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Grazing intensity alters soil respiration in an alpine meadow on the Tibetan plateau

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Abstract

Grazing intensity may alter the soil respiration rate in grassland ecosystems. The objectives of our study were to (1) determine the influence of grazing intensity on temporal variations in soil respiration of an alpine meadow on the northeastern Tibetan Plateau; and (2) characterise the temperature response of soil respiration under different grazing intensities. Diurnal and seasonal soil respiration rates were measured for two alpine meadow sites with different grazing intensities. The light grazing (LG) meadow site had a grazing intensity of 2.55 sheep ha^{-1}, while the grazing intensity of the heavy grazing (HG) meadow site, 5.35 sheep ha^{-1}, was approximately twice that of the LG site. Soil respiration measurements showed that CO_2 efflux was almost twice as great at the LG site as at the HG site during the growing season, but the diurnal and seasonal patterns of soil respiration rate were similar for the two sites. Both exhibited the highest annual soil respiration rate in mid-August and the lowest in January. Soil respiration rate was highly dependent on soil temperature. The Q_{10} value for annual soil respiration was lower for the HG site (2.75) than for the LG site (3.22). Estimates of net ecosystem CO_2 exchange from monthly measurements of biomass and soil respiration revealed that during the period from May 1998 to April 1999, the LG site released 2040 g CO_2 m^{-2} y^{-1} to the atmosphere, which was about one third more than the 1530 g CO_2 m^{-2} y^{-1} released at the HG site. The results suggest that (1) grazing intensity alters not only soil respiration rate, but also the temperature dependence of soil CO_2 efflux; and (2) soil temperature is the major environmental factor controlling the temporal variation of soil respiration rate in the alpine meadow ecosystem.

Keywords: Biomass; Carbon cycle; CO_2 efflux; Q_{10} value; Soil temperature

1. Introduction

Grassland occupies a large proportion of the global terrestrial ecosystem (Adams et al., 1990). An understanding of grassland C dynamics is essential for clarifying the contribution of grassland ecosystems to the global C budget (Frank et al., 2002). In East Asia, most grassland ecosystems are subject to varying degrees of grazing pressure. Grazing intensity is likely to affect the quantity of C released from the soil to the atmosphere, but insufficient data are available to assess the influence of grazing on C release. Current evidence suggests no clear relationships between grazing and the C budget in grassland ecosystems (Derner et al., 1997; Milchunas and Laurenroth, 1993; Reeder and Schuman, 2002). Because almost all grasslands in East Asia are subject to some degree of grazing pressure, a quantitative evaluation of the influence of grazing intensity on soil respiration would enhance our understanding of the C budget of grassland ecosystems in this region.

Temperate grassland ecosystems, which comprise 32% of the earth's natural vegetation (Adams et al., 1990), may be significant C sinks (Batjes, 1998; Frank, 2002; Janzen et al., 1998; Sims and Bradford, 2001; Sundquist, 1993). However, some studies suggest that the C budget of grassland ecosystems is near equilibrium (Frank and Dugas, 2001; Kim et al., 1992). For example, Kim et al. (1992) reported that a temperate grassland ecosystem dominated by warm season tallgrass had net fixation of

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750 g CO_2 m^{-2} through the growing season from May to October, but the ecosystem released about 3 g CO_2 m^{-2} d^{-1} into the atmosphere during a drought period. Dugas et al. (1999) also showed evidence that a prairie and a sorghum field were in approximate equilibrium for C storage because the estimated annual CO_2 fluxes were near zero. The uncertainty of C budget for grasslands seems mainly due to the variability of soil respiration.

Soil CO_2 fluxes reported to date vary considerably for different grassland ecosystems. The soil respiration rate was only 4.6 g CO_2 m^{-2} d^{-1} in August for a tallgrass prairie in Nebraska (Norman et al., 1992), but reached 25.3 g CO_2 m^{-2} d^{-1} in a northern semiarid grassland (Frank et al., 2002). Changes in soil respiration rate in grassland ecosystems are closely related to soil temperature. CO_2 efflux generally increases with increasing soil temperature, and soil temperature accounts for 65% of CO_2 efflux variability (Frank et al., 2002).

