

# Non-growing season soil CO<sub>2</sub> efflux and its changes in an alpine meadow ecosystem of the Qilian Mountains, Northwest China

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**Abstract:** Most soil respiration measurements are conducted during the growing season. In tundra and boreal forest ecosystems, cumulative, non-growing season soil CO<sub>2</sub> fluxes are reported to be a significant component of these systems' annual carbon budgets. However, little information exists on soil CO<sub>2</sub> efflux during the non-growing season from alpine ecosystems. Therefore, comparing measurements of soil respiration taken annually versus during the growing season will improve the accuracy of estimating ecosystem carbon budgets, as well as predicting the response of soil CO<sub>2</sub> efflux to climate changes. In this study, we measured soil CO<sub>2</sub> efflux and its spatial and temporal changes for different altitudes during the non-growing season in an alpine meadow located in the Qilian Mountains, Northwest China. Field experiments on the soil CO<sub>2</sub> efflux of alpine meadow from the Qilian Mountains were conducted along an elevation gradient from October 2010 to April 2011. We measured the soil CO<sub>2</sub> efflux, and analyzed the effects of soil water content and soil temperature on this measure. The results show that soil CO<sub>2</sub> efflux gradually decreased along the elevation gradient during the non-growing season. The daily variation of soil CO<sub>2</sub> efflux appeared as a single-peak curve. The soil CO<sub>2</sub> efflux was low at night, with the lowest value occurring between 02:00–06:00. Then, values started to rise rapidly between 07:00–08:30, and then descend again between 16:00–18:30. The peak soil CO<sub>2</sub> efflux appeared from 11:00 to 16:00. The soil CO<sub>2</sub> efflux values gradually decreased from October to February of the next year and started to increase in March. Non-growing season Q<sub>10</sub> (the multiplier to the respiration rate for a 10°C increase in temperature) was increased with raising altitude and average Q<sub>10</sub> of the Qilian Mountains was generally higher than the average growing season Q<sub>10</sub> of the Heihe River Basin. Seasonally, non-growing season soil CO<sub>2</sub> efflux was relatively high in October and early spring and low in the winter. The soil CO<sub>2</sub> efflux was positively correlated with soil temperature and soil water content. Our results indicate that in alpine ecosystems, soil CO<sub>2</sub> efflux continues throughout the non-growing season, and soil respiration is an important component of annual soil CO<sub>2</sub> efflux.

**Keywords:** non-growing season soil CO<sub>2</sub> efflux; spatial and temporal variation; alpine meadow; Q<sub>10</sub> values; Qilian Mountains

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Soil CO<sub>2</sub> efflux is the primary pathway by which CO<sub>2</sub>, fixed by plants, returns to the atmosphere (Chapin et al., 1996). Estimating the CO<sub>2</sub> emission rate from soil, as well as establishing its relationship with environ-

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mental factors and human activities, are not only crucial for determining the carbon budget of ecosystems, but also important for evaluating the functions of the terrestrial ecosystem in the global carbon cycle (Fang et al., 1998). Soil CO<sub>2</sub> efflux is one of the fastest changing soil variables, and its quantification is challenging (Aiken et al., 1991). Temporal trends in soil CO<sub>2</sub> efflux are important for understanding and predicting atmospheric concentrations and the global carbon cycle (Oechel et al., 1993; Brooks et al., 1997; Fahnestock et al., 1998). Most soil CO<sub>2</sub> efflux measurements are conducted during the growing season, in part because of the difficulty of measuring soil CO<sub>2</sub> efflux under snow. However, this practice also reflects the general assumption that microbial activity in frozen or snow-covered soils is negligible (Fahnestock et al., 1998; Wang et al., 2010). Soil is a major source of atmospheric CO<sub>2</sub>, the primary contributor of which is autotrophic respiration by both living roots and heterotrophic soil microbes. Given the large, organic-carbon reserves stored in soil (Post et al., 1982), the release of CO<sub>2</sub> from the soil may augment the effects of climate change (Oechel et al., 1993). Direct feedback is due to an increase in soil respiration caused by increases in soil temperature. These have been described in depth with simple temperature-sensitivity equations (Fang and Moncrieff, 2001). Interacting effects include changes in the availability of substrate and liquid water as a function of soil temperature (Davidson and Janssens, 2006). Feedback mechanisms of soil processes to atmospheric concentrations of greenhouse gases and the climate are furthermore complicated by several environmental constraints. In winter ecosystems, these constraints include the content of unfrozen water and the thickness and duration of snow cover; these constraints influence the effect of climate changes on subsurface temperatures.

In boreal ecosystems, significant rates of CO<sub>2</sub> emission from snow-covered soils have been reported (Groffman et al., 2006; Ludwig et al., 2006). However, most of these studies have focused on soil processes occurring during the growing season. This is despite the fact that subsurface conditions during the cold season are more complex in terms of substrate avail-

ability, and are warmer than expected in terms of above-ground conditions. Published data has convincingly demonstrated that soil microbial activity in the field occurs at freezing temperatures (Schmidt and Lipson, 2004; Nobrega and Grogan, 2007), and laboratory tests have confirmed that soil can release CO<sub>2</sub> when incubated in the laboratory at freezing temperatures down to -39°C (Panikov et al., 2006). Therefore, comparing measurements of soil respiration taken annually versus during the growing season is important for accurately estimating annual carbon budgets, modeling the effects of climate changes on both soil carbon storage and release (Chapin et al., 1996), and calculating belowground carbon allocation by plants (Giardina and Ryan, 2000). Respiratory losses during the winter may offset a major portion of the carbon fixed during the growing season, and could be critical in determining annual carbon cycling (Monson et al., 2005, 2006; Nobrega and Grogan, 2007). For example, the inclusion of wintertime losses of CO<sub>2</sub> into annual carbon budgets could increase the annual carbon efflux of arctic tundra ecosystems by 17%, and change some ecosystems from net annual sinks to net annual sources of CO<sub>2</sub> (Fahnestock et al., 1999). Annual carbon sequestration is overestimated by 72% in deciduous forests, and 111% in coniferous forests when winter CO<sub>2</sub> efflux is not included (Brooks et al., 2004).

