<sup>2</sup> quadrats (six per plot) before plots were grazed in the second rotation (August 2008). Samples were dissected into live and dead components, dried at 65°C until a constant weight was obtained, and results reported as live, dead, and total DM (g · m<sup>-2</sup>).

### Statistical Analysis

Data were analyzed using the Statistical Package for the Social Sciences (SPSS) for Windows (version 13.0; SPSS Inc., Chicago, IL, USA). The data were evaluated by multiple regression analysis using the “standardized regression coefficients” as path coefficients for the regression equation. The normality of the data and error variance were assessed and standard transformations used when errors were not normally distributed (Sefcik et al., 2007). Differences among treatment means were evaluated by one-way ANOVA. Path analyses were used to quantify the interactive effects of stocking rate, grazing period, soil moisture, soil temperature, and root biomass

(independent factors) on Rs (dependent factor) (Murphy et al., 2008). The residual coefficient (Pr) was used to assess the ability of stocking rate, grazing period, and site environmental factors to explain Rs.

## Results

### Aboveground and Belowground Biomass

Total aboveground DM ranged from 126.9 to 68.6 g·m<sup>-2</sup> (Table 1) for the low (2.7-sheep·ha<sup>-1</sup>) and high stocking rate (8.7-sheep·ha<sup>-1</sup>) treatments, respectively, on the summer-grazed site ( $P = 0.02$ ). The largest component of total DM was live DM, which ranged from 93.0 to 54.7 g·m<sup>-2</sup> for the low and high stocked treatments, respectively ( $P < 0.02$ ). Dead DM was not influenced by stocking rate at the winter-grazed site.

Root DM ranged from 409 to 606 g·m<sup>-2</sup> and 459 to 593 g·m<sup>-2</sup> for the summer- and winter-grazed sites, respectively (Table 1). On the summer-grazed site root DM was significantly reduced ( $P = 0.02$ ) by the high stocking rate treatment (8.7 sheep·ha<sup>-1</sup>) (409.0 g·m<sup>-2</sup>), whereas on the winter-grazed site root DM tended to increase with higher stocking.

### Soil Moisture

Soil moisture was generally low on both sites (Table 1) and was not influenced by stocking rate on the winter-grazed sites. Soil moisture was significantly correlated with root DM at both sites:  $R^2 = 0.6241$  ( $P = 0.01$ ) and  $R^2 = 0.8649$  ( $P = 0.0003$ ) for the summer- and winter-grazed sites, respectively (Fig. 1).

### Soil Respiration

Soil respiration declined as stocking rate increased at both sites; however, treatment differences were significant ( $P < 0.02$ ) for the summer-grazed site only; Rs for the high stocking rate (4.3 g CO<sub>2</sub>·m<sup>-2</sup>·day<sup>-1</sup>) was significantly lower than the low (6.0 g CO<sub>2</sub>·m<sup>-2</sup>·day<sup>-1</sup>) and medium (5.1 g CO<sub>2</sub>·m<sup>-2</sup>·day<sup>-1</sup>) stocking rates (Table 1). Soil respiration was positively correlated with soil moisture;  $r = 0.80$  ( $P = 0.01$ ),  $r = 0.75$  ( $P = 0.02$ ) on the summer- and winter-grazed sites, respectively, and with root DM:  $r = 0.69$  ( $P = 0.04$ );  $r = 0.91$  ( $P = 0.0006$ ) on the summer- and winter-grazed sites, respectively.

