Biogeosciences, 11, 1743–1750, 2014
www.biogeosciences.net/11/1743/2014/
doi:10.5194/bg-11-1743-2014

Biogeosciences
Open Access

Response of carbon dioxide emissions to sheep grazing and N application in an alpine grassland – Part 1: Effect of sheep grazing

Y. M. Gong[1], A. Mohammat[1], X. J. Liu[2], K. H. Li[1], P. Christie[3], F. Fang[4], W. Song[1,5], Y. H. Chang[1,5], W. X. Han[2], X. T. Lü[6], Y. Y. Liu[1], and Y. K. Hu[1]

[1]Key Laboratory of Biogeography and Bioresource in Arid Land, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, 830011, China
[2]College of Resources and Environmental Sciences, China Agricultural University, Beijing, 100193, China
[3]Agri-Environment Branch, Agri-Food and Biosciences Institute, Belfast BT9 5PX, UK
[4]State Key Laboratory of Earth Surface Processes and Resource Ecology, Institute of Resources Science, College of Resources Science and Technology, Beijing Normal University, Beijing, 100875, China
[5]Graduate University of the Chinese Academy of Sciences, Beijing, 100039, China
[6]State Key Laboratory of Forest and Soil Ecology, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang, 110164, China

Correspondence to: A. Mohammat (anwar@ms.xjb.ac.cn) and Y. K. Hu (gongym@ms.xjb.ac.cn)

Received: 27 May 2013 – Published in Biogeosciences Discuss.: 22 July 2013
Revised: 19 December 2013 – Accepted: 27 February 2014 – Published: 3 April 2014

Abstract. Previous work has failed to address fully the response of (autotrophic and heterotrophic) respiration to grazing in different ecosystems, particularly in alpine grasslands outside the growing season. From 2010 to 2011 a field experiment combined two methods (static closed chambers and a closed dynamic soil CO_2 flux system) in alpine grasslands located in the Tianshan Mountains. We examined the effects of grazing regime on ecosystem respiration (R_e) both outside (NGS) and during (GS) the growing season and determined the pattern of R_e in relation to climate change. There was no significant change in CO_2 emissions under grazing. Heterotrophic respiration (R_h) accounted for 78.5 % of R_e with short-term grazing exclusion and 93.2 % of R_e with long-term grazing exclusion. R_e, R_h and autotrophic respiration (R_a) fluxes outside the growing season were equivalent to 12.9 %, 14.1 % and 11.4 % of the respective CO_2 fluxes during the growing season. In addition, our results indicate that soil water content played a critical role in R_a in the cold and arid environment. Both R_h and R_e were sensitive to soil temperature. Moreover, our results suggest that grazing exerted no significant effect on CO_2 emissions in these alpine grasslands.

1 Introduction

Global carbon dioxide (CO_2) emissions have increased from 6.1 ± 0.3 Pg C year^{-1} in 1990 to 9.5 ± 0.5 Pg C year^{-1} in 2011 and will increase to 9.7 ± 0.5 Pg C year^{-1} in 2012 or 2.6 % above 2011 levels (Le Quéré et al., 2012; Peters et al., 2013). Ecosystem respiration (R_e), consisting of heterotrophic respiration (R_h) and autotrophic respiration (R_a) of plant biomass, is the primary route by which CO_2 from plants and soils returns to the atmosphere (Hogberg and Read, 2006). Due to the large cover area (White et al., 2000) and high content of soil organic carbon (Eswaran et al., 1993), seasonal and annual variation in R_e in grasslands plays an important role in moderating the global carbon cycle. However, current evidence indicates that seasonal and annual R_e in grassland has been significantly altered by grassland management, especially by grazing intensity and grazing exclusion.

Several hypotheses have addressed the direct and indirect effects of grazing on R_e. High grazing intensity directly reduces above-ground biomass, litter input into the soil (Johnson and Matchett, 2001), and labile C from microorganisms and roots (Stark and Grellmann, 2002). Grazing also indirectly aggravates the degree of water and nitrogen limitation because grazing-induced changes in soil properties increase the risk of surface runoff (Rauzi and Hanson, 1996; Daniel et al., 2006) and nitrogen leaching loss (Eckard et al., 2003; Di and Cameron, 2004). The negative direct and indirect effects ultimately restrict or alter seasonal and annual R_e in grasslands. For example, Craine et al. (1999) and Wan and Luo (2003) reported that grazing reduced the CO_2 flux by 19–50 % in some temperate grasslands.

Traditionally, grazing exclusion is considered to be a helpful measure to restore ecosystem functioning in grazing-induced deteriorating grassland. Although indirect evidence indicates increasing trends in community biomass and mitigation of soil nutrient availability under conditions of grazing exclusion (Medina-Roldan et al., 2012; Qiu et al., 2013), comparisons of seasonal and annual response patterns of R_e to grazing and grazing exclusion are still unclear. A recent study in sandy grasslands demonstrated that short-term effects of grazing exclusion on ecosystem CO_2 flux were regulated by annual rainfall (Czobel et al., 2012). However, the effects of long-term grazing exclusion and the differences between long-term and short-term grazing exclusion on annual and seasonal R_e in grasslands are still two major gaps in our knowledge of carbon exchange between the terrestrial biosphere and the atmosphere.

In the present study we compared the effects of grazing and short-term and long-term grazing exclusion on seasonal and annual R_e (R_h and R_a) variation in alpine grasslands in central Asia. Our objectives were to clarify the effects of short- and long-term grazing exclusion on CO_2 fluxes in alpine grasslands, to evaluate whether or not CO_2 emissions outside the growing season constitute an indispensable portion of ecosystem respiration on a year-round basis, and to demonstrate the effects of soil temperature and soil water content (both to 10 cm depth) on ecosystem respiration under grazing management in alpine grasslands.