The Tibetan Plateau, which extends over 2.5 million km^2, is the youngest and highest plateau in the world. The plateau ecosystem is very fragile and sensitive to global climate changes. The plateau may act as a 'starting region' for climate change in China and East Asia (Li and Tang, 1988; Tang et al., 1986). Alpine meadows, covering about 35% of the plateau area, comprise the representative vegetation and the major pastureland on the plateau. The soil of these alpine meadows is rich in organic C (80–100 g kg^{-1} at depths of 0–20 cm) and has a moderate rain fall (Cao et al., 1998, 2001b; Bao et al., 1995). The grassland ecosystem may be a major C sink because of its high productivity during the growing season and the low rate of decomposition resulting from low temperature. However, it may also provide an important C source if grazing intensity increases or if the grassland is converted to cropland. In the alpine grassland ecosystem, long-term overgrazing has resulted in considerable deterioration and even desertification, which may release considerable quantities of C from the ecosystem to the atmosphere. Grazing intensity is therefore one of the critical factors controlling the C budget for these grassland ecosystems. However, there is little information about the effect of grazing intensity on the C budget of alpine grassland ecosystems on the Tibetan plateau.

The purposes of our study were to (1) determine the influence of grazing intensity on temporal variation of soil CO_2 efflux from alpine meadows on the northeastern Tibetan plateau; and (2) characterize the temperature response of soil CO_2 efflux under different grazing intensities.

2. Material and methods

2.1. Study site

The study was conducted at the Chinese Academy of Science's Haibei Research Station, located at lat 37°32′N, long 101°15′E and at an altitude of 3240 m above sea level. The average annual precipitation recorded at the Haibei Research Station from 1976 to 2001 was 560 mm, and 85% of that rainfall was concentrated within the growing season from May through September. Total annual precipitation was 568, 398, and 501 mm in 1998, 1999, and 2000, respectively. The average annual air temperature for the 25 years from 1976 to 2001 was −1.7 ° C. The mean, maximum and minimum of averaged air temperature from 1980 to 1990 were 8.7,15.6 and 2.5 °C, respectively, in summer and −13.2, −2.2 and −22.1 °C, respectively, in winter (Wang et al., 1999). The soil of the study site is classified as Mat Cry-gelic Cambisols (Chinese soil taxonomy research group, 1995).

Two experimental sites with different grazing intensity were defined on the alpine *Kobresia humilis* Serg meadow. The light grazing (LG) site was dominated by *K. humilis* Serg. and *Festuca ovina* Linn. The most common species included *Elymus nutans* Griseb., *Leontopodium nanum* Hand.-Mazz., *Poa* sp., *Gentiana lawrencei* Burk.var *farreri* T.N.Ho, *Gentiana straminea* Maxim., *Potentilla nivea* Linn., *Potentilla saundersiana* Royle, *Saussurea superba* Anth., *Scirpus distigmaticus* Tang et Wang, *Kobresia pygmaea* C.B. Clarke in Hook,and *Carex* sp. The vegetation coverage ranged between 90 and 95%. The soil surface is well developed with a mixture of root mass and clay to a depth of about 5–10 cm. The grazing intensity of the LG site was 2.55 sheep ha^{-1} with only lambs and sheep. The heavy grazing (HG) site had a grazing intensity of 5.35 sheep ha^{-1}. This site was dominated by *Oxytropis* sp., *Pedicularis kasuensis* Maxim, *Morina chinensis* Diels, *Ligularia virgaurea* Mattf., *Leontopodium nanum* Hand.-Mazz, and *Gentiana straminea* Maxim. with vegetation coverage between 15 and 20%. Both sites had been used as winter pasture with a grazing period from late September to the end of April from about 1982. The treatment of different grazing intensities started since 1985, which was designed for a grazing experiment (Wang et al., 2000). As it is the winter pasture, summer growth was not removed by grazing. The grazing intensity, however, will influence litter deposition, soil structure, which further affect soil respiration and growth indirectly.