Climate patterns in the Arctic suggest that high northern latitudes warm up more than the average observed for other latitudes during the winter (Maxwell, 1997). Patterns also indicate that increasing air temperatures mainly occur during the winter, and that climate changes are closely linked to changes in factors such as winter precipitation and wind regimes. These factors, in turn, have direct effects on snow thickness and thus subsurface temperatures. However, the carbon loss from mid-latitude soils during the winter and the contribution of winter soil respiration to total annual soil carbon efflux are seldom determined (Mariko et al., 2000; Uchida et al., 2005).

The global-surface temperature is predicted to increase by 1.8–4.0°C over the next century (IPCC, 2007). The response of soil CO<sub>2</sub> efflux to global warming is sensitive to slight changes in the relationship between soil respiration and soil temperature

(Davidson et al., 2006).  $Q_{10}$  (the multiplier to the respiration rate for a 10°C increase in temperature) is commonly used to express the relationship between soil respiration and soil temperature (Kirschbaum, 2006). Most estimates of the  $Q_{10}$  are based on measurements made during the growing season, without considering soil CO<sub>2</sub> efflux during the non-growing season.  $Q_{10}$  values range between 60°C and 200°C below zero, while the maximum  $Q_{10}$  above 0°C is 9°C (Mikan et al., 2002). Thus, there exists an urgent need for *in situ* measurements of soil respiration rates throughout the cold season, and for field-based sensitivity functions describing the apparent temperature dependency of soil CO<sub>2</sub> production at sub-zero temperatures. Finally, there is also a need to understand the environmental drivers (other than temperature) that control soil microbes during non-growing season.

Up to now, a large number of studies have examined the relationship between soil CO<sub>2</sub> efflux and related factors (Hanson et al., 2000; Rayment, 2000; Pendall et al., 2004). However, a paucity of data has been reported on the structural changes of plant communities at different elevations, as well as the soil respiration intensity at a regional scale. This study describes the non-growing season soil CO<sub>2</sub> efflux of alpine meadow at different elevations in the Qilian Mountains. We examined the changes in soil CO<sub>2</sub> efflux, and its relationship with environmental factors such as elevation, soil water content and soil temperature. Our results help augment the scientific community's current understanding of carbon-exchange mechanisms between soil and the atmosphere, and help illuminate the source-sink changes in terrestrial ecosystems. Hence, the study of non-growing season soil CO<sub>2</sub> efflux in alpine meadow at different altitudes we examined will contribute to a better understanding of the feedback effect of soil CO<sub>2</sub> efflux on the climate, as well as land-use changes under high altitude and low temperature conditions.

## 1 Materials and methods

### 1.1 Experimental site

The Qilian Mountains are located at the northern edge of the Tibet Plateau, and have peaks upwards of

4,000 m in altitude (e.g. Tuanjie Peak, 5,826 m). These mountains create a strong, rain-shadow effect for monsoons coming from the southeast. Gansu province, located north of the Qilian Mountains, has a climate that is transitional between temperate monsoon and continental type. Northwest of Gansu is gobi desert. From the Qilian Mountains' north to the gobi desert lies a sharp, geographic ecotone between forest and desert communities. *Picea crassifolia* is one of the dominant tree species in the Qilian Mountains; studies show that *P. crassifolia* forest is tolerant to cold, dry and poor soil environments, permitting the species to grow across a large elevation range that spans from 2,350 to 3,300 m (Gansu Forest Department, 1998).

The experimental site for this study is located in the Xishui Forest Farm of Sunan county, Gansu province (Fig. 1). The Pailugou basin covers an area of 2.95 km<sup>2</sup>, and is composed of 55% grassland and 40% forest land. The study area has a high, cold, semi-arid and sub-humid mountain forest and grassland climate, with an annual mean temperature of 0.5°C. The area has a mean annual precipitation of 435 mm, most of which occurring between June and September. The average (over 27 years) minimum daily temperature in January was -12.2°C, the average maximum daily temperature in July was 26.5°C, and the annual potential evaporation was 1,051 mm (Chang et al., 2005a). The main tree species in the experimental site was *P. crassifolia*, and shrub species included *Dasiphora fruticosa*, *Dasiphora glabra*, *Berberis diphara*, and *Sabina vulgaris*. The main plant species are presented in Table 1. Trees covered approximately 60% of the total ground area, shrubs 12%, and grass, stumps and bare soil the remaining 28%. Soil type in the region is mountain-grey, cinnamon soil, with a depth of about 1 m. The experimental site is located on a gradient approximately 2,500–3,500 m asl.