2 Materials and methods

2.1 Study sites

The study was conducted at the Bayinbuluk Grassland Ecosystem Research Station, Chinese Academy of Sciences (42°53.1′ N, 83°42.5′ E). Bayinbuluk alpine grassland is located in the southern Tianshan mountains, Xinjiang Uygur Autonomous Region, Central Asia, and covers a total area of approximately 23 000 km^2. The grassland is at a mean altitude of 2500 m a.s.l. Local meteorological data (1980–1999) show a mean annual precipitation of 265.7 mm, with 78.1 % occurring during the growing season from May to September, and a mean annual temperature of -4.8 °C, with the lowest mean monthly temperature in January (-27.4 °C) and the highest in July (11.2 °C). General characteristics of the sites are shown in Table 1.

Five grazing management sites were established. The alpine grassland is dominated by *Stipa purpurea* and all sites are cold and dry grassland. There were two grazing regimes, namely short- and long-term grazing exclusion. The short-term grazing exclusion sites comprised site LG_B grazed by 4.3 sheep ha^{-1} in a full year (100 ha), site UG_5 ungrazed since 2005 (10 ha), and site UG_8 ungrazed since 2003 (0.25 ha). The long-term grazing exclusion sites were site UG_{27} ungrazed since 1984 (0.25 ha) and site LG_A lightly grazed by 2.0 sheep ha^{-1} in winter (October to April; 100 ha). Each treatment comprised four blocks (each 4 × 8 m with an 1 m-wide buffer zone) in the long-term grazing exclusion sites.

2.2 Measurement methods

CO_2 fluxes were measured using two methods. The first was a static closed chamber method (opaque, static, manual stainless steel chambers, each 50 × 50 × 10 cm) at sites UG_{27} and LG_A. The external surface of each chamber was covered with white plastic foam to minimize any impact of direct radiative heating during sampling. The chamber was placed on a collar (50 × 50 × 10 cm) with a groove to prevent leakage during gas sampling. Each site had four replicate chambers. Gas samples were taken from inside the chamber 0, 15 and 30 min after chamber closure using a 60 ml plastic syringe and transferred immediately into a pre-evacuated 50 ml air bag (Hede Inc., Dalian, Liaoning, China). CO_2 fluxes of R_e were sampled during the same time period (12:00–14:00, GMT + 8 h) from May 2010 to September 2011 (no sampling in January and February 2011 because of mean temperatures of -33.3 and -23.0 °C, respectively) and four times per month during the growing season (10 May to 8 October, about 152 days), and twice per month outside the growing season (9 October to 9 April, about 213 days) at sites UG_{27} and LG_A. CO_2 samples, which were stored in separate air bags, were analyzed by gas chromatography (Agilent 4890D, Agilent Technologies, Wilmington, DE) within one week. Calculation of CO_2 fluxes followed the description of Zhang et al. (2005).

The second method was a closed dynamic soil CO_2 flux system (Li-Cor 8100, Model 8100-101 or 8100-104, Li-Cor, Lincoln, NE) at sites LG_B, UG_5 and UG_8. R_e was measured by inserting three polyvinyl chloride (PVC) collars (10.2 cm inside diameter, 6 cm height) 3 cm into the soil at each site in July 2009. The collars were arranged 1 m apart to form a triangle. All living plants were maintained intact. Heterotrophic respiration (R_h, microbial respiration) was also determined by inserting three PVC collars into the soil at each site. Living roots were removed from the soil and the soil was replaced to maintain the original horizons of the profile. A diaphragm was inserted into the soil outside the root zone to prevent re-growth. Soil respiration (R_h) was measured at least one day after exclusion of the living roots (Hanson et al., 2000). Autotrophic respiration (R_a, the below-ground parts

Table 1. Characteristics of the ten alpine grassland sites in the Tianshan mountains of Central Asia.

Site	Latitude (N)	Longitude (E)	Altitude (m)	Aboveground biomass (Jul 2010) ±S.E. ($g\,m^{-2}$)	Below-ground biomass (Jul 2010) ±S.E. ($g\,50\,cm^{-2}$)	Plant cover (Jul 2010) ±S.E. (%)	Soil BD (0–10 cm) (Jul 2010) ±S.E. ($g\,m^{-3}$)	pH (top 10 cm)	Soil EC (0–10 cm) ($mS\,cm^{-1}$)	Grazing intensity (sheep units ha^{-1})	Method
UG_8	42°52.802′	83°42.437′	2468	122 ± 10.5	11.0 ± 3.22	97 ± 4.2	1.0 ± 0.01	7.9	0.34	0	Li-8100
UG_5	42°52.802′	83°42.442′	2468	110 ± 7.4	12.4 ± 2.60	77 ± 8.7	1.1 ± 0.03	7.7	0.31	0	
LG_B	42°52.798′	83°42.437′	2468	56 ± 4.4	7.4 ± 1.81	48 ± 5.7	1.1 ± 0.01	7.8	0.21	4.3	Static
UG_{27}	42°52.802′	83°42.173′	2472	207 ± 15.2	11.2 ± 2.13	78 ± 6.6	0.9 ± 0.02	8.0	0.33	0	closed
									0.27		
LG_A	42°52.832′	83°42.125′	2473	72 ± 9.7	9.8 ± 1.58	55 ± 2.9	1.1 ± 0.01	8.0		2.0	chamber

NB: AGB, Above-ground biomass; BGB, Below-ground biomass; PC, Plant cover; SBD, soil bulk density; SEC, soil electrical conductivity

of the plant and root respiration) was calculated as follows:

$$R_p = R_e - R_m. \quad (1)$$

In order to minimize disturbance to the plots when installing the PVC columns, we measured the CO_2 efflux rate at least 1 week after the installation/application. A soil CO_2 flux chamber attached to a Li-8100 was placed on each collar for 3 min to measure R_h (or R_e) and then moved to the next collar. R_e and R_h were measured during the same time period (11:00–20:00, GMT + 8 h) from August 2010 to July 2011 (no sampling in January or February 2011), four times per month during the growing season, and twice per month outside the growing season at sites LG_B, UG_5 and UG_8.