Moreover, during the summer, dead leaf materials were not a significant proportion of dry matter as compared with fresh biomass in the grassland. Almost all visible stubble and dead leaf materials were grazed during the winter period, even in the LG site. The stubble and recent dead plant materials were not considered as a significant part in our experiment.

Soil moisture was measured with gravimetric method. The method involves drying a soil sample in the oven at 105 °C for 24 h to determine the soil moisture content. Soil moisture varied with rainfall. The mean soil moisture at depths of 0–10 cm during the growing season in 1998 was 51.9 ± 9.4 and 40.2 ± 9.0% for the LG and HG sites, respectively.

Both mean air and soil temperatures were higher at the HG site than at the LG site. The air temperature was measured 5 cm above ground. The higher air temperature in the HG site thus seems due to the less vegetation and lower soil moisture, which both tend to increase surface albedo and the air temperature close to ground surface. Daytime soil temperature averaged 6.74 ± 6.29 and 7.73 ± 6.95 for the LG site and the HG site, respectively. The average daily soil temperature was ≥5 °C for about 150 days from mid-May to mid-October, based on measurements at depths of 5–30 cm. The soil was frozen beginning in October and ending in April.

Soil bulk density, above ground organic matter, and soil organic matter of the two sites are shown in Table 1.

2.2. Plant biomass

Plant biomass was measured by clipping vegetation samples from 3 to 6 representative $0.5 \times 0.5\ m^2$ quadrats about every 30 days from the beginning of May to the end of September. Plant materials were divided into living and dead parts before they were oven dried at 65 °C for 48 h and then weighed. Root biomass was measured by collecting soil samples from depths of 0–30 cm from six $0.25 \times 0.25\ m^2$ quadrats, which were co-located with the above ground biomass measurement quadrat. The soil cores were cut into segments corresponding to sampling depths of 0–10, 10–20, and 20–30 cm. Roots were first washed and then oven dried at 65 °C for 72 h before being weighed. As there is currently no effective method available for separating live and dead roots in field investigation, we distinguished the roots with naked eye. It is reliable for most broad-leaved herbaceous species with large-sized roots, but there might be some errors for small-sized roots.

Table 1
Soil characteristics for two plots with different grazing intensity in Haibei, Qinghai

	Light grazing plot	Heavy grazing plot
Biomass organic matter		
Above ground biomass (kg m^{-2})	0.50 ± 0.05	0.21 ± 0.05
Existent live root (kg m^{-2})	1.95 ± 0.46	1.03 ± 0.37
Existent dead root (kg m^{-2})	0.58 ± 0.12	0.36 ± 0.23
Soil porosity (%)		
0–10 cm	64.3	59.0
10–20 cm	47.1	58.9
20–30 cm	55.8	61.9
Soil organic matter (%)		
0–10 cm	11.88 ± 1.19	8.18 ± 0.86
10–20 cm	5.51 ± 0.56	6.95 ± 1.29
20–30 cm	4.41 ± 0.48	5.46 ± 1.26

Data for biomass and soil organic matter are indicated by the mean ± standard deviation of six plots.

2.3. Soil respiration measurements

Soil CO_2 efflux was measured using a closed chamber method with either a CID-301PS CO_2 infrared gas analyzer (CID, Inc., Camas, WA, USA), or a LI-COR 6252 CO_2 analyzer (LI-COR, Lincoln, NE, USA). The chamber, which had an inner diameter of 25 cm and an inner height of 30 cm, was made of opaque fiberglass. Two small fans were mounted on the chamber ceiling to circulate the air within the chamber. To reduce the air temperature, a water bath was set within the chamber at a height of 10 cm. We measured the chamber temperature with a glass thermometer inserted from the top of the chamber. Soil moisture was measured every 10 cm from depths of 0–50 cm at 16:00 Beijing standard time (BST).