### 1.2 Vegetation in the experimental site

The main tree species in the Qilian Mountains is *P. crassifolia*, and the upper limit of the tree line lies at 3,300 m, while the lower lies at 2,350 m. The zone between 2,500 and 3,000 m is dominated by mountain forest and grassland vegetation. The ice snow and permafrost lies at 3,600 m. Alpine meadow mainly

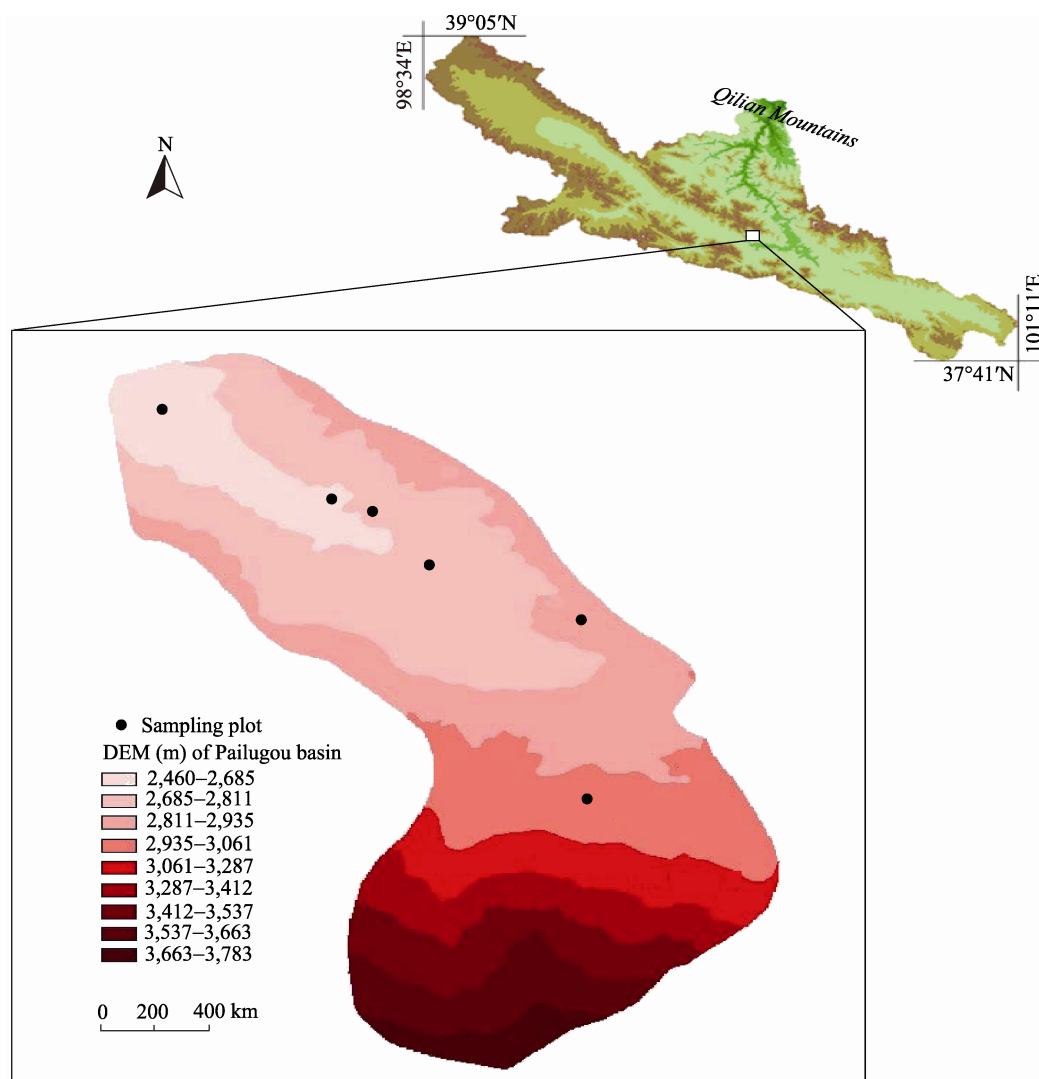


Fig. 1 Map of the study area

Table 1 Soil physical-chemical properties and vegetation composition at different altitudes in the study area

Altitude (m)	Plant species	Soil physical-chemical properties		
		Bulk density (g/cm <sup>3</sup> )	Porosity (%)	Organic matter (g/kg)
2,500–2,600	<i>Iris ensata</i> , <i>Achnatherum inebrians</i> , <i>Stipa grandis</i> , <i>Agropyron cristatum</i> , <i>Potentilla</i> spp.	0.52	53.2	71.06
2,600–2,700	<i>Potentilla</i> spp., <i>Achnatherum inebrians</i> , <i>Carex</i> spp., <i>Chenopodium album</i> , <i>Oxytropis ochrocephala</i> , <i>Stipa grandis</i>	0.58	52.8	74.71
2,700–2,800	<i>Carex</i> spp., <i>Achnatherum inebrians</i> , <i>Polygonum viviparum</i> , <i>Oxytropis ochrocephala</i> , <i>Achnatherum splendens</i>	0.62	51.3	75.38
2,800–2,900	<i>Carex</i> spp., <i>Iris ensata</i> , <i>Pop sibirica</i> , <i>Agropyron cristatum</i> , <i>Oxytropis ochrocephala</i> , <i>Potentilla</i> spp.	0.65	49.6	77.25
2,900–3,000	<i>Carex</i> spp., <i>Stipa grandis</i> , <i>Oxytropis ochrocephala</i> , <i>Potentilla</i> spp., <i>Anaphalis lacteal</i>	0.76	48.9	78.30

occurs in the mountain forest grassland zone at an elevation of 2,500–3,000 m, and occupies about 28.27% of the total area of the Qilian Mountains region.