Above-ground biomass of different species was obtained in July 2010 (1×1 m plots and $n = 3$ at each site). Below-ground biomass was obtained based on estimation using root cores (8 cm dia; $n = 5$ at each site) to a depth of 30 cm. Plant (above-ground and below-ground) biomass was determined by oven drying at 60 °C for 24 h. Plant cover was determined by visual measurement. Soil bulk density was measured using 100 cm^3 soil wreath knives to 10 cm depth ($n = 5$ at each site). Soil samples were collected from each site (n = 5) to determine pH (1:5) and soil electrical conductivity to a depth of 10 cm (Table 1). An Auto Weather Station (Campbell Scientific, Logan, UT) adjacent to plots around the whole experiment (sites UG27, LG_A, LG_B, UG_5 and UG_8) monitored air temperature, soil temperature at 10 cm depth and soil water content at 10 cm depth.

2.3 Calculations and statistical analysis

Statistical analysis was carried out using SPSS 13.0 for Windows (SPSS Inc., Chicago, IL) and SigmaPlot (SigmaPlot for Windows, Version 10, SyStat Software Inc., San Jose, CA). As CO_2 flux were measured repeatedly across time, we used repeated measures ANOVA (RMANOVA) to examine inter-annual variability in CO_2 flux when combined with grazing management as treatment. Monthly mean CO_2 fluxes in each plot were calculated by averaging all measurements in the same month. If significant interactive effects between grazing management (short-term grazing exclusion) and year were detected (i.e., $P < 0.05$ for year effects), RMANOVA was used again to examine treatment effects on CO_2 flux within each year. Between-subject effects were examined such as grazing management, and within-subject effects were time of month and its interaction with grazing management. Linear and non-linear curve fitting was performed with SigmaPlot software to identify significant correlations between environmental variables and CO_2 fluxes.

3 Results

3.1 Biotic and abiotic conditions under long- and short-term grazing exclusion

Plant cover and above- and below-ground biomass increased by 41.8 %, 187.5 % and 14.2 %, respectively, under long-term grazing (27 years) exclusion and increased 0.6–1.0 times, 0.9–1.2 times and about 60.0 % under short-term grazing exclusion (Table 1). There was no significant variation in soil bulk density (0–10 cm) among treatments, with an average of 1.04 $g\,cm^{-3}$. Average pH and soil electrical conductivity (0–10 cm) under long- and short-term grazing exclusion was 7.8, 8.0, 0.325 and 0.300 $mS\,cm^{-1}$, respectively.

Air temperature (AT), soil temperature at 10 cm depth (ST) and soil water content at 10 cm depth (SWC) showed clear seasonal variation throughout the observation period (Fig. 1). The annual AT, ST and SWC reached maximum values of 17.9 °C (early August 2010), 15.8 °C (late July 2010) and 26.4 % (June 2011), and minimum values of −38.3 °C (January 2011), −10.8 °C (late January 2011) and 5.6 % (March 2011), respectively. Average AT, ST and SWC in GS were 9.6 °C, 10.2 °C and 18.4 %, respectively, and −18.5 °C, −4.8 °C and 9.7 % in NGS.

3.2 CO_2 fluxes with long-term grazing exclusion

Results from RMANOVA show that significant inter-annual variability in Re fluxes was detected ($P < 0.001$), but treatment (long-term grazing exclusion) and treatment × year had no significant effects on R_e fluxes ($P = 0.132$ and 0.064, respectively). When RMANOVA was conducted separately for each year, both treatment and treatment × month had no significant effects on R_e fluxes ($P = 0.673$ and 0.987, respectively), but significant seasonal patterns were observed in both years ($P < 0.001$). When monthly mean R_e fluxes were reclassified into growing season (GS) and outside

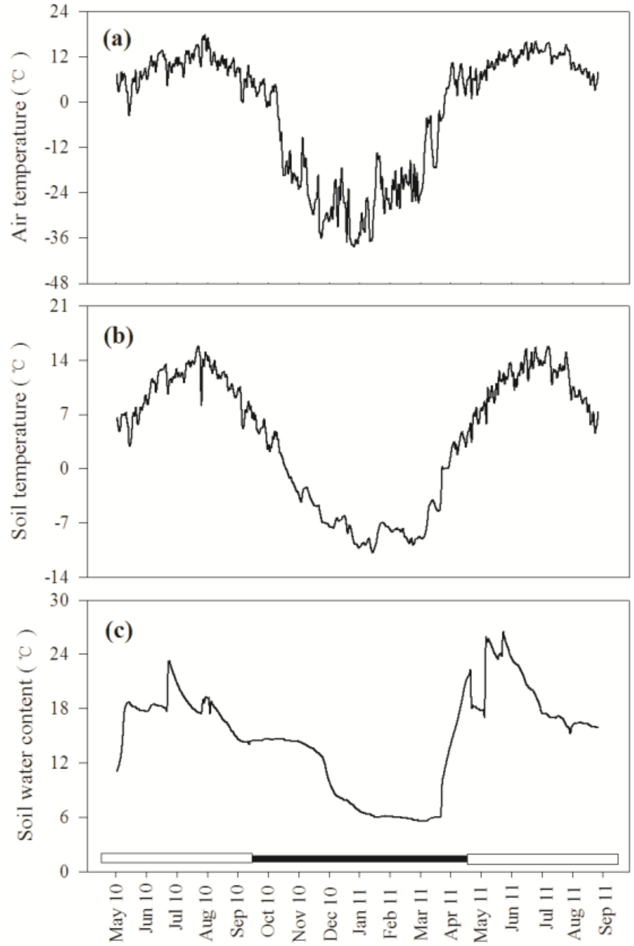

Fig. 1. Air temperature **(a)**, soil temperature at 10 cm depth **(b)** and soil water content at 10 cm depth **(c)** from May 2010 to September 2011 in an alpine grassland in the Tianshan mountains. White and black horizontal bars represent within (2010 and 2011) and outside the growing season, respectively.