To reduce the disturbance caused by installation of the chamber, the chamber was inserted into the soil (to a depth of 5 cm) 24 h before the experiment began. At each site, measurements were made in triplicate. The CO_2 flux measurements from three locations in each site were averaged for each sample day. To measure CO_2, we used the analytical procedures described in detail by Zhang et al. (2001). During the growing season, measurements were taken at 2 h intervals for 2 days each month. During dormant periods, measurements were taken at 3 h intervals for 1 day each month.

3. Results

3.1. Above ground and below ground biomass

Above ground biomass increased rapidly beginning in May and reached a maximum of 471 g m^{-2} in September at the LG site. The HG site had much lower above ground biomass with a maximum of 211 g m^{-2} in August (Fig. 1).

Below ground biomass showed a different seasonal variation pattern than above ground biomass. With a slight decrease from May to June, below ground biomass increased gradually and peaked in the later growing season at the LG site, but it was at a minimum in July and slowly increased until September at the HG site. The total root biomass values averaged for 1998 were 1951 and 1032 g m^{-2} for the LG and HG sites, respectively.

3.2. Diurnal variation of CO_2 efflux

We measured the diurnal changes of CO_2 efflux at the two meadow sites on clear days. The diurnal patterns of CO_2 efflux at both sites were similar to the diurnal patterns of soil surface temperature. The soil respiration rate at the LG site peaked at around 13:00 BST and then dropped rapidly to its minimum at midnight (Fig. 2). The soil respiration at the HG site showed a similar temporal pattern as that in the LG site, but the fluctuations were much smaller. Diurnal CO_2 efflux was significantly higher at the LG site than at the HG

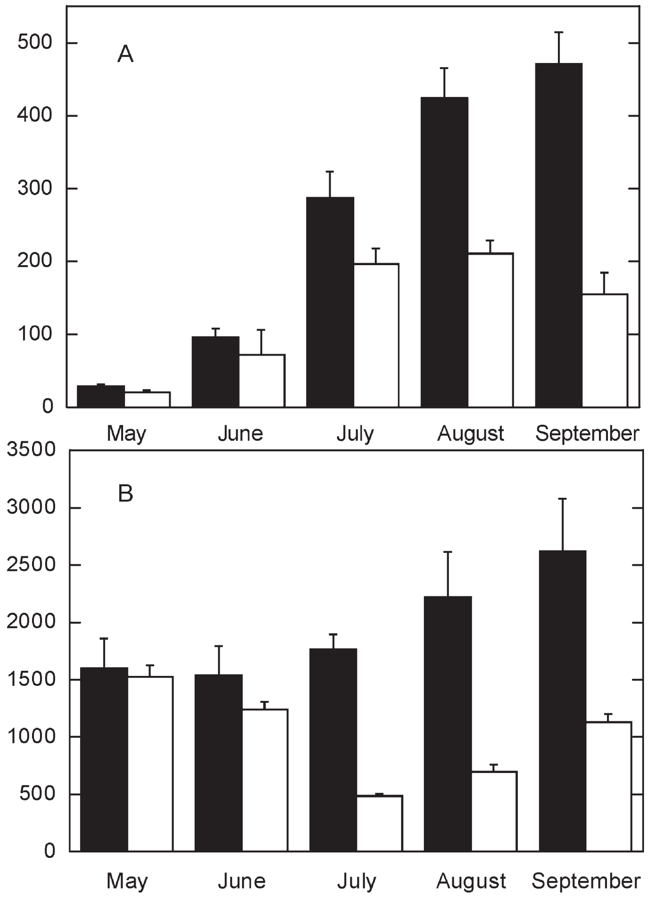

Fig. 1. Seasonal variation of averaged above ground biomass (A) and below ground biomass (B) in two alpine meadow sites with different grazing intensities. Vertical bars indicate standard deviation of six quadrats for each month. Black boxes show the LG site and white boxes the HG site. The means were significantly different between the LG and the HG sites ($P < 0.1$ and 0.05 for above ground biomass and below ground biomass, respectively, paired comparison test).