### 1.3 Measurement of soil CO<sub>2</sub> efflux and experimental design

The sampling plots (5 m<sup>2</sup>) were selected along an ele-

vation gradient (at approximately 2,500, 2,600, 2,700, 2,800, 2,900, and 3,000 m) in the Pailugou basin (Fig. 1). All the plots contain similar vegetation and soil types. These plots reflect the gradient changes of water and soil, and are representative of the general community characteristics of alpine meadows in the Qilian Mountains. We monitored phenological changes from October of 2010 to April of 2011. A Li-6400 portable photosynthesis system and a 6400-09 soil respiration chamber made by American Li-cor were used for field-data collection. Five soil-isolation rings (80 cm<sup>2</sup>, 4.4 cm high) were randomly placed in each of the sampling plots, and soil CO<sub>2</sub> efflux in each plot was measured at one-hour intervals for two days (48 hours), i.e. the 10<sup>th</sup> and 25<sup>th</sup>, each month. Three measurements at each plot were recorded. To avoid influencing the measurement of soil CO<sub>2</sub> efflux, the soil-isolation rings were buried in the soil to a depth of approximately 2 cm one week before the measurement of soil CO<sub>2</sub> efflux. The surface vegetation inside the soil isolation rings was cleared one day before the measurement, and the topsoil was kept intact to avoid its influence on the measured results. While measuring the soil CO<sub>2</sub> efflux, the temperature probe of the portable photosynthesis system was used to measure the soil temperature in the upper 5-cm soil layer of each plot. Soil water content was measured at depths of 5 cm with water content reflectometers (CS-616, Campbell Scientific, Inc.). The soil samples were then collected from 10- and 20-cm soil layers. The collected soil samples were placed in bags and their circle numbers and sampling depths were numbered. The samples were then transported to the laboratory. Models were

used to examine the relationship between soil CO<sub>2</sub> efflux and soil temperature or soil water content. The models are listed as below:

$$S_R = ae^{bT}, \quad (1)$$

$$S_R = a \ln(w) - c. \quad (2)$$

Where  $S_R$  is soil CO<sub>2</sub> efflux rate (μmol/(m<sup>2</sup>·s)),  $T$  is soil temperature (°C) at 5-cm depth,  $w$  is volumetric soil water content (%) at 5-cm depth, and  $a$ ,  $b$  and  $c$  are constants fitted by the least-square technique. The  $Q_{10}$  values, known as the multiplier to the respiration rate for a 10°C increase in temperature, were calculated as:

$$Q_{10} = e^{10b}. \quad (3)$$

Where  $b$  is taken from Eq. 1.

The relationship between soil CO<sub>2</sub> efflux and soil temperature or soil water content was analyzed using the statistical analysis software SPSS 12.0 for Windows.

## 2 Results and analysis

### 2.1 Spatial variations of soil CO<sub>2</sub> efflux in alpine meadow

The data in Table 2 reflect the spatial changes in soil CO<sub>2</sub> efflux of alpine meadow in the Qilian Mountains during the non-growing season (October 2010 to April 2011). From October of 2010 to April of 2011, the minimum value of soil CO<sub>2</sub> efflux was 0.026 μmol/(m<sup>2</sup>·s), with a maximum value of 1.436 μmol/(m<sup>2</sup>·s) and a spatial variation coefficient of over 50%.

It can be seen from Table 2 that the mean soil CO<sub>2</sub> efflux from October of 2010 to April of 2011 was 0.395–0.738 μmol/(m<sup>2</sup>·s), and that there were sig-

**Table 2** Spatial variation in soil CO<sub>2</sub> efflux based on different altitudes from October of 2010 to April of 2011

Altitude (m)	Mean soil temperature at 5-cm soil depth (°C)	Mean soil water content at 5-cm soil depth (%)	Soil CO <sub>2</sub> efflux (μmol/(m <sup>2</sup> ·s))				
			Average	Min	Max	Standard deviation	Variation coefficient (%)
2,500	−6.90	11.37	0.738	0.061	1.436	0.553	53.48
2,600	−6.11	12.75	0.703	0.058	1.368	0.521	54.26
2,700	−6.98	13.33	0.587	0.056	1.162	0.474	55.27
2,800	−7.35	13.86	0.498	0.043	0.957	0.409	56.19
2,900	−8.21	14.64	0.416	0.037	0.816	0.394	56.78
3,000	−8.69	15.81	0.395	0.026	0.784	0.335	57.11

Note: Sample number is the mean value of five measuring points randomly selected in one sampling plot.

nificant differences in the soil CO<sub>2</sub> efflux of alpine meadow at different altitudes. The largest soil CO<sub>2</sub> efflux (1.436  $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ ) occurred at 2,500 m, followed by 2,600–2,900 m, and finally the smallest at 3,000 m (0.026  $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ ). This shows that soil CO<sub>2</sub> efflux during the non-growing season gradually decreased with the increasing elevation gradient.