growing season (NGS), long-term grazing enclosure management (ungrazed for 27 years) had no significant effects on the CO_2 emissions of ecosystem respiration (R_e) during GS 2010 ($P = 0.896$), 2011 ($P = 0.960$) or NGS ($P = 0.462$) (Fig. 2b). Across the entire period of observations (May 2010–September 2011) R_e fluxes showed clear seasonal fluctuation. The maximum monthly R_e fluxes were 122.8 $mg\,m^{-2}\,h^{-1}$ at UG_{27} and 103.7 $mg\,m^{-2}\,h^{-1}$ at LG_A in June 2011. The minimum values were 2.0 $mg\,m^{-2}\,h^{-1}$ at UG_{27} and 2.6 $mg\,m^{-2}\,h^{-1}$ at LG_A in December 2010 (Fig. 2a). In addition, total R_e emissions were 179.1 and 12.8 $g\,m^{-2}$ at UG_{27} and 165.3 and 10.6 $g\,m^{-2}$ at LG_A in GS and NGS, respectively (Fig. 2b). R_e during NGS accounted for 7.1 % and 6.4 % of R_e during GS in 2010 and 2011, respectively. One conclusion that can be drawn is that if the R_e emission for NGS is not taken into account the annual CO_2 emissions can be underestimated by at least 6.0 %.

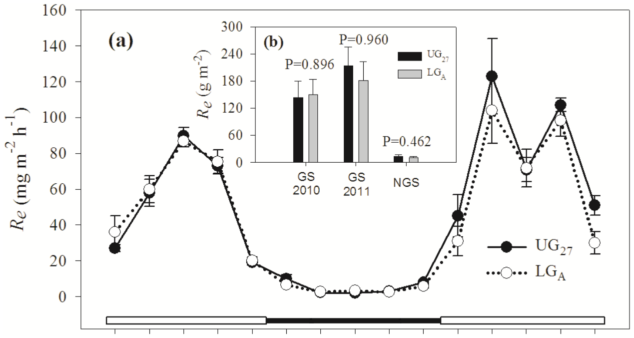

Fig. 2. Rates of CO_2 emission with ecosystem respiration (R_e) **(a)** and the magnitude of CO_2 fluxes within and outside the growing season **(b)** at sites UG_{27} (ungrazed since 1984) and LG_A (grazed in winter) using the static closed chamber method. White and black horizontal bars represent within the growing season (GS, 2010 and 2011) and outside the growing season (NGS), respectively.

3.3 CO_2 fluxes with short-term grazing exclusion

Observations were conducted over a full year (August 2010–July 2011) to determine CO_2 emissions with short-term grazing exclusion. RMANOVA analysis shows that treatment (short-term grazing exclusion) and treatment × month interaction had no significant effects on R_e ($P = 0.538$ and 0.147, respectively), R_h ($P = 0.339$ and 0.813, respectively) and R_a fluxes ($P = 0.204$ and 0.128, respectively), but significant seasonal patterns were observed over the whole year ($P < 0.001$). When monthly mean R_e, R_h and R_a fluxes were reclassified into growing season (GS) and outside growing season (NGS) there were also no significant changes in R_e ($P = 0.931$, 0.915), R_h ($P = 0.990$, 0.859) and R_a ($P = 0.192$, 0.842) emissions under short-term grazing enclosure management in GS and NGS at UG_8, UG_5 and LG_B (Fig. 3bdf). R_e, R_h and R_a flux results show substantial seasonal change based on year-round observation. The maximum monthly R_e values were 314.9, 327.7 and 316.2 $mg\,m^{-2}\,h^{-1}$ at UG_8, UG_5 and LG_B, respectively. The maximum monthly R_h fluxes were 305.3, 263.4, and 270.6 $mg\,m^{-2}\,h^{-1}$ at UG_8, UG_5 and LG_B. The maximum monthly R_a fluxes were 76.2, 88.7 and 52.2 $mg\,m^{-2}\,h^{-1}$ at UG_8, UG_5 and LG_B. The minimum monthly R_e, R_h and R_a fluxes were 9.6, 10.7 and 0 $mg\,m^{-2}\,h^{-1}$ at UG_8; 10.3, 14.5 and 0 $mg\,m^{-2}\,h^{-1}$at UG_5; 2.7, 5.0 and 0 $mg\,m^{-2}\,h^{-1}$ at LG_B (Fig. 3a, c, e). Furthermore, the ranges in total R_e, R_h and R_a emissions were 584.2–644.1, 483.4–504.2 and 98.9–169.6 $g\,m^{-2}$ under short-term grazing exclusion in GS, and 67.5–85.8, 58.0–80.8 and 12.6–20.9 $g\,m^{-2}$ in NGS, respectively (Fig. 3b, d, f).