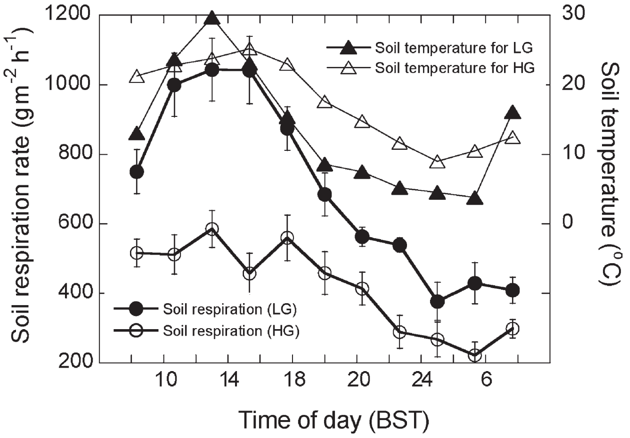

Fig. 2. Diurnal changes of soil temperature and soil respiration rate (LG (●); HG (○)) in two alpine meadow sites with different grazing intensities. Vertical bars indicate the standard error of the measurement mean ($n = 3$) for each time.

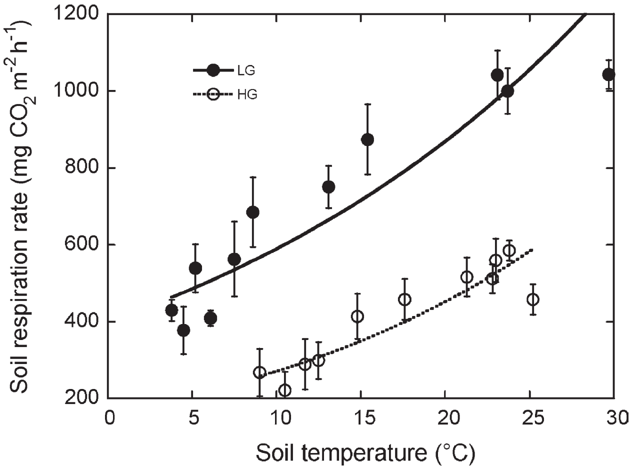

Fig. 3. Measured diurnal soil CO_2 flux vs. soil temperature. The equations for the predicted model are soil CO_2 flux $(y) = 420$ exp (0.039 soil temperature), $r = 0.913$, $p < 0.001$ for the LG site and CO_2 flux $(y) = 163$ exp (0.051 soil temperature), $r = 0.897$, $p < 0.001$ for the HG site. Vertical bars indicate the standard error of the measurement mean ($n = 3$) for each time.

site (paired comparison, $p < 0.001$). The diurnal variation of CO_2 efflux was mainly affected by soil temperature (Fig. 3). The Q_{10} value was lower at the LG site (1.47) than at the HG site (1.67).

3.3. Seasonal change of CO_2 efflux

CO_2 efflux reached its maximum in mid-July or August with values of 16.7 and 12.0 g m^2 d^{-1} for the LG and HG sites, respectively (Fig. 4). Paired comparison shows that seasonal CO_2 efflux was significantly higher in the LG site than in the HG site ($P < 0.01$). In winter, however, soil respiration rate was similar at the two sites and both had values of