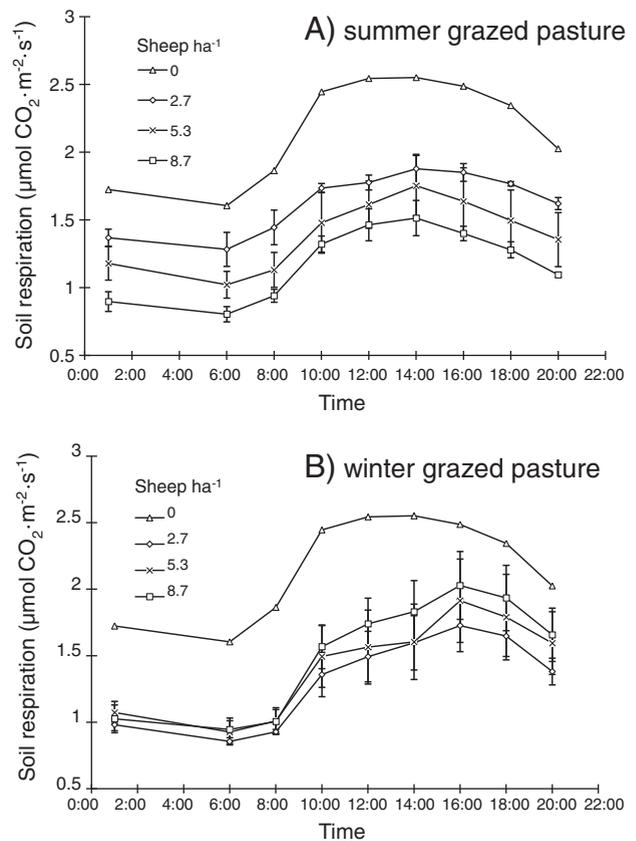
The diurnal curve of Rs closely resembled a unimodal curve (Fig. 1), similar to the diurnal pattern of soil temperature (data not shown). Soil respiration rates in summer-grazed pastures peaked at

**Table 1**

The effect of stocking rate (sheep·ha<sup>-1</sup>) and grazing site on soil–respiration (Rs), soil moisture (SM), root dry matter (RDM), aboveground live dry matter (LDM), dead dry matter (DDM), and total dry matter (TDM) at the beginning of the second rotation.

Stocking rate	Rs	SM	RDM	LDM	DDM	TDM
Sheep·ha <sup>-1</sup>	g CO <sub>2</sub> ·m <sup>-2</sup> ·day <sup>-1</sup>	%	g·m <sup>-2</sup>			
<b>Summer-grazed</b>						
2.7	6.0 <sup>a</sup>	7.8 <sup>a</sup>	606 <sup>a</sup>	93.0 <sup>a</sup>	33.9 <sup>a</sup>	126.9 <sup>a</sup>
5.3	5.1 <sup>a</sup>	7.3 <sup>a</sup>	536 <sup>a</sup>	90.6 <sup>a</sup>	24.9 <sup>b</sup>	115.5 <sup>a</sup>
8.7	4.3 <sup>b</sup>	5.5 <sup>b</sup>	409 <sup>b</sup>	54.7 <sup>b</sup>	13.9 <sup>c</sup>	68.6 <sup>b</sup>
Significance	0.02	0.02	0.02	<0.02	0.02	0.02
<b>Winter-grazed</b>						
2.7	5.1	6.3	459	105.5	59.2	164.7
5.3	5.2	7	486	90.9	55	145.9
8.7	5.2	7.1	593	87.4	47.5	134.9
Significance	NS	NS	NS	NS	NS	NS

<sup>a,b,c</sup>Treatments with different letter superscripts are significantly different ( $P = 0.05$ ).