Over the whole year total R_e accounted for 78.5 % of R_h and 21.5 % of R_a (percentages calculated from the averages of UG_8, UG_5 and LG_B). Furthermore, CO_2 emissions of R_h and R_a in NGS were 14.1 % and 11.4 % in GS, respectively. At UG_8, UG_5 and LG_B, R_e during NGS accounted

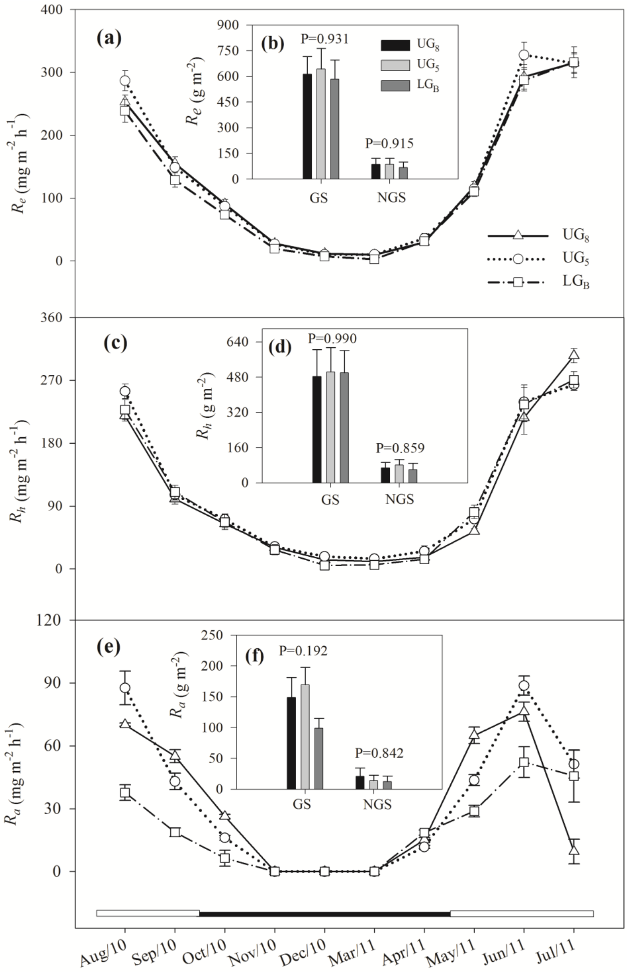

Fig. 3. CO_2 fluxes of ecosystem respiration (R_e), heterotrophic respiration (R_h) and autotrophic respiration (R_a) at sites UG_8 (ungrazed since 2003), UG_5 (ungrazed since 2005) and LG_B (grazed all year) within (GS) and outside (NGS) the growing season respectively using a Li-8100. White and black horizontal bars represent within (GS, 2010 and 2011) and outside (NGS) the growing season, respectively.

for 13.9 %, 13.3 % and 11.6 % of that in GS, respectively. R_h in GS was reduced by 1.2 % under short-term zero-grazing management. In contrast, the R_e emissions rate increased by 24.3 % under short-term grazing exclusion in NGS. Moreover, R_a was more sensitive to short-term zero-grazing, with enhancements by 61.1 % and 38.9 % in GS and NGS, respectively. The effects of R_h and R_a emissions from NGS under grazing management therefore merit further investigation.

3.4 Sensitivity of CO_2 emissions to abiotic factors under varying grazing management

The relationships between CO_2 fluxes and fluctuating environmental conditions were analyzed from May 2010 to September 2011 (the duration of short-term grazing exclusion sites was from August 2010 to July 2011). CO_2 fluxes of R_e, R_h and R_a were related exponentially to air temperature, soil temperature and soil moisture (P <0.001) (Fig. 4).

4 Discussion

4.1 Effects of grazing exclusion on CO_2 flux

Our results show that grazing exclusion (long-term or short-term) led to no significant change in mean R_e despite detection of increasing trends in plant cover and above- and below-ground biomass, which were consistent with analogous studies in a short grass prairie of Colorado (LeCain et al., 2002), an alpine meadow on the Tibetan plateau (Lin et al., 2011) and the semiarid northern Great Plains of North America (Liebig et al., 2013), but were inconsistent with studies in temperate grasslands and alpine meadows in China (Cao et al., 2004; Jia et al., 2005). Three factors may explain this. Firstly, grazing exclusion increased above-ground and below-ground biomass (Table 1), which augmented plant autotrophic respiration (R_a) (Fig. 3f) (Cao et al., 2004). Secondly, soil respiration (R_h) and its main components (i.e., fungal and bacterial respiration) were positively associated with temperature (Pietikainen et al., 2005). Furthermore, grazing elevated soil temperature by the low plant cover (Luo et al., 2010), which increased R_h (Bahn et al., 2006). Thirdly, in the cold and dry conditions litter decomposition was limited by low temperatures (Couteaux et al., 1995; Zhang et al., 2008), which in turn led to low carbon input to the soil under grazing exclusion (Polley et al., 2008), coupled with the high soil pH that finally resulted in no significant variation in R_h (Xu and Qi, 2001). Therefore, the low levels of carbon inputs and microbial activity at low temperatures contributed jointly to the absence of significant variation in CO_2 emissions.

In the present study R_h accounted for 78.5 % of R_e under short-term grazing exclusion and 93.2 % of R_e under long-term grazing exclusion, and both were higher than in an alpine meadow on the Tibetan plateau (52.6 %) (Lin et al., 2011). The range in CO_2 efflux of 20.0–76.9 $mg\,m^{-2}\,h^{-1}$ in our study was lower than the range of 81.1–100.1 $mg\,m^{-2}\,h^{-1}$ in the semiarid northern Great Plains of North America (Liebig et al., 2013) and the range of 174.7–232.9 $mg\,m^{-2}\,h^{-1}$ in an alpine meadow on the Tibetan plateau (Cao et al., 2004). We conclude that R_h reached its maximum at a value of 305.3 $mg\,m^{-2}\,h^{-1}$, which was much lower than the maximum of 695.8 $mg\,m^{-2}\,h^{-1}$ in an alpine meadow (Cao et al., 2004), and the minimum R_h (5.0 $mg\,m^{-2}\,h^{-1}$) accounted for about 12 % of that in the alpine meadow on the Tibetan plateau (41.7 $mg\,m^{-2}\,h^{-1}$) (Cao et al., 2004). R_e outside the growing season contributed 21.5 % in short-term grazing exclusion and 6.8 % in long-term grazing exclusion to the annual respiration emissions, which were similar to a sub-alpine grassland at Rigi Seebodenalpin (23.3 %) (Merbold et al., 2012). In addition, the