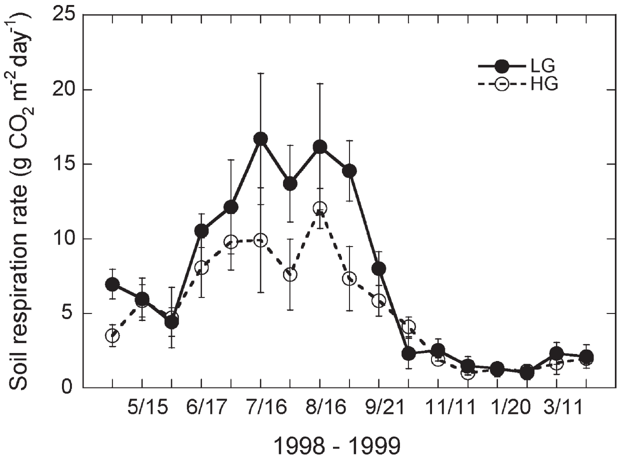

Fig. 4. Seasonal changes of soil respiration rate measured in two alpine meadow ecosystems with different grazing intensities. Vertical bars indicate the standard error of the measurement mean ($n = 3$) for each period.

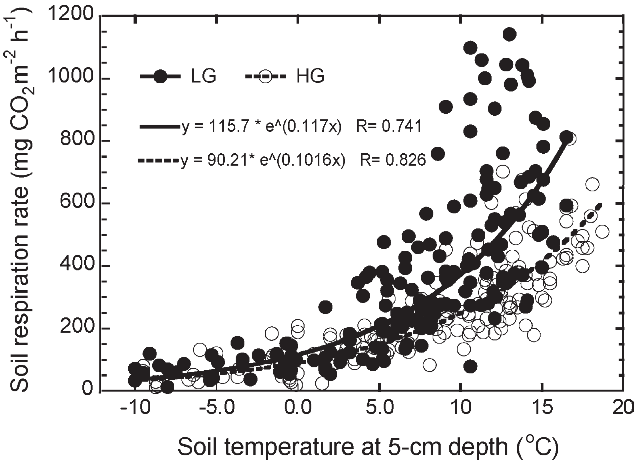

Fig. 5. Dependence of soil respiration on soil temperature measured during the period from May 1999 to April 2000. The equations for predicting soil respiration from soil temperature are $y = 115.7\ \exp(117 \times)$, $r = 0.826$ for the LG site and $y = 90.2\ \exp\ (101 \times)$, $r = 0.740$ for the HG site. $P < 0.001$ for all regression coefficients and intercepts.

approximately 1 g CO_2 m^{-2} d^{-1} between December and February when the soil was frozen. Seasonal variation of CO_2 efflux depended largely on soil temperature at both meadow sites (Fig. 5). Based on the annual variation of soil respiration, we estimated the annual total CO_2 efflux at the LG site to be 2035 g CO_2 m^{-2} y^{-1} during the period from May 1998 to April 1999; at the HG site, however, we estimated only 1533 g CO_2 m^{-1} y^{-1} for the same period (Fig. 6).

4. Discussion

4.1. Effects of grazing intensity on grassland biomass and soil respiration

Above ground biomass values for temperate grasslands range from 100 to 1500 g m^{-2} (Iwaki, 1973). Frank et al. (2001) reported that the maximum above ground biomass values averaged for 3 years were 103, 323, and 383 g m^{-2} at Mandan, Woodward, and Temple, respectively, in the Great Plains region of North America. In grasslands, below ground biomass is generally 5–10 times higher than above ground biomass (Iwaki, 1973). In the Haibei alpine meadow, the ratio of above ground to below ground biomass reached to about 1:5 and 1:8 in LG and HG plot, respectively, in September (Fig. 1). The actual ratio may decrease to some extent because roots deeper than 50 cm were not sampled. A recent investigation on a similar alpine meadow near the Haibei station showed that the ratio of above ground to below ground biomass ranged from 1:14 to 1:23 when below ground biomass was sampled to depth of 1 m depending on vegetation type and soil conditions (Shen, 2002).