## 2.2 Temporal changes of soil CO<sub>2</sub> efflux in alpine meadow

From the changes of soil CO<sub>2</sub> efflux at different altitudes in December 2010 (Fig. 2), it is clear that the daily changes of soil CO<sub>2</sub> efflux in alpine meadow had the following features: soil CO<sub>2</sub> efflux was low at night, and the minimum value occurred between 02:00 and 06:00. Soil CO<sub>2</sub> efflux started to rise between

07:00 and 08:30, with the maximum value occurring between 11:00 and 16:00, and then it began to drop between 16:00 and 18:30. The whole course appeared as a single-peak curve (Fig. 2). The length of the time from rise to drop (taking the data measured in December 2010 as an example) was 13.8 h at 2,500 m, 12.7 h at 2,600–2,700 m, 12.3 h at 2,800–2,900 m, and 11.5 h at 3,000 m. Overall, the duration decreased as the altitude increased.

The continuously observed results of soil CO<sub>2</sub> efflux of alpine meadow in the Qilian Mountains (Table 3) showed that soil CO<sub>2</sub> efflux was associated with seasonal variations, and soil CO<sub>2</sub> efflux values gradually decreased from October to February of the next year, reached a minimum value 0.026  $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ , and finally started to increase in March.

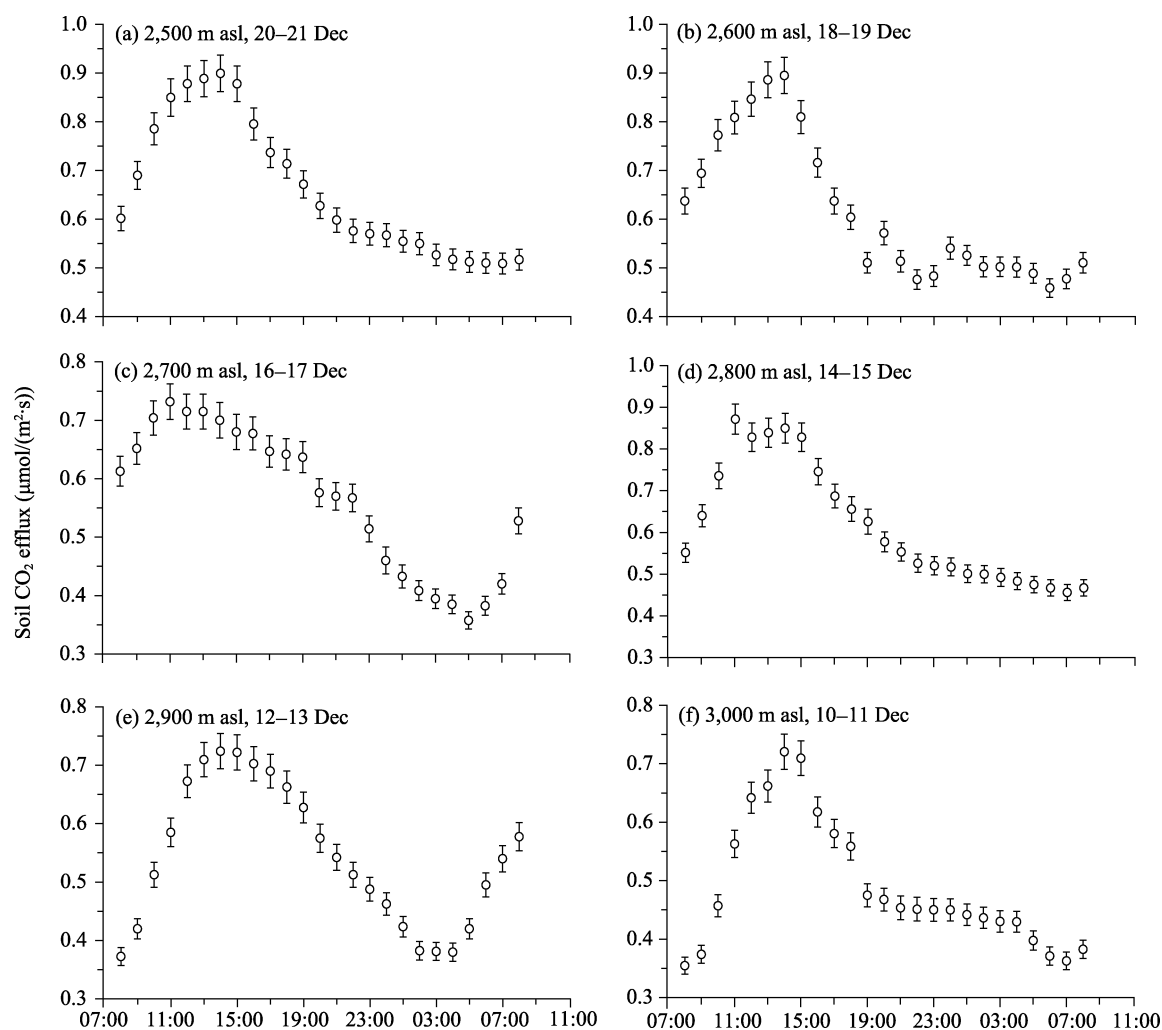


Fig. 2 Diurnal variation of soil CO<sub>2</sub> efflux at different altitudes of alpine meadows in the Qilian Mountains in December 2010