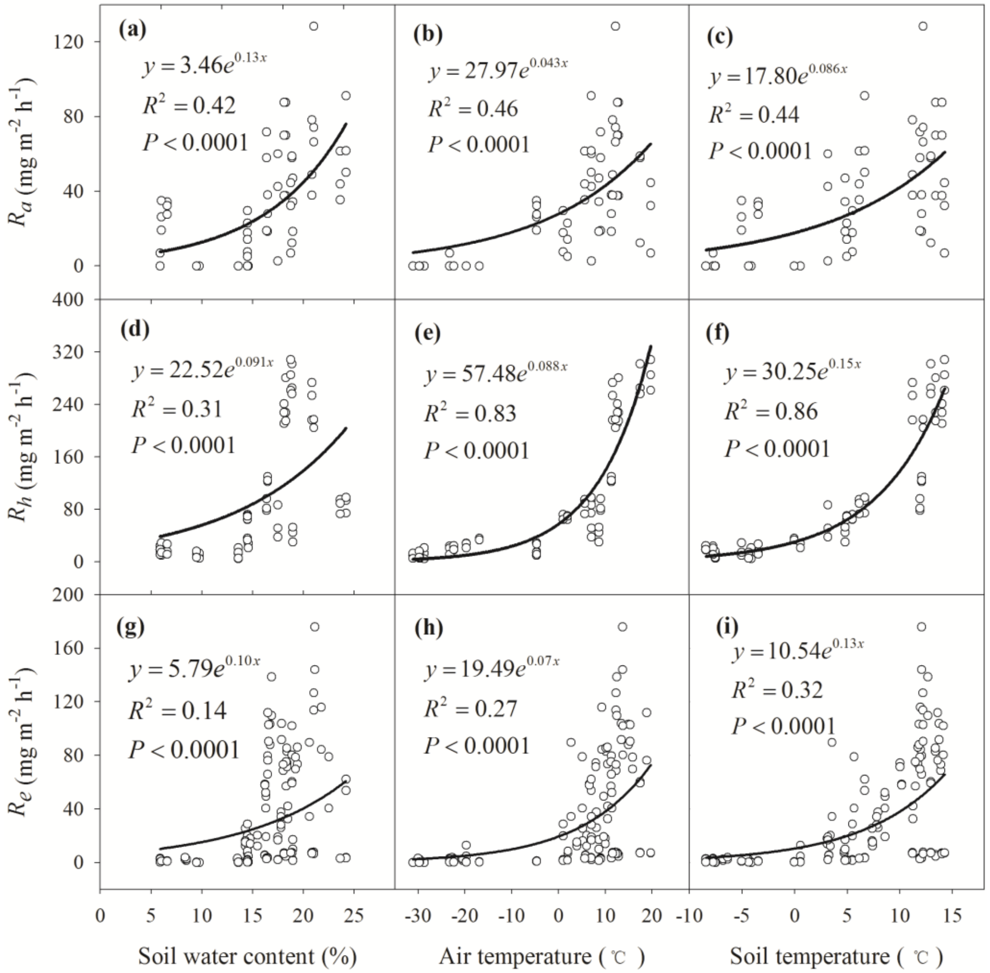

Fig. 4. Relationships between CO_2 fluxes (R_a, R_h and R_e) and soil water content at 10 cm depth (**a, d** and **g**), air temperature (**b, e** and **h**) and soil temperature at 10 cm depth (**c, f** and **i**).

CO_2 flux (2.1–16.8 mg m^{-2} h^{-1}) outside the growing season from the alpine grassland in our study was comparable with previous studies in arctic tundra (2.5–7.5 mg m^{-2} h^{-1}) (Fahnestock et al., 1999; Bubier et al., 2002), in temperate semiarid steppe (3.3–9.6 mg m^{-2} h^{-1}) (Chen et al., 2013), and in sagebrush steppe (7.5–15.0 mg m^{-2} h^{-1}) (Gilmanov et al., 2004). However, soil CO_2 emissions during the growing season (483.4–504.2 mg m^{-2} h^{-1}) were lower than in subalpine grassland (610.0–810.0 mg m^{-2} h^{-1}) (Rich et al., 2013).

4.2 Biotic and abiotic effects of grazing on carbon budget

According to the CO_2 flux calculation, R_e emissions decreased by 8.7 % owing to long-term grazing exclusion, but the above-ground biomass increased by 187.5 %. Thus, there was more litter accumulation or decomposition to enhance the quantity of soil organic C with long-term grazing exclusion in the alpine grassland. Short-term grazing exclusion produced increases in R_e emissions of about 12.0 % and 7.1 %, but increases in above-ground biomass of 96.4 % and 117.9 %, below-ground biomass of 67.6 % and 48.6 %, and plant cover of 60.4 % and 102.1 %, in UG_5 and UG_8, respectively. Therefore, soil C stocks may be augmented by short-term grazing exclusion although R_e emissions may or may not increase. Consequently, there was a net C fixation or sequestration with grazing exclusion in alpine grasslands.