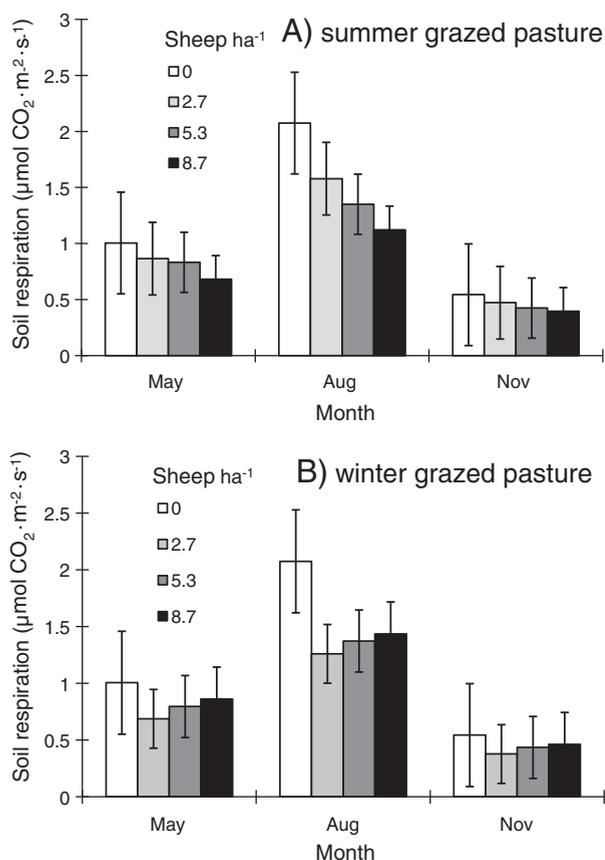
**Figure 1.** Diurnal course of soil respiration measured in summer for **A**, summer- and **B**, winter-grazed pastures under different stocking rates. Error bars = 2 × SEM.

around 1400 hours and then dropped rapidly to the minimum at 0600 hours. In winter-grazed pastures maximum Rs occurred at around 1600 hours with the minimum also at 0600 hours. Maximum and minimum Rs ranged from 1.51 to 2.55 µmol·m<sup>-2</sup>·s<sup>-1</sup> and from 0.80 to 1.60 µmol·m<sup>-2</sup>·s<sup>-1</sup>, respectively, in summer- and winter-grazed pastures.

Seasonal estimates of Rs revealed a large seasonal influence at both sites: Rs was highest in August, intermediate in April, and least in December (Fig. 2) at both sites ( $P < 0.01$ ). At the summer-grazed site, Rs decreased as the stocking rates increased in August but was not influenced by stocking rate at other times of the year. On the winter-grazed site Rs tended to increase as stocking rate increased, though differences were not significant at any time. Enclosure plot Rs was generally higher than the grazed plots.

### Soil Temperature

Soil temperatures peaked at around 1600 hours for both winter- and summer-grazed sites at both soil depths; the minimum occurred at about 0600. Maximum temperatures were about 40°C and 35°C at 2- and 5-cm soil depth, respectively. For summer-grazed sites the minimum temperature was just above 15°C at both 2-cm and 5-cm soil depths. The fluctuations in soil temperature at 2-cm depth were greater than those at 5-cm. This was primarily due to a combination of slightly higher maximum and lower minimum temperatures at 2-cm compared with 5-cm depth at the summer-grazed site, whereas at the winter-grazed site maximum temperatures were similar but minimum temperatures at 2-cm were 2–3°C lower than at 5-cm depth. Despite slightly lower night temperatures in the enclosure plot, soil temperature did not differ among grazed



**Figure 2.** Seasonal differences in mean daily soil respiration efflux in **A**, summer- and **B**, winter-grazed pastures. Error bars = 2 x SEM.