**Table 3** Average soil CO<sub>2</sub> efflux values at different altitudes from October of 2010 to April of 2011

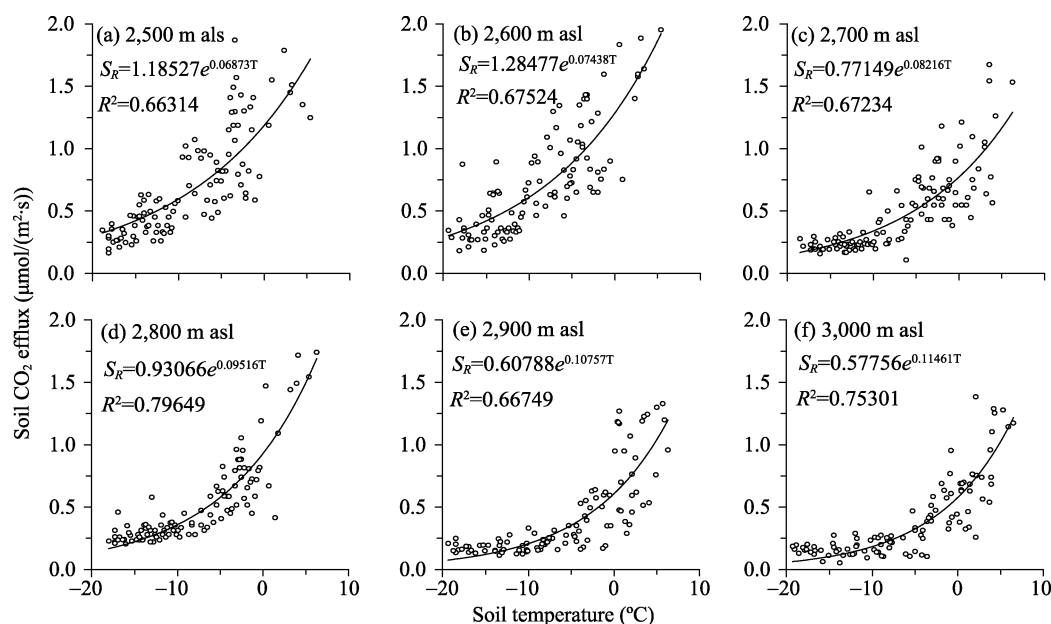
Date	2,500 m	2,600 m	2,700 m	2,800 m	2,900 m	3,000 m
	(μmol/(m <sup>2</sup> ·s))					
Oct 2010	0.96±0.51	0.83±0.47	0.75±0.43	0.68±0.39	0.62±0.35	0.56±0.32
Nov 2010	0.92±0.65	0.76±0.58	0.72±0.67	0.66±0.44	0.61±0.45	0.54±0.39
Dec 2010	0.89±0.58	0.71±0.44	0.69±0.55	0.65±0.47	0.60±0.35	0.51±0.38
Jan 2011	0.87±0.79	0.68±0.57	0.66±0.47	0.63±0.46	0.59±0.36	0.48±0.35
Feb 2011	0.82±0.55	0.66±0.51	0.63±0.46	0.61±0.59	0.57±0.33	0.46±0.37
Mar 2011	0.93±0.64	0.83±0.58	0.79±0.55	0.72±0.57	0.70±0.48	0.57±0.38
Apr 2011	1.11±0.45	1.09±0.34	0.96±0.62	0.78±0.53	0.77±0.47	0.62±0.47

### 2.3 The magnitude of soil CO<sub>2</sub> efflux and its relationship with soil temperature and soil water content

#### 2.3.1 Relationship between soil CO<sub>2</sub> efflux and soil temperature at 5-cm depth

Soil temperature at the depth of 5 cm was generally at a minimum in January, and then increased from February to April, responding to changes in air temperature (data not shown). Mean soil temperatures from October to March of the next year in the alpine meadow were −7.21°C. However, when combining the April data (early spring) with the soil CO<sub>2</sub> efflux data, a significant positive trend was found between soil respiration and soil temperature (Fig. 3). Non-linear

regression analysis showed that the exponential model can best describe the relationship between soil CO<sub>2</sub> efflux and the soil temperature at 5-cm depth in alpine meadow in the Qilian Mountains (Fig. 3). An exponential regression of observed soil CO<sub>2</sub> efflux onto soil temperature showed that Q<sub>10</sub> values during the non-growing season were 1.988, 2.104, 2.274, 2.590, 2.932 and 3.146 from altitude 2,500 to 3,000 m (Fig. 3). The average Q<sub>10</sub> value in the Qilian Mountains was higher than the average growing season Q<sub>10</sub> value in the Heihe River Basin (Chang et al., 2005b). The model describing an exponential relationship between soil respiration and soil temperature at a depth of 5 cm simulated the variation of soil CO<sub>2</sub> efflux very well during the non-growing season.



**Fig. 3** Relationship between soil CO<sub>2</sub> efflux and soil temperature at 5-cm depth of different altitudes during the non-growing season in an alpine meadow

### 2.3.2 Relationship between soil CO<sub>2</sub> efflux and soil water content at 5-cm depth

During the non-growing season, the variation trends of soil CO<sub>2</sub> efflux in alpine meadow in the Qilian Mountains were consistent with those from soil water measurements. The soil water content at 5-cm depth increased with altitude (Fig. 4a). When soil water content was low, the variations of soil CO<sub>2</sub> efflux and soil water content were almost synchronous, i.e. soil CO<sub>2</sub> efflux increased with increases in soil water content, but at certain high levels of soil water content,

soil CO<sub>2</sub> efflux increased slowly. Analytical results show that the soil CO<sub>2</sub> efflux exhibited a linearly increasing trend along with an increase in the soil water content, and this relationship was explained by the equation  $S_R = 1.049 \ln(w) - 0.621$  ( $P < 0.001$ ,  $R^2 = 0.588$ ; Fig. 4b). Thus, soil water content alone explained 58.8% of the variation in soil CO<sub>2</sub> efflux, indicating that the inclusion of soil water content into the function did not improve the explanation of soil CO<sub>2</sub> efflux, when compared with regressions based on the soil temperature only.