R_h was limited primarily by soil temperature that explained 86 % of the variability in the alpine grassland (Fig. 4f). In contrast, R_a was dominated by soil water content (Fig. 4a). In addition, R_h accounted for 78.5–93.2 % of R_e, so that CO_2 flux was more sensitive to elevated temperatures rather than precipitation in the alpine grassland (Wohlfahrt et al., 2008). Thus grazing exclusion (short- or long-term) will amplify the CO_2 emission of alpine grassland under global warming in the future.

5 Conclusions

Our results confirm no significant changes in R_e, R_h and R_a under short- or long-term grazing exclusion in GS and NGS in our alpine grassland. R_h account for 78.5–93.2 % of R_e. Furthermore, CO_2 emissions from NGS cannot be ignored because during NGS, R_e, R_h and R_a account for 12.9 %, 14.1 % and 11.4 % of the values from GS, respectively. Under grazing management CO_2 emissions were more sensitive to global climate change in NGS than in GS. Our observations strongly indicate that grazing exclusion played a critical role in the accumulation of soil organic C in this frigid and arid environment in the Tianshan Mountains.

Acknowledgements. This study was supported by the National Basic Research Program of China (grants 2010CB950602, 2009CB825103 and 2014CB954200) and the National Natural Science Foundation of China (40873068 and 41273098).

Edited by: R. Conant

References

Bahn, M., Knapp, M., Garajova, Z., Pfahringer, N., and Cernusca, A.: Root respiration in temperate mountain grasslands differing in land use, Global Change Biol., 12, 995–1006, 2006.

Bubier, J., Crill, P., and Mosedale, A.: Net ecosystem CO_2 exchange measured by autochambers during the snow-covered season at a temperate peatland, Hydrol. Process., 16, 3667–3682, 2002.

Cao, G. M., Tang, Y. H., Mo, W. H., Wang, Y. A., Li, Y. N., and Zhao, X. Q.: Grazing intensity alters soil respiration in an alpine meadow on the Tibetan plateau, Soil Biol. Biochem., 36, 237–243, 2004.

Chen, W. W., Wolf, B., Zheng, X. H.,Yao, Z. S., Butterbach-Bahl, K., Brueggemann, N., Han, S. H., Liu, C. Y., and Han, X. G.: Carbon dioxide emission from temperate semiarid steppe during the non-growing season, Atmos. Environ., 64, 141–149, 2013.

Couteaux, M. M., Bottner, P., and Berg, B.: Litter decomposition, climate and litter quality, Trends Ecol. Evol., 10, 63–66, 1995.

Craine, J. M., Wedin, D. A., and Chapin, F. S.: Predominance of ecophysiological controls on soil CO_2 flux in a Minnesota grassland, Plant Soil, 207, 77–86, 1999.

Czobel, S., Szirmai, O., Nemeth, Z., Gyuricza, C., Hazi, J., Toth, A., Schellenberger, J., Vasa, L., and Penksza, K.: Short-term effects of grazing exclusion on net ecosystem CO_2 exchange and net primary production in a Pannonian sandy grassland, Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 40, 67–72, 2012.

Daniel, J. A., Phillips, W. A., and Northup, B. K.: Influence of summer management practices of grazed wheat pastures on runoff, sediment, and nutrient losses, Transactions of the ASABE, 49, 349–355, 2006.

Di, H. J. and Cameron, K. C.: Treating grazed pasture soil with a nitrification inhibitor, eco-n (TM), to decrease nitrate leaching in a deep sandy soil under spray irrigation – a lysimeter study, New Zealand Journal of Agricultural Research, 47, 351–361, 2004.

Eckard, R. J., Chen, D., White, R. E., and Chapman, D. F.: Gaseous nitrogen loss from temperate perennial grass and clover dairy pastures in south-eastern Australia, Aust. J. Agr. Res., 54, 561–570, 2003.

Eswaran, H., Vandenberg, E., and Reich, P.: Organic-Carbon in Soils of the World, Soil Sci. Soc. Am. J., 57, 192–194, 1993.

Fahnestock, J. T., Jones, M. H., and Welker, J. M.: Wintertime CO_2 efflux from arctic soils: implications for annual carbon budgets, Glob. Biogeochem. Cycles, 13, 775–779, 1999.

Gilmanov, T. G., Johnson, D. A., Saliendra, N. Z., Svejcar, T. J., Angell, R. F., and Clawson, K. L.: Winter CO_2 fluxes above sagebrush-steppe ecosystems in Idaho and Oregon. Agric. Forest Meteorol., 126, 73–88, 2004.

Hanson, P. J., Edwards, N. T., Garten, C. T., and Andrews, J. A.: Separating root and soil microbial contributions to soil respiration: A review of methods and observations, Biogeochemistry, 48, 115–146, 2000.

Hogberg, P. and Read, D. J.: Towards a more plant physiological perspective on soil ecology, Trends Ecol. Evol., 21, 548–554, 2006.

Jia, B. R., Zhou, G. S., Wang, F. Y., and Wang, Y. H.: Soil respiration and its influencing factors at grazing and fenced typical *Leymus chinensis* Steppe, Nei Monggol, Huanjing Kexue, 26, 1–7, 2005.

Johnson, L. C. and Matchett, J. R.: Fire and grazing regulate belowground processes in tallgrass prairie, Ecology, 82, 3377–3389, 2001.

Le Quéré, C., Andres, R., Boden, T., Conway, T., Houghton, R. A., House, J. I., Marland, G., Peters G. P, van der Werf, G., Ahlström, A., Andrew, R. M., Bopp, L., Canadell, J. G., Ciais, P., Doney, S. C., Enright, C., Friedlingstein, P., Huntingford, C., Jain, A. K., Jourdain, C., Kato, E., Keeling, R. F., Goldewijk, K. K., Levis, S., Levy, P., Lomas, M., Poulter, B., Raupach, M. R., Schwinger, J., Sitch, S., Stocker, B. D., Viovy, N., Zaehle, S., and Zeng, N.: The global carbon budget 1959–2011, Earth System Science Data Discussions, 5, 1107–1157, 2012.