Grazing can increase or decrease biomass depending on the grazing intensity and history (Milchunas and Lauenroth, 1993). In an Inner Mongolian grassland ecosystem, different grazing intensities showed significant effects on grass biomass, with biomass decreasing under high grazing pressure (Wang and Wang, 1999). Our results suggested that grazing intensity markedly affected the above ground biomass of the meadow ecosystem. The intensive grazing at the HG site reduced both above ground and below ground biomass, particularly during the later growing season (Fig. 1). Moreover, coefficients of variation (CV) for below ground biomass were significantly lower (paired *t*-test, $p < 0.01$) in the HG site (6.2%) than in the LG site (15%). CV of the above ground biomass, however, tended to be higher in the HG site than in the LG site, but showed no statistically significant difference at the level of $p = 0.01$ (paired *t*-test, $p = 0.223$). The decrease of spatial heterogeneity in below ground biomass in the HG site may be partly due to the considerable low biomass. However, because of the limited sample number (3–6 quadrats for each site and each sampling period) and no variation in sampling quadrat size, it is difficult to make a general conclusion on the grazing effects on the spatial heterogeneity of biomass in the current study.

Few data are available for a detailed comparison of soil respiration rate under different grazing intensities (Frank et al., 2002; Johnson and Matchett, 2001; LeCain et al., 2000). Grazing significantly reduced soil respiration rate throughout the growing season from July to October compared with ungrazed tallgrass prairie (Johnson and Matchett, 2001), but grazed prairie showed a higher soil CO_2 flux than nongrazed prairie (Frank et al., 2002). Cao et al. (2001a, 2002) found that different land-use patterns affect CO_2 emissions in alpine meadow ecosystems; but we believe that our study provides the first observational data with a relatively long period for assessing the effects of grazing intensity on soil respiration for a grassland ecosystem in East Asia. The soil respiration rate was lower at the HG site than at the LG site through most of the growing season.

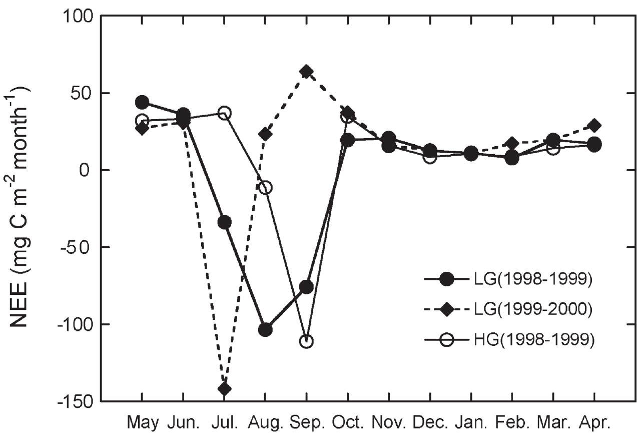

Fig. 6. Estimated net ecosystem CO_2 exchange (NEE) for LG and HG from May 1998 to April 1999 and LG from May 1999 to April 2000. Data are not available for HG for 1999–2000. NEE = *R*-NPP, where *R* is the monthly integrated soil respiration based on the soil respiration measurements. NPP was estimated as the difference of biomass C content between two consecutive months.

Although the detailed mechanisms involved in the effect of grazing on soil respiration must be clarified, we believe that the low soil respiration rate at the HG site may be mainly due to the low below ground biomass (Figs. 1 and 4) and a smaller quantity of microorganisms to aid decomposition. Previous studies found that both the number of cellulose-decomposing bacteria and the fungal biomass were significantly lower at the HG site than at the LG site (Jiang et al., 1995; Wang and Li, 1995). Moreover, grazing intensity can change soil physical and soil chemical properties, which in general will further affect soil respiration (see review Lal, 2001). Few evidences, however, are currently available for us to further understand the possible mechanism involved in the different soil respiration under the two grazing intensity. Further studies are needed to clarify the interactions between soil properties and soil respiration under different grazing intensity.