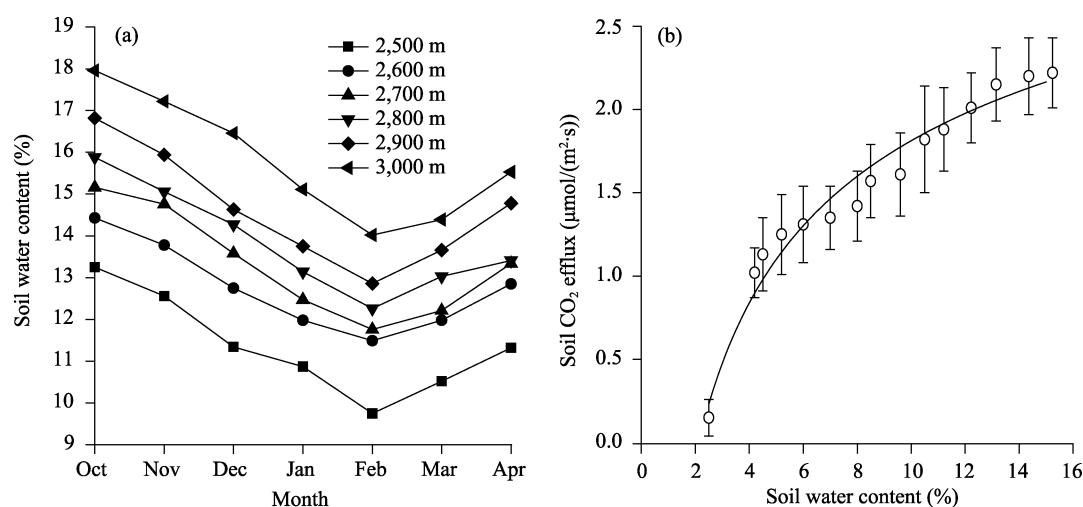


Fig. 4 Temporal changes in mean soil water content at 5-cm depth (a) and relationship between soil CO<sub>2</sub> efflux and mean soil water content at 5-cm depth (b) of different altitudes during the non-growing season in an alpine meadow

## 3 Discussion

Soil CO<sub>2</sub> efflux has spatial variation at various scales. Raich et al. (1998) analyzed the measured soil CO<sub>2</sub> efflux worldwide, and pointed out that there are large differences in the mean rates of soil CO<sub>2</sub> efflux within and between different vegetation types. These authors also noted that the soil CO<sub>2</sub> efflux of the coldest (tundra) and the driest (desert) ecosystems is the lowest, while the highest rate occurs in the tropical rain forest. This latter ecosystem corresponds to high annual temperature and water availability. For most ecosystems, variation coefficients exceed 10%. From the sample collection at intervals of 2–4 m along a 40-m line-transect in a mature poplar forest, Russell and Voroney (1998) found that the variation coefficients of soil CO<sub>2</sub> efflux varied between 16% and 45%. This paper studied an alpine meadow in the Qilian Moun-

tains during the non-growing season, and found that the variation coefficients of soil CO<sub>2</sub> efflux exceed 50%, and that there exist large differences in soil CO<sub>2</sub> efflux at different altitudes. The standard deviation of their measurements gradually decreased with the increasing altitude gradient (Table 2). Soil CO<sub>2</sub> efflux over the non-growing season at all plots varied by a factor of 20. The importance of soil temperature as a key environmental factor controlling seasonal trends of soil respiration processes is consistent with most other soil temperate field studies (e.g. Brooks et al., 1997; Buchmann, 2000; Nordstroem et al., 2001). In addition, seasonal differences also existed in soil CO<sub>2</sub> efflux. Evidence from the observations made in our study led to the conclusion that the soil CO<sub>2</sub> efflux of alpine meadow in the Qilian Mountains is sensitive, while environmental factors varied less.



The daily variations of the soil CO<sub>2</sub> efflux in alpine meadow also showed an obvious diurnal pattern. During the nighttime, the soil CO<sub>2</sub> efflux was lower, while in the daytime it was higher, with the maximum value occurring between 11:00–16:00. The daily variation appeared as a single-peak curve, which is similar to the findings from other grassland studies (Li et al., 2000; Cao et al., 2001; Cui et al., 2001; Jia et al., 2005).