LeCain, D. R., Morgan, J. A., Schuman, G. E., Reeder, J. D., and Hart, R. H.: Carbon exchange and species composition of grazed pastures and exclosures in the shortgrass steppe of Colorado, Agr. Ecosyst. Environ., 93, 421–435, 2002.

Liebig, M. A., Kronberg, S. L., Hendrickson, J. R., Dong, X., and Gross, J. R.: Carbon dioxide efflux from long-term grazing management systems in a semiarid region, Agr. Ecosyst. Environ., 164, 137–144, 2013.

Lin, X. W., Zhang, Z. H., Wang, S. P., Hu, Y. G., Xu, G. P., Luo, C. Y., Chang, X. F., Duan, J. C., Lin, Q. Y., Xu, B., Wang, Y. F., Zhao, X. Q., and Xie, Z. B.: Response of ecosystem respiration to warming and grazing during the growing seasons in the alpine meadow on the Tibetan plateau, Agr. Forest Meteorol., 151, 792–802, 2011.

Luo, C.Y., Xu, G. P., Chao, Z. G., Wang, S. P., Lin, X. W., Hu, Y. G., Zhang, Z. H., Duan, J. C., Chang, X. F., Su, A. L., Li, Y. N., Zhao, X. Q., Du, M. Y., Tang, Y. H., and Kimball, B.: Effect of warming and grazing on litter mass loss and temperature sensitivity of litter and dung mass loss on the Tibetan plateau, Global Change Biol., 16, 1606–1617, 2010.

Medina-Roldan, E., Paz-Ferreiro, J., and Bardgett, R. D.: Grazing exclusion affects soil and plant communities, but has no impact on soil carbon storage in an upland grassland, Agr. Ecosyst. Environ., 149, 118–123, 2012.

Merbold, L., Rogiers, N., and Eugster, W.: Winter CO_2 fluxes in a sub-alpine grassland in relation to snow cover, radiation and temperature, Biogeochemistry, 111, 287–302, 2012.

Peters, G. P., Andrew, R. M., Boden, T., Canadell, J. G., Ciais, P., Le Quéré, C., Marland, G., Raupach, M. R., and Wilson, C.: The challenge to keep global warming below 2°, Nat. Clim. Change, 3, 4–6, 2013.

Piao, S. L., Luyssaert, S., Ciais, P., Janssens, I. A., Chen, A. P., Cao, C., Fang, J. Y., Friedlingstein, P., Luo, Y. Q., and Wang, S. P.: Forest annual carbon cost: a global-scale analysis of autotrophic respiration, Ecology, 91, 652–661, 2010.

Pietikainen, J., Pettersson, M., and Baath, E.: Comparison of temperature effects on soil respiration and bacterial and fungal growth rates, FEMS Microbiology Ecology, 52, 49–58, 2005.

Polley, H. W., Frank, A. B., Sanabria, J., and Phillips, R. L.: Interannual variability in carbon dioxide fluxes and flux–climate relationships on grazed and ungrazed northern mixed-grass prairie, Global Change Biol., 14, 1620–1632, 2008.

Qiu, L., Wei, X., Zhang, X., and Cheng, J.: Ecosystem carbon and nitrogen accumulation after grazing exclusion in semiarid grassland, PLoS One, 8, 2013.

Rauzi, F., and Hanson, C. L.: Water intake and runoff as affected by intensity of grazing, Journal of Range Management, 19, 351–356, 1996.

Risch, A. C., Haynes, A. G., Busse, M. D., Filli, F., and Schuetz, M.: The response of soil CO_2 fluxes to progressively excluding vertebrate and invertebrate herbivores depends on ecosystem type, Ecosystems, 16, 1192–1202, 2013.

Stark, S., and Grellmann, D.: Soil microbial responses to herbivory in an arctic tundra heath at two levels of nutrient availability, Ecology, 83, 2736–2744, 2002.

Wan, S. Q., and Luo, Y. Q.: Substrate regulation of soil respiration in a tallgrass prairie: Results of a clipping and shading experiment, Global Biogeochem. Cy., 17, 1054–1065, 2003.

White, R., Murray, S., and Rohweder, M.: Pilot analysis of global ecosystems: grassland ecosystems technical report, World Resources Institute, 2000.

Wohlfahrt, G., Anderson-Dunn, M., Bahn, M., Balzarolo, M., Berninger, F., Campbell, C., Carrara, A., Cescatti, A., Christensen, T., Dore, S., Eugster, W., Friborg, T., Furger, M., Gianelle, D., Gimeno, C., Hargreaves, K., Hari, P., Haslwanter, A., Johansson, T., Marcolla, B., Milford, C., Nagy, Z., Nemitz, E., Rogiers, N., Sanz, M. J., Siegwolf, R. T. W., Susiluoto, S., Sutton, M., Tuba, Z., Ugolini, F., Valentini, R., Zorer, R., and Cernusca, A.: Biotic, Abiotic, and Management Controls on the net ecosystem CO_2 exchange of european mountain grassland ecosystems, Ecosystems, 11, 1338–1351, 2008.

Xu, M., and Qi, Y.: Soil-surface CO_2 efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California, Global Change Biol., 7, 667–677, 2001.

Zhang, D., Hui, D., Luo, Y., and Zhou, G.: Rates of litter decomposition in terrestrial ecosystems: global patterns and controlling factors, Journal of Plant Ecol., 1, 85–93, 2008.

Zhang, J. B., Song, C. C., and Yang, W. Y.: Cold season CH_4, CO_2 and N_2O fluxes from freshwater marshes in northeast China, Chemosphere, 59, 1703–1705, 2005.