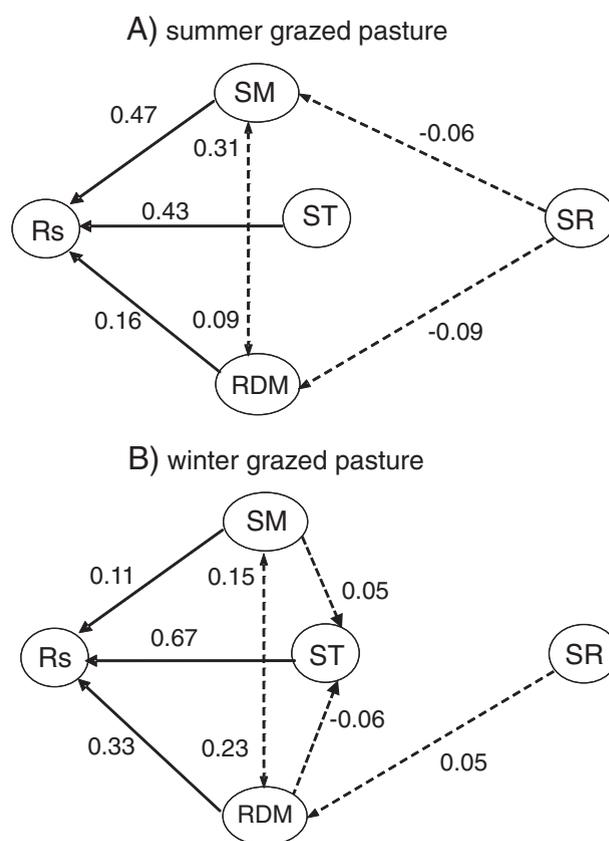
plots at either site ( $P > 0.05$ ). Soil temperatures for the summer-grazed site were generally higher than for the winter-grazed site ( $P = 0.05$ ).

*Temperature Sensitivity of Soil Respiration*

The  $Q_{10}$  values for the relationship between soil temperature and diurnal  $R_s$  at 5-cm soil depth ranged from 1.3 to 1.4 and 1.5 to 1.6 and those at 2-cm from 1.2 to 1.3 and 1.3 to 1.4 in summer- and winter-grazed pastures, respectively, whereas the  $Q_{10}$  value of the enclosure plot was 1.2 at both soil depths (Table S1; available online at <http://dx.doi.org/10.1016/j.rama.2014.12.002>). The  $Q_{10}$  values estimated under seasonal scales (Table S2; available online at <http://dx.doi.org/10.1016/j.rama.2014.12.002>) were considerably higher than the diurnal  $Q_{10}$  values (2.3 in the enclosure plot), but differences between stocking rates and grazing time were generally small.

*Effect of Environmental Factors on Soil Respiration*

Path analysis was used to assess the effects of soil temperature, soil moisture, root DM, and stocking rate on  $R_s$ . Soil moisture and soil temperature were the most important factors at the summer-grazed site (Fig. 3A); the path coefficients with direct influence were soil moisture (0.47), root DM (0.16), and soil temperature (0.43). Stocking rate had a small negative effect on  $R_s$  acting indirectly through root DM; the coefficients were (-0.09) and (-0.06) for root DM soil temperature, respectively. This indicates that grazing reduced the efflux of  $CO_2$ , primarily via a reduction in the root DM. At the winter-grazed site (Fig. 3B), soil temperature was the most important direct factor



**Figure 3.** Path diagram with path coefficients showing the effects of soil moisture (SM), soil temperature (ST), root dry matter (RDM), and grazing (SR) on soil respiration ( $R_s$ ) for **A**, summer- and **B**, winter-grazed pastures. Solid and dashed lines denote direct and indirect effects on  $R_s$ , respectively. Coefficients associated with bidirectional arrows are placed adjacent to the arrowhead, indicating the relevant direction of influence.

followed by root DM and soil moisture with coefficients of 0.67, 0.37, and 0.11, respectively; stocking rate had a weak indirect influence on  $R_s$  (coefficient = 0.05) through root DM.

**Discussion**

In the steppe biomes, root biomass has a relatively strong influence on  $R_s$  because aboveground biomass is periodically removed, either by grazers or fire. Most studies have recorded root biomass in rangelands of between 50 and 800  $g \cdot m^{-2}$ , most of which is in the upper 20 cm (Bonin et al., 2013), consistent with the results of this study. The response of root biomass and  $R_s$  to grazing varied with grazing time; in summer-grazed pasture, root biomass and  $R_s$  were reduced at high stocking rates while grazing had no influence in winter-grazed pasture. The effect of grazing on soil  $CO_2$  flux depends on grazing intensity and history (Owensby et al., 2006; Väisänen et al., 2014). The results of this study can be explained by the close association between root biomass and  $R_s$  and the negative impacts of grazing on root DM in the summer-grazed pasture (Table 1). In the winter-grazed pasture the interval between grazing (from middle November through December 2007) and measurement (August 2008) probably allowed root DM to recover from any grazing effects.