Measurements of the soil CO<sub>2</sub> efflux of alpine meadow in the Qilian Mountains provide a basis for the estimation of the soil CO<sub>2</sub> efflux in that region. Our results showed that during the non-growing season, the average soil CO<sub>2</sub> efflux value was 0.556  $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ , the maximum value was 1.436  $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ , the minimum value was 0.026  $\mu\text{mol}/(\text{m}^2\cdot\text{s})$  (Table 2), and that alpine meadow measurements were congruent with previously reported values (0.025–1.550  $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ ) (Sommerfeld et al., 1993; Frank et al., 2002). For instance, in a semi-arid mixed-grass prairie in North Dakota, Frank et al. (2002) found an average winter respiration rate of 0.48  $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ . We observed a rapid increase in soil CO<sub>2</sub> efflux from late winter (March) to early spring (April) among different altitudes (Table 3). This rapid increase in soil CO<sub>2</sub> efflux from late winter to early spring has also been found in tundra ecosystems (Brooks et al., 1997). This pattern of soil CO<sub>2</sub> efflux most likely reflects abiotic conditions that are conducive to microbial and root respiration at the end of the winter, such as warmer soil temperatures, the greater availability of unfrozen water (Ostroumov and Siegert, 1996), and root growth (Hanson et al., 2003).

With regards to the causes of the spatial variations in soil CO<sub>2</sub> efflux, different researchers have different views. Raich (1998) found that there was a better linear relationship between soil CO<sub>2</sub> efflux of different biomes with soil temperature and soil water content at global scale. Fang et al. (1998) reported that the magnitude of the biomass controls the spatial distribution of soil CO<sub>2</sub> efflux, while the effects of soil temperature and soil water content can be overlooked. Xu and Qi (2001) reported that root system and microorganism biomass, soil physical-chemical properties, soil

temperature and soil water content are highly correlated with the spatial variation of soil CO<sub>2</sub> efflux. Our study on an alpine meadow ecosystem in the Qilian Mountains shows that soil CO<sub>2</sub> efflux was highly correlated with both soil temperature and soil water content during the non-growing season.  $Q_{10}$  values have been reported positively correlated with soil temperature (Atkin and Tjoelker, 2003). The  $Q_{10}$  value during the non-growing season in the alpine meadow that we recorded was 1.988–3.146 from altitudes 2,500 to 3,000 m, and average  $Q_{10}$  values was 2.506, which is well within the range (2.0–6.3) reported for other temperate ecosystems (Kirschbaum, 1995; Davidson et al., 1998; Wang et al., 2006). This suggests that soil CO<sub>2</sub> efflux is more sensitive to soil temperature change with the rise of altitude.

Although soil temperature is a key environmental factor controlling spatial and temporal variations in soil respiration, our results indicate that soil water content is also one of the major factors determining the spatial and temporal variations in soil CO<sub>2</sub> efflux in alpine meadows of the Qilian Mountains. Similar results were reported for other sites, and indicated that a critical threshold of soil temperature may exist for active respiration, below which the absence of free water limits contemporaneous heterotrophic contributions to winter CO<sub>2</sub> loss (Schimel and Clein, 1996; Brooks et al., 1997). The exponential relationship reported by Keith et al. (1997) and a bimodal relationship reported by Xu and Qi (2001) showed that soil CO<sub>2</sub> efflux and soil water content were positively correlated at low soil water content (<19%) and negatively correlated at high soil water content (>19%). In our study area, soil water content is lower than 18% in different altitudes at 5-cm depth from October of 2010 to April of 2011. The equation  $S_R=1.049\ln(w)-0.621$  ( $P<0.001$ ,  $R^2=0.588$ ) was found herein, which showed that soil CO<sub>2</sub> efflux and soil water content were positively correlated. The unfrozen water content of soil below 0°C was reported to decline as an exponential or power function of temperature (Romanovsky and Osterkamp, 2000). However, it should be noted that the effect of each of these factors may not be individually explained, because these factors are often covary with soil organic matter content and mete-

orological conditions for soil CO<sub>2</sub> efflux. More detailed analyses are required to understand these interactions.

## 4 Conclusions

This paper described the field measurements of soil CO<sub>2</sub> efflux values during the non-growing season from an alpine meadow ecosystem along an elevation gradient in the Qilian Mountains of arid Northwest China. We conclude that the spatial variation of soil CO<sub>2</sub> efflux in alpine meadow in the Qilian Mountains during the non-growing season showed that the soil CO<sub>2</sub> efflux gradually decreased along the elevation gradient. Furthermore, the variation coefficient of the soil CO<sub>2</sub> efflux gradually increased (53.48%–57.11%) with the increase of elevation gradient. Soil CO<sub>2</sub> efflux values measured in our study area during the nighttime stayed low. The soil CO<sub>2</sub> efflux was the lowest between 02:00 and 06:00, started to rise between 07:00 and 08:30, and after reaching a maximum value between 11:00 and 16:00, began to drop from 16:00 to 18:30. Seasonally, the monthly mean minimum value of the soil CO<sub>2</sub> efflux occurred in February ( $0.46 \pm 0.37 \mu\text{mol}/(\text{m}^2 \cdot \text{s})$ ).

The results showed that soil temperature and soil water content are the dominant abiotic controls of soil respiration in the alpine meadow of the Qilian Mountains. The spatial-temporal pattern of soil CO<sub>2</sub> efflux cannot be explained by soil temperature alone, but can be explained by the combination of soil water content and soil temperature. Soil temperature was the major environmental factor controlling CO<sub>2</sub> exchange: low soil temperature limited ecosystem respiration. The soil water content might affect respiration rates in the ecosystem. It is challenging to separate the effects of soil temperature and soil water content on the ecosystem carbon budget. However, simulation models that include the driving factors of soil temperature and soil water content can explain most of the spatial-temporal variations in soil CO<sub>2</sub> efflux. Continuous measurements are needed to explain more aspects of the spatial-temporal variation that we have documented here, particularly for diurnal patterns and extreme events.

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