Dung and urine inputs could be an important issue to account for the difference of soil CO_2 efflux between the two grazing intensities. In the current study, direct influence of livestock excreta could be limited because (1) the grazing took place during the winter when temperature was low (see site description) and (2) we excluded all visible animal excreta in the chamber during the measurement of soil respiration. The indirect effects of livestock excreta, however, could be still an important factor because of its influence on plant growth in the summer and effects on microorganism activity as well as soil physical and chemical properties. Quantitative evaluation is necessary in further studies.

The lower Q_{10} value at the HG site also clarifies the effect of grazing on soil respiration. It is known that respiration of both plant root systems and microbial communities is sensitive to changes in soil temperature (Rey et al., 2002). Both the amount of below ground biomass and the quantity of microbial organisms affect Q_{10} values. The low below ground biomass and small quantity of fungi and bacteria may therefore result in the lower Q_{10} value at the HG site. Q_{10} values can vary widely from 1.5 to 5.6, depending on soil types (Rey et al., 2002). The Q_{10} values for the alpine meadow fall in the middle of this range. Moreover, the values of Q_{10} were much lower for the diurnal data, which may due to the smaller range of temperature changes and the higher temperature for the particular diurnal variation data. The results suggest that it is essential that scaling up soil respiration rates from a limited diurnal data is made with care.

Current knowledge provides no clear general relationship between the grazing intensity and C sequestration in grassland ecosystems (Milchunas and Laurenroth, 1993; Reeder and Schuman, 2002). The estimates of net CO_2 released from soil and biomass production at the two sites indicates that the high grazing intensity reduced the net ecosystem CO_2 fixation in the alpine meadow ecosystem (Fig. 6). Further studies and some other approaches including eddy covariance measurements of ecosystem C flux are needed to confirm our present findings on the effects of grazing intensity on ecosystem C budget.

4.2. Temporal variation of CO_2 efflux

Despite the large variability in daily CO_2 efflux, the diurnal pattern of CO_2 efflux was very similar to those of three Great Plains grasslands sites (Frank et al., 2001). Diurnal variations of CO_2 efflux were expected to be mainly affected by diurnal change in soil temperature. It was evident that both the diurnal and seasonal variations of soil respiration at the Haibei alpine meadow were significantly dependent on soil temperature (Figs. 2–5). Compared with grassland ecosystems in other arid regions such as Mongolia, the alpine meadow has more moisture, particularly during the growing season. The larger changes in diurnal temperature in the alpine meadow seem to be the major environmental factor controlling soil respiration. In addition, grazing intensity markedly influences the effect of soil temperature on soil CO_2 efflux by increasing the intercept of dependence of soil respiration rate on soil temperature, but with a slight change in the slope (Figs. 3 and 5). At the same temperature, the soil respiration rate was higher at the LG site than at the HG site. The low soil respiration for the HG site seems mainly because of the lower root biomass at the HG site. The soil CO_2 efflux may also have been limited to some extent by soil organic matter from 0 to 10 cm, but on the whole soil organic matter seems not contribute a significant part to the difference of soil respiration between the two sites (Table 1; Fig. 1). The results, therefore, indicate importance of root systems as the source of respired C in the alpine grassland ecosystem.

5. Conclusions

Grazing intensity markedly altered the soil respiration rate of an alpine meadow ecosystem. Soil CO_2 efflux decreased by about 50% when grazing intensity was approximately doubled. Soil temperature was the major environmental factor controlling soil respiration rate in the alpine meadow ecosystem. The soil respiration rate was lower at the HG site than at the LG site at the same soil temperature. The HG site had a significantly lower root biomass and a lower soil organic C content at the surface soil from 0 to 10 cm than the LG site. The results suggest that the lower proportion of root biomass at the HG site is mainly responsible for the low soil respiration rate.

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