The temperature sensitivity of  $R_s$  has received a great deal of attention due to its importance in the global C cycle and potential for feedback regarding climate change (Karhu et al., 2014). The  $Q_{10}$  values in the current study are typical (Yan et al., 2013), as is the

positive response to soil temperature (Boone et al., 1998) and soil moisture (Chen et al., 2004). In the diurnal dynamic of Rs, lower  $Q_{10}$  values were observed for lightly grazed treatments, clarifying the effect of grazing on Rs and indicating that soil moisture may have been limiting (Gulledge and Schimel, 2000; Xu and Qi, 2001). The increased  $Q_{10}$  values observed under high stocking rates are probably due to the effect of stocking rate on below-ground biomass and numbers of microbial organisms. Low root biomass and microorganism populations probably resulted in the lower  $Q_{10}$  values observed under high stocking rates.

One of the main objectives of this study was to identify the key biotic and abiotic factors controlling Rs. Plant roots are largely responsible for soil Rs through their influence on the size of the biological pools in the soil (Smith and Johnson, 2004) and C supply (Fang et al., 1998; Rey et al., 2002; Epron et al., 2004). Environmental factors such as temperature and soil moisture influence the rate at which these biological components respire (Chang et al., 2012). In this study soil moisture and soil temperature were found to have a much greater influence on Rs than grazing in both summer- and winter-grazed pasture.

Long-term overgrazing has resulted in degradation of rangelands on the Loess Plateau. When expressed as stock unit months (1 stock unit = 45 kg ewe) typical stocking rates on the Plateau are about 22.8 stock unit months ( $1.9 \text{ stock units} \cdot \text{ha}^{-1}$ ), near the upper end of stocking rates used in the current study (Wang et al., 2011a). Hou and Nan (2006) suggested that appropriate stocking rates for this region are between 0.6 and 1.0 stock units  $\cdot \text{ha}^{-1}$ , depending on annual rainfall variation. The results of this research indicate that reducing stocking rates may increase livestock production as a result of increased forage availability (Table 1). Increased feed intake can produce efficiency gains through, for example, increased weight of lambs sold per ewe carried. This increased efficiency can result in increased per ha production despite decreased stocking rates (Michalk et al., 2011). These results suggest that the implications for Rs are minimal because Rs is directly controlled by soil temperature, soil moisture, and root biomass. The linear regression functions of Rs against ST (average at 2-cm and 5-cm) and SM could well predict Rs in both summer-grazed pasture ( $R_s = -0.138 + 0.032 \text{ ST} + 0.107 \text{ SM}$ ,  $R^2 = 0.485$ ,  $P = 0.000$ ) and winter-grazed pasture ( $R_s = -2.527 + 0.052 \text{ ST} + 0.366 \text{ SM}$ ,  $R^2 = 0.646$ ,  $P = 0.000$ ) in summer.

## Implications

This study was conducted to examine the roles that stocking rate, grazing period, and environmental factors (soil moisture, soil temperature, root biomass) played on Rs. The results revealed that soil temperature, soil moisture, and grazing were important factors in regulation of the spatial and temporal variability of Rs in semiarid rangelands in northern China. Rs decreased with increasing stocking rates on the summer-grazed site but was not influenced by grazing on the winter-grazed site. Soil moisture and soil temperature had the greatest influence on Rs at both sites. Grazing affected Rs indirectly, primarily through its influence on root biomass. During summer grazing, high stocking rates ( $8.7 \text{ sheep} \cdot \text{ha}^{-1}$ ) significantly reduced soil moisture, root DM, and aboveground DM, indicating that overgrazing occurred at this stocking rate.

## Acknowledgment

We acknowledge Professor Zhibiao Nan for his direction with implementing the experiment